Block course on Computational Neuroscience, Fall 2011
ETH course number 551-0335-00L

Neuromorphic Engineering, with Biological and Silicon Retinas

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Outline of course

- Neuromorphic Engineering (NE)
  - Context of electronics (synchronous logic)
  - Motivation for NE by contrasting computers and brains
- Silicon technology and the operation of a single transistor
  - CMOS vs. complementary channels in neurons
- The biology of the retina
  - How retinas uses adaptive photoreceptors and horizontal cells, together with bipolar cells, to compute rectified local contrast
  - The Physiologist's Friend Chip
  - The Dynamic Vision Sensor

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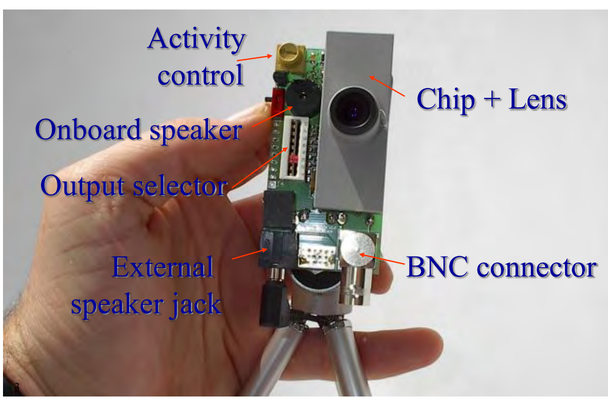
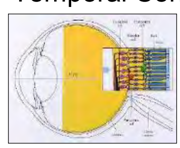
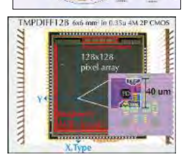
The Physiologist's Friend Chip

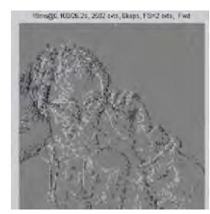


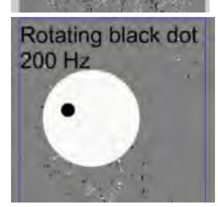
Temporal Contrast Dynamic Vision Sensor (DVS)





1. This silicon retina **asynchronously** outputs **pixel address-events**.
2. Each event represents a fixed ***temporal contrast*** (ΔlogI), corresponding to change in scene reflectance.





1. Models transient pathway in retina.
2. Reduces redundancy
3. Responds quickly and preserves timing
4. Has wide dynamic range

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Neuromorphic Electronics?

What is it all about?

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The context, of silicon electronics with synchronous logic

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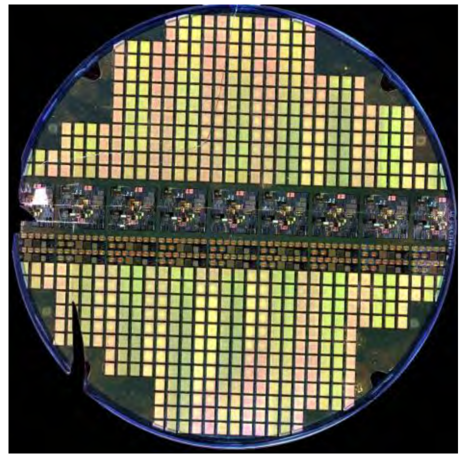
•1947

7

•2000



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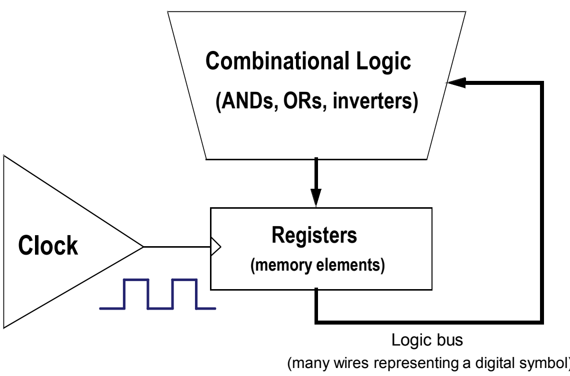
Synchronous logic is ubiquitous



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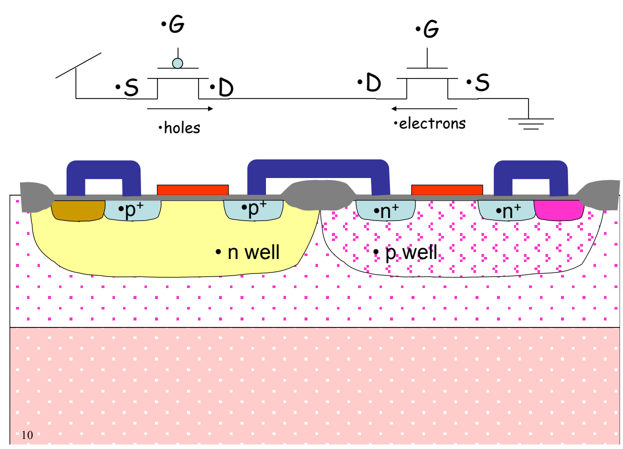

