Block course Fall 2013
ETH course 227-1049-00L Insights into Neuroinformatics

Neuromorphic Engineering, with Biological and Silicon Retinas

Tobi Delbruck

Teaching assistants

Haza Montanero

Minhao Yang

Outline of course

- 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
- Silicon technology and the operation of a single transistor
  - CMOS vs. complementary channels in neurons
- Neuromorphic Engineering (NE)
  - Context of electronics (synchronous logic)
  - Motivation for NE by contrasting computers and brains

Reading

Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in Neurobiology
ELSEVIER

Neuromorphic sensory systems

Shih-Chii Liu and Tobi Delbruck

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Vision Research 44 (2004) 2083–2089
Vision Research
www.elsevier.com/locate/visres

A silicon early visual system as a model animal

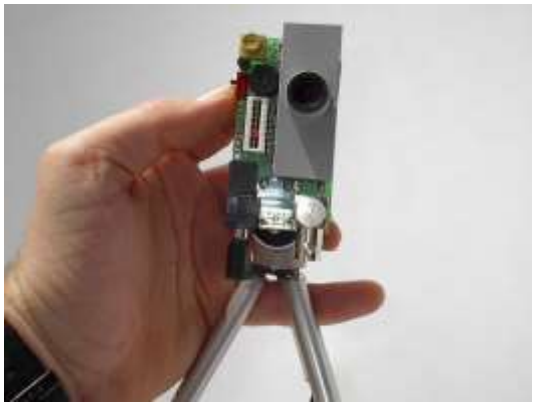
Tobi Delbrück *, Shih-Chii Liu

Institute of Neuroinformatics, University of Zürich and ETH Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