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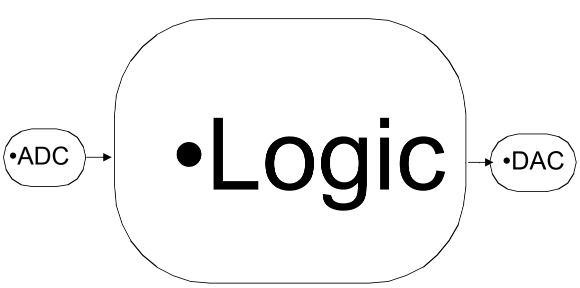
Artificial real-world computation
(or: How industry thinks of analog)



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The motivation

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•Natural computation

•Flies acrobatically
•Recognizes patterns
•Navigates
•Forages
•Communicates

•10^{-15} J/op

•Digital silicon 10^{-7} to 10^{-11} J/op

•10^{8} to 10^{4} times as efficient as digital silicon

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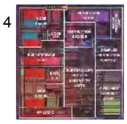
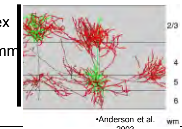
•Computer vs. Brain

•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 activating 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 precision adaptive data-driven quantizers
Devices frozen on fabrication	Constant adaptation and self-modification

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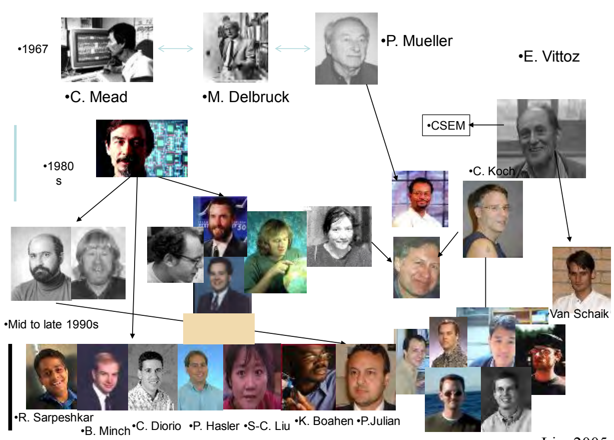

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•Liu, 2005

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.

C. Mead, Proc. IEEE, 1990

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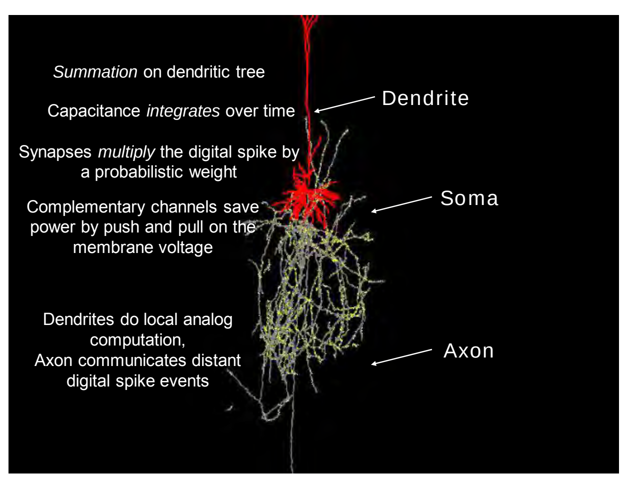
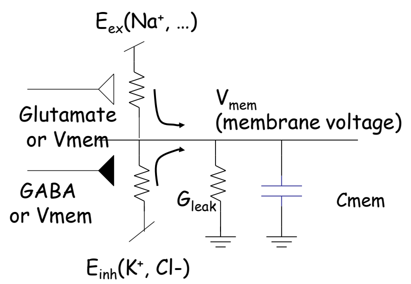


The membrane voltage is controlled by complementary transmitter or voltage gated channels



Almost no power is burned when both channels are off!

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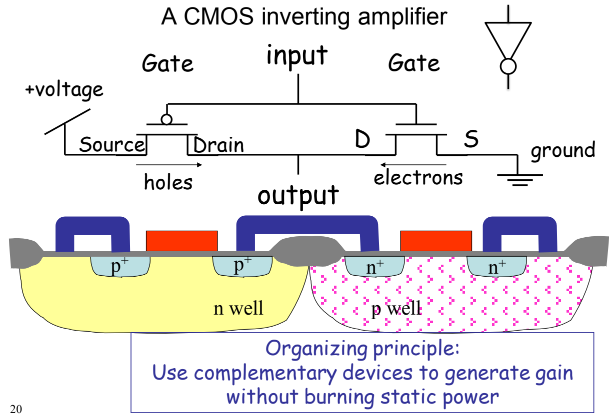
CMOS (complementary metal oxide semiconductor)

A CMOS inverting amplifier



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Interlude on semiconductors and transistors

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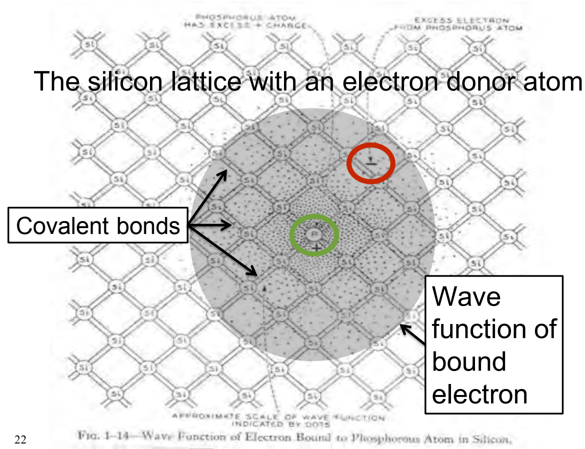
The silicon lattice with an electron donor atom



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Donors and Acceptors in the periodic table

I	II	III	IV	V	VI	VII	Zero
H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Cd	In	Sn	Sb	Te	I	Xe

Acceptors 1 missing electron | Donors 1 extra electron

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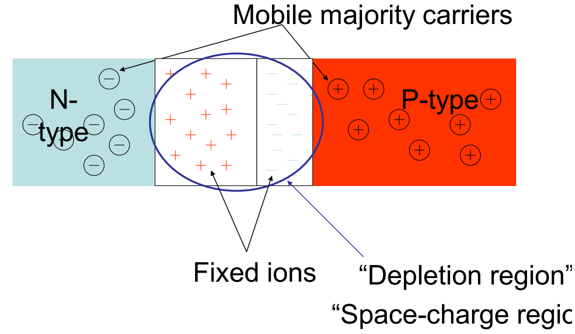
A P-N junction



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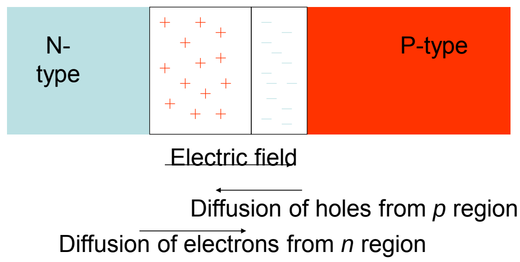
A P-N junction



In equilibrium, *Drift* = *Diffusion* for electrons *and* holes

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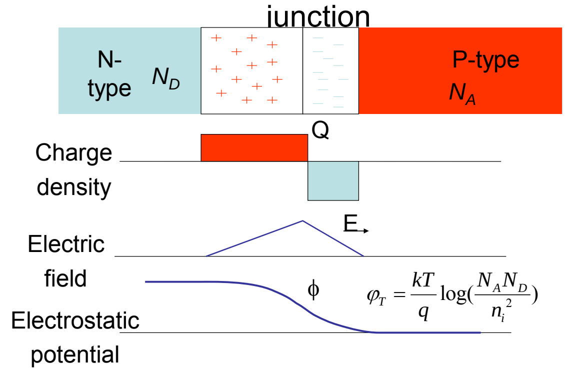
Charges, fields, and potentials in a PN junction



$$\varphi_T = \frac{kT}{q}\log\left(\frac{N_A N_D}{n_i^2}\right)$$

Typically, the *built-in voltage*, φ_T, is about 0.75V

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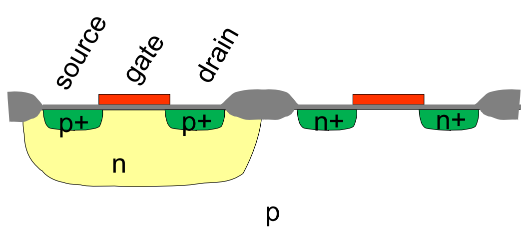
MOS transistors use insulated gates to control barrier energies at PN surface junctions at source and drain



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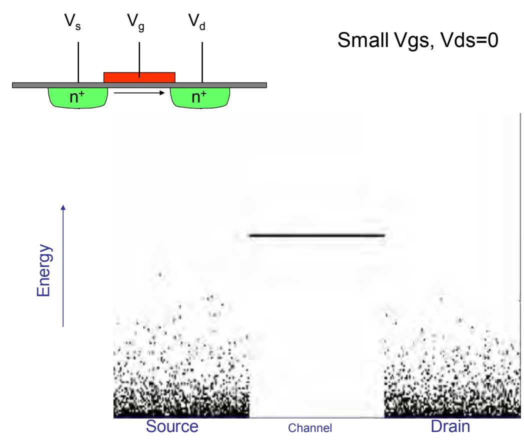
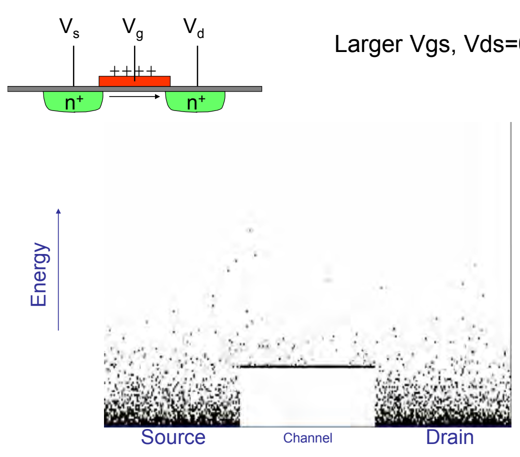
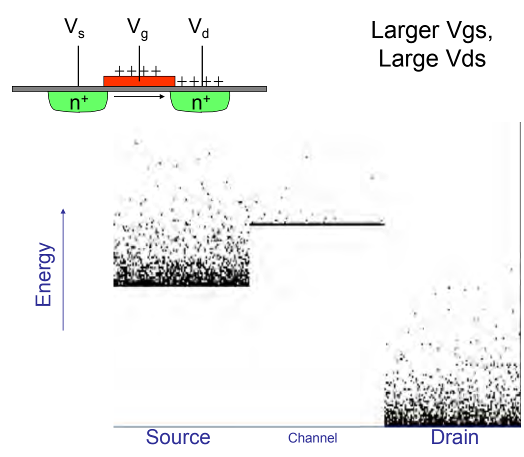
Small Vgs, Vds=0



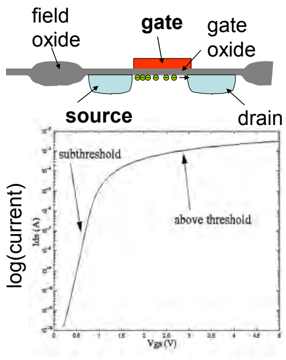
Larger Vgs, Vds=0



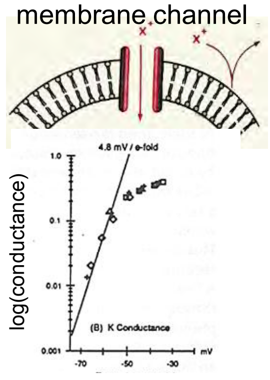
Larger Vgs,
Large Vds



Transistor



Voltage activated membrane channel



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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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Biological and silicon retinas

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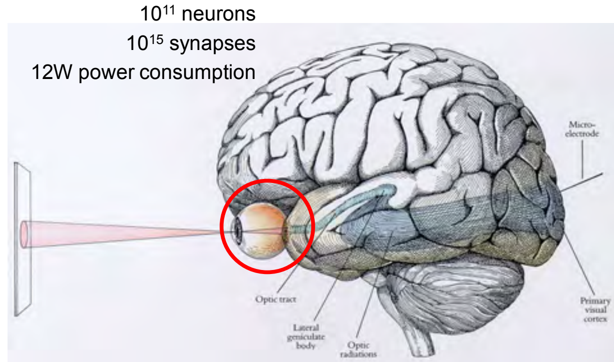
How do we see?

10^{11} neurons
10^{15} synapses
12W power consumption



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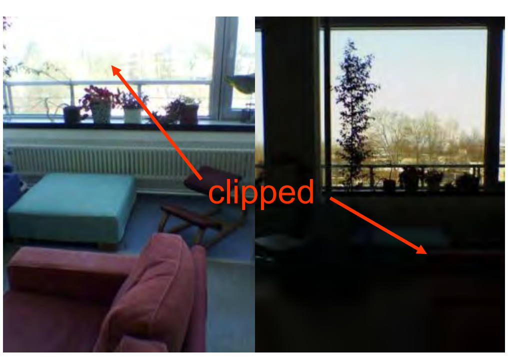
Is your eye a camera?



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Light ranges

1 lux of sunlight is about 10^4 photons/um^2/sec

Direktes Sonnenlicht	100'000 Lux
Sonniger Tag	10'000 Lux
Bedeckter Tag	1'000 Lux
Büro	100 Lux
Einbrechende Dämmerung	10 Lux
Dämmerung	1 Lux
Vollmond	0.1 Lux
Viertelmond	0.01 Lux
Klare mondlose Nacht	0.001 Lux
Bedeckte mondlose Nacht	0.0001 Lux

Camera range
Entire range

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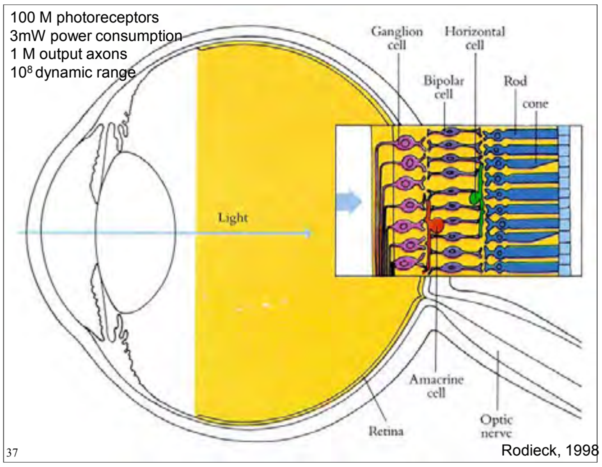
100 M photoreceptors
3mW power consumption
1 M output axons
10^8 dynamic range



Rodieck, 1998

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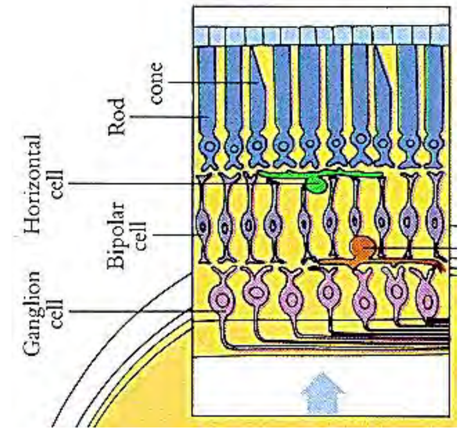

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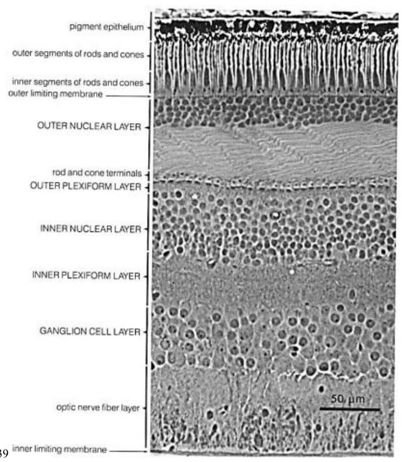

Cross section of human retina

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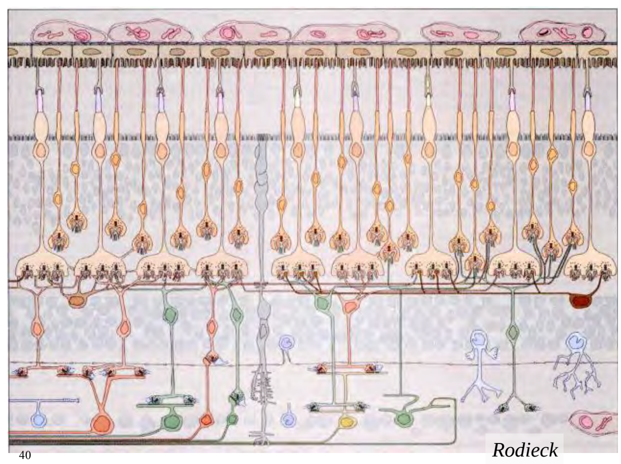

Rodieck

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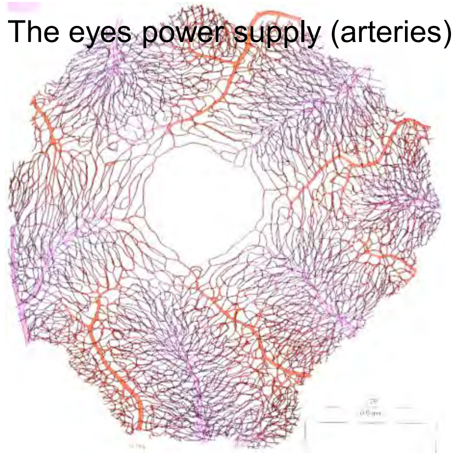
The eyes power supply (arteries)



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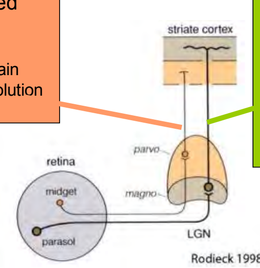
All animals (from insects to us) partition vision into **sustained** and **transient** visual pathways

Sustained (Parvo, X)
Has sustained response
Sees color
Low contrast gain
Higher spatial resolution
Slower

Transient (Magno, Y)
Blind to DC
Monochrome
High contrast gain
Lower spatial resolution
Faster

Standard image sensors do this



Rodieck 1998

Temporal contrast sensor does this

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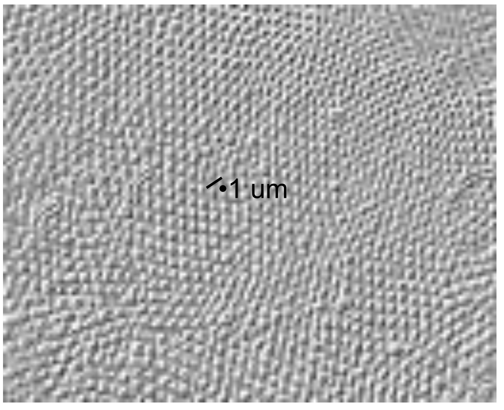
The photoreceptor mosaic in the eye



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Rodieck 1998
The first steps in seeing

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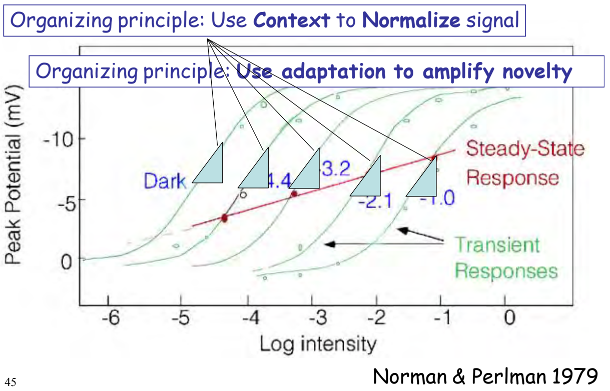
Biological photoreceptors adapt their operating point and gain



Norman & Perlman 1979

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log(Intensity) is self-normalizing and automatically preserves reflectance differences, by normalizing away the constant illumination term in the product of (scene reflectance) * (illumination)

$$d(\log X)=dX/X$$

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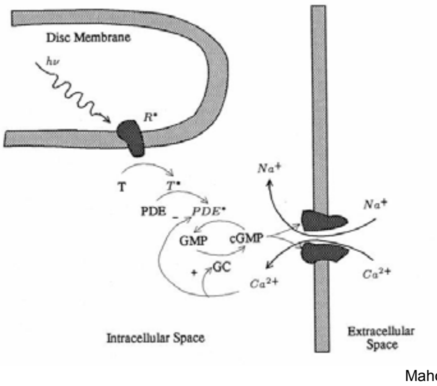
Biological phototransduction uses distributed chain of amplifiers



Mahowald, 1992

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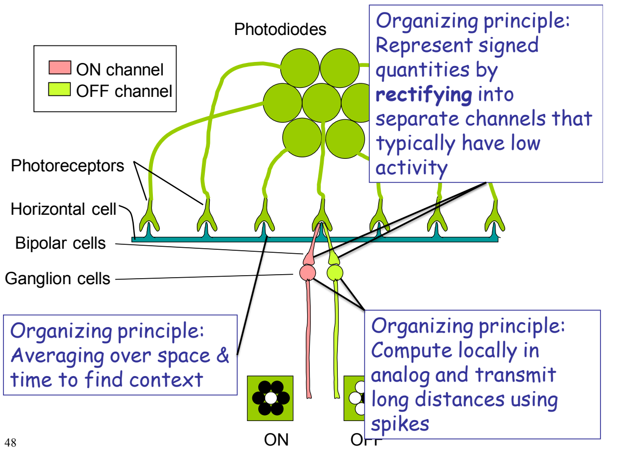

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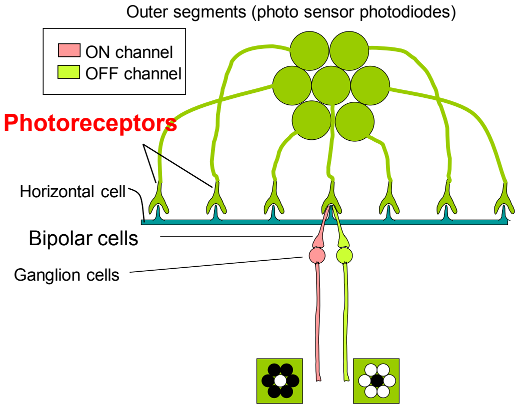

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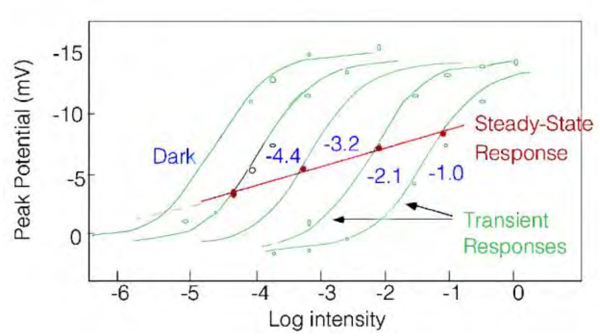
Biological photoreceptors adapt their operating point and gain



Norman & Perlman 1979

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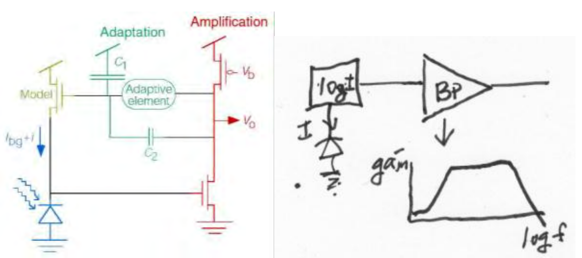
Adaptive Photoreceptor Circuit

Actual circuit

Conceptual circuit



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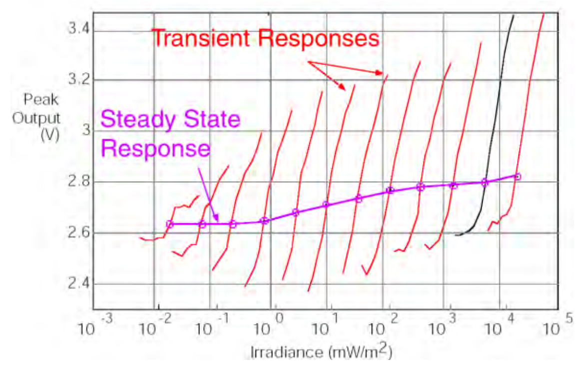
Adaptive photoreceptor responses



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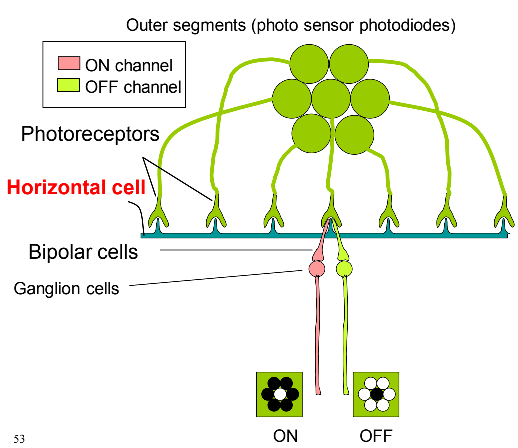

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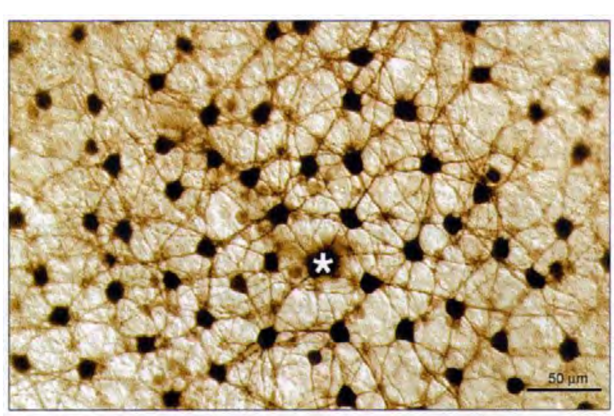

HI horizontal cells labeled following injection of one HI cell (*) ×300

after Dacey, Lee, and Stafford, 1996

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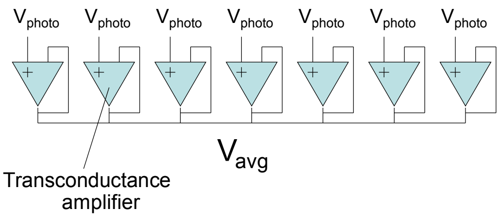
Horizontal cell

A *Follower-Aggregator* averages the photoreceptor outputs to compute the average of the inputs. This average is the *context* which is compared to the photoreceptor.



Because the follower output current saturates, the follower-aggregator computes **mean** for small signals and **median** for large signals

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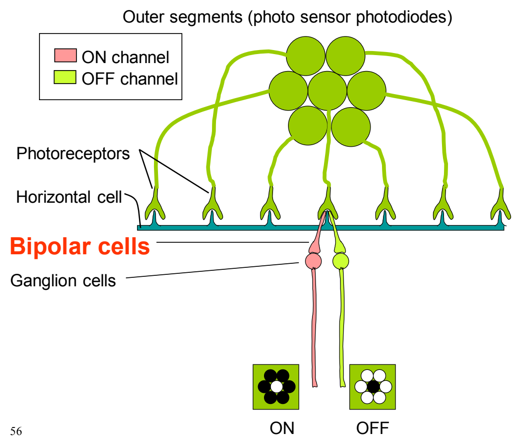

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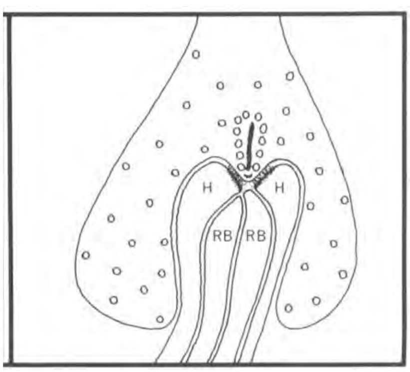
Rod-Horizontal Cell-Bipolar cell junctions



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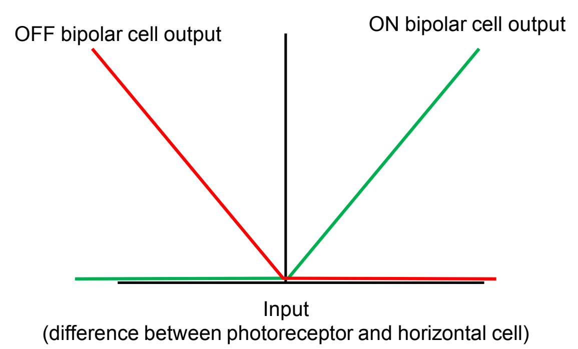
Rectification at the photoreceptor-horizontal cell-bipolar cell synapse



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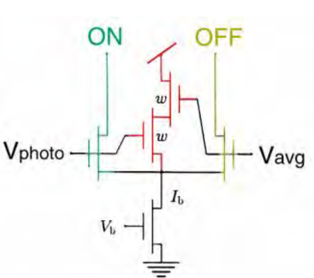
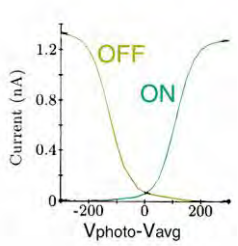
Bipolar Cell (Anti-bump circuit)

Rectifies into ON and OFF currents





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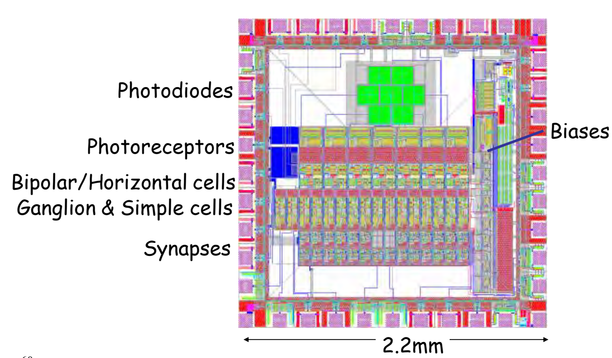
Physio Friend Layout



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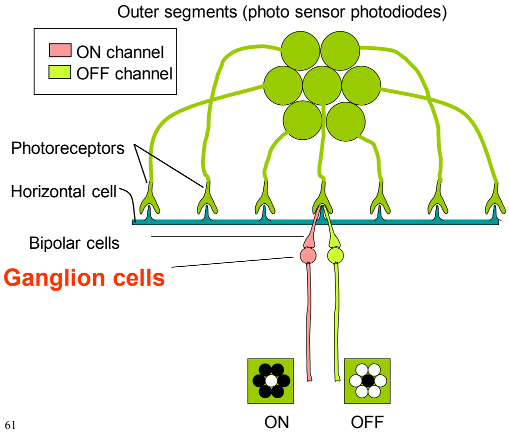

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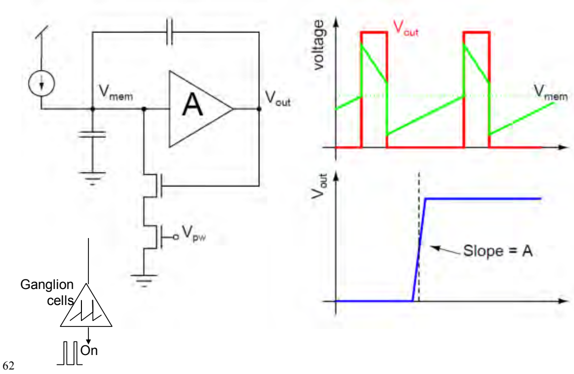
"Axon-hillock" spiking soma circuit turns the bipolar outputs into ganglion cell spikes



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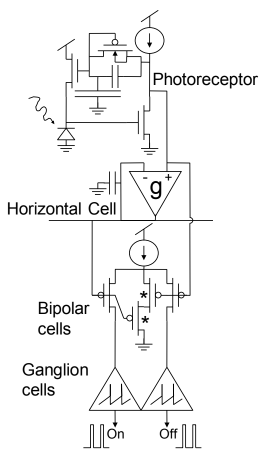
Complete circuit for retina part of Physiologist's Friend circuit



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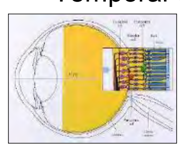
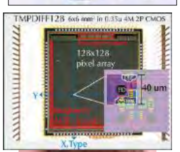
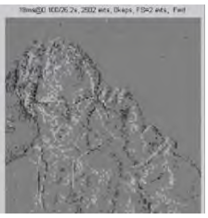
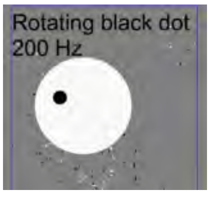
Temporal Contrast Dynamic Vision Sensor





1. This silicon retina **asynchronously** outputs **spiking pixel identities**.
2. Each spike represents a fixed ***temporal contrast*** (ΔlogI), corresponding to change in scene reflectance.





Models transient pathway in retina.
Reduces redundancy
Preserves timing
Has wide dynamic range

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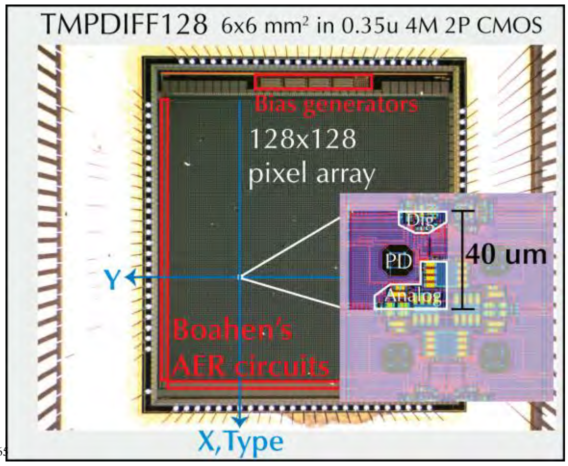

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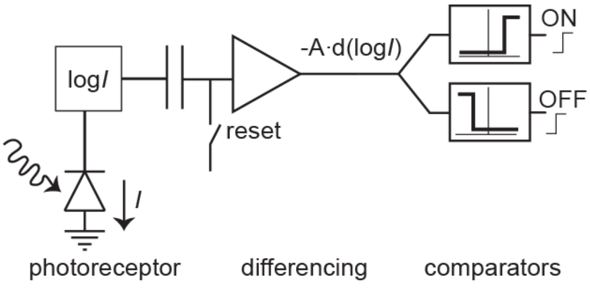
DVS pixel architecture



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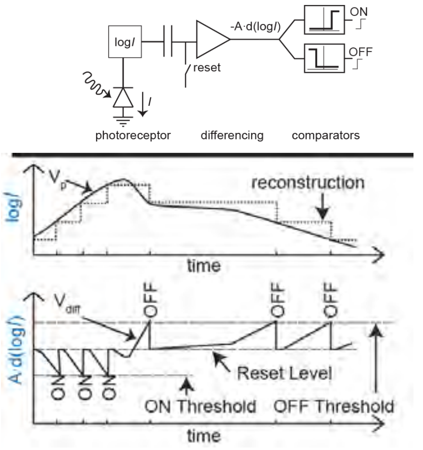

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Embedded DVS Pencil Balancer

Jorg Conradt, Matt Cook

3 microcontrollers, 600mW

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Review

- Neuromorphic Engineering (NE)
  - Context of electronics (synchronous logic)
  - Motivation for NE by contrasting computers and brains
- Silicon technology and the operation of a single transistor
  - CMOS vs. complementary channels in neurons
- The biology of the retina
  - How retinas uses adaptive photoreceptors and horizontal cells, together with bipolar cells, to compute rectified local contrast
  - The Physiologist's Friend Chip
  - The Dynamic Vision Sensor

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