Received 3 July 2003; received in revised form 7 March 2004

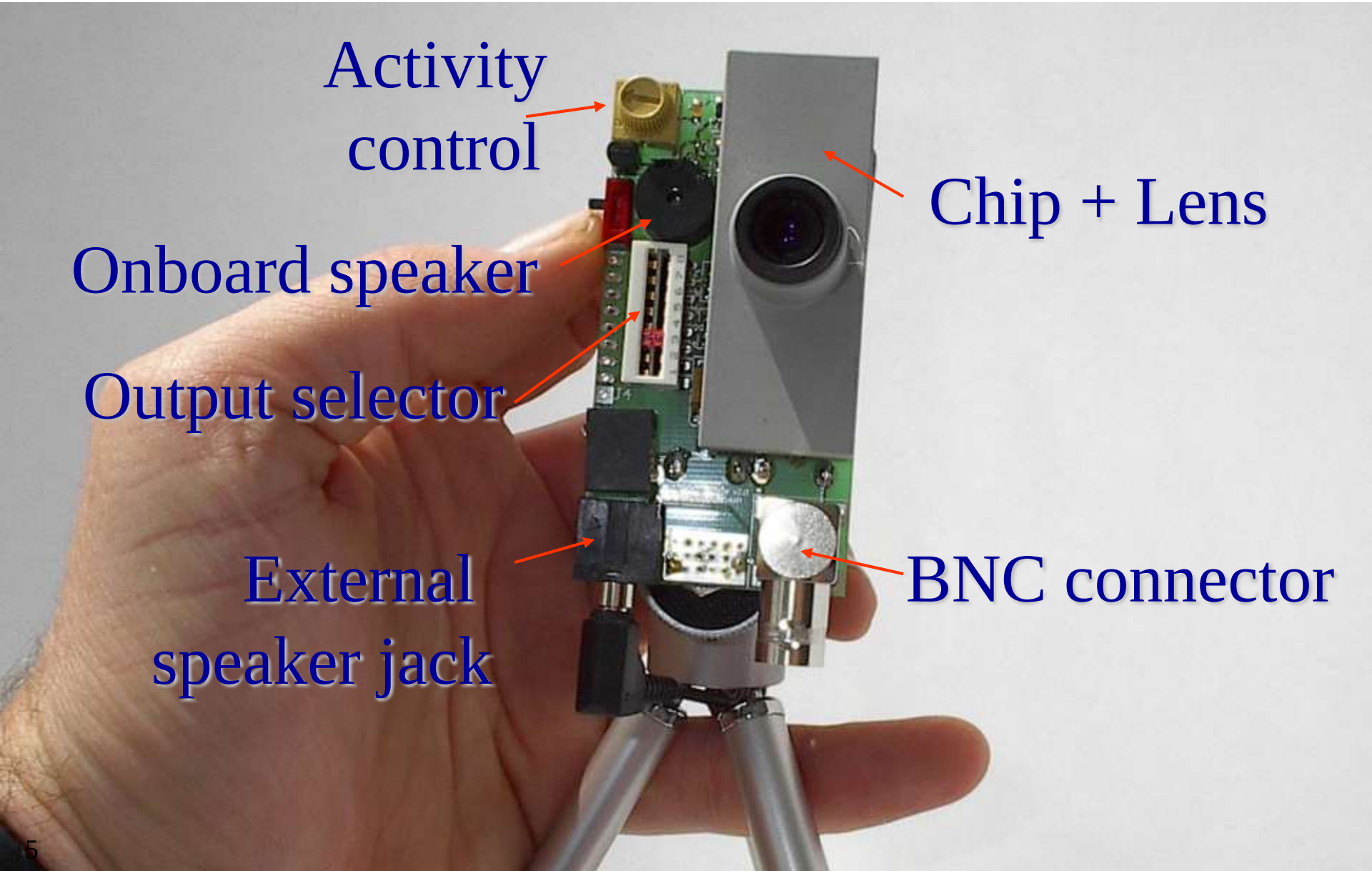
Practical work with

Physiologist's Friend Chip

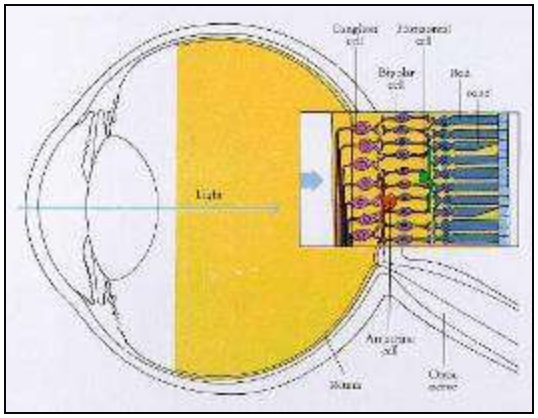


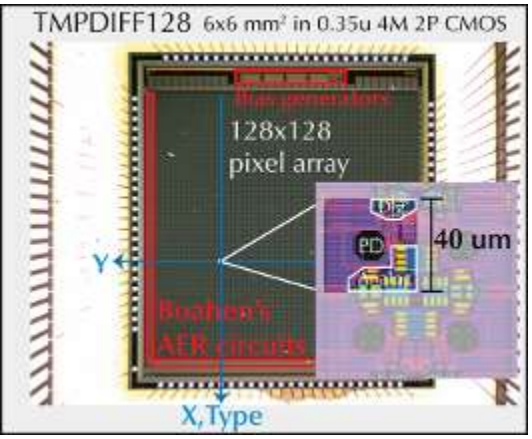
Dynamic Vision Sensor (DVS) silicon retina

The Physiologist's Friend Chip

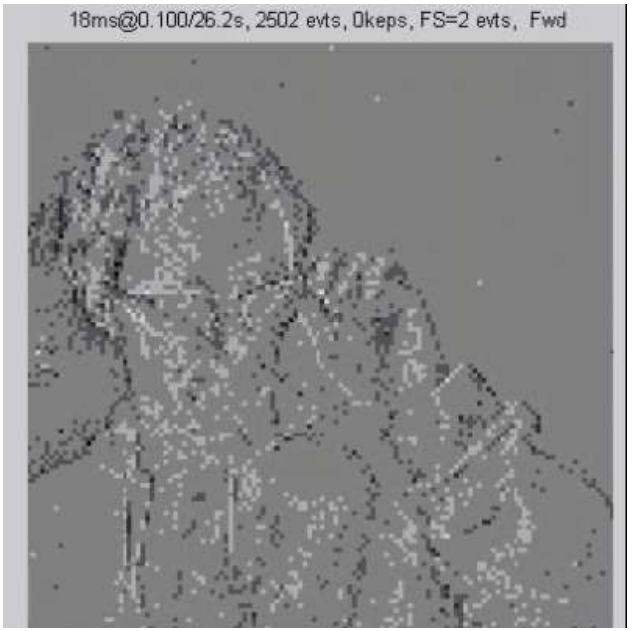


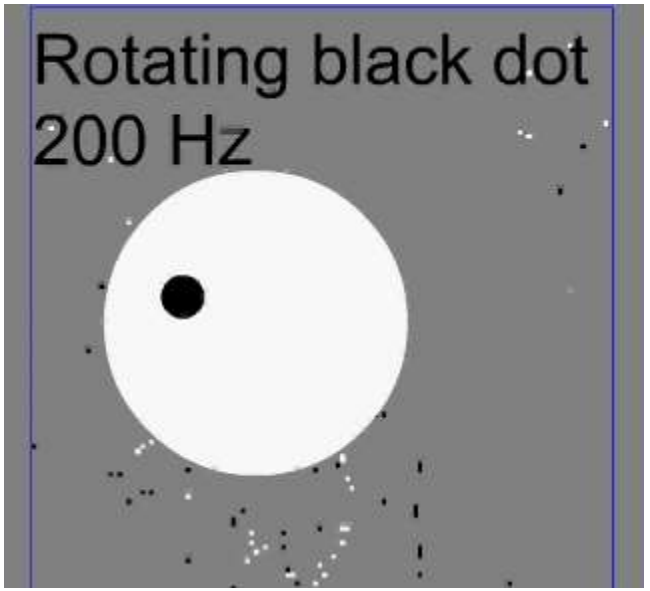
Temporal Contrast Dynamic Vision Sensor (DVS)





1. This silicon retina **asynchronously** outputs **pixel address-events**.
2. Each event represents a fixed ***temporal contrast*** ($\Delta \log I$), 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

Quiz and Grading

- You will have 30 minutes to individually answer a quiz at the end of the course
- Your grade will be based on a combination of quiz and your group report

Schedule

Day 1 (13:00-17:00)

- Lecture on biological retina
- Tutorial on using Physiologist's Friend and DVS
- Start first practical (split into groups and select either Physio Friend or DVS for first exercise)
- Read parts of Physio Friend paper and Neuromorphic Sensory Systems

Day 2 (morning, 9:00-12:00)

- Lecture on electronics and transistors
- Practical work
- Finish reading papers

Afternoon (13:30-17:00)

- Lecture continued
- Finish practical work, write reports
- Quiz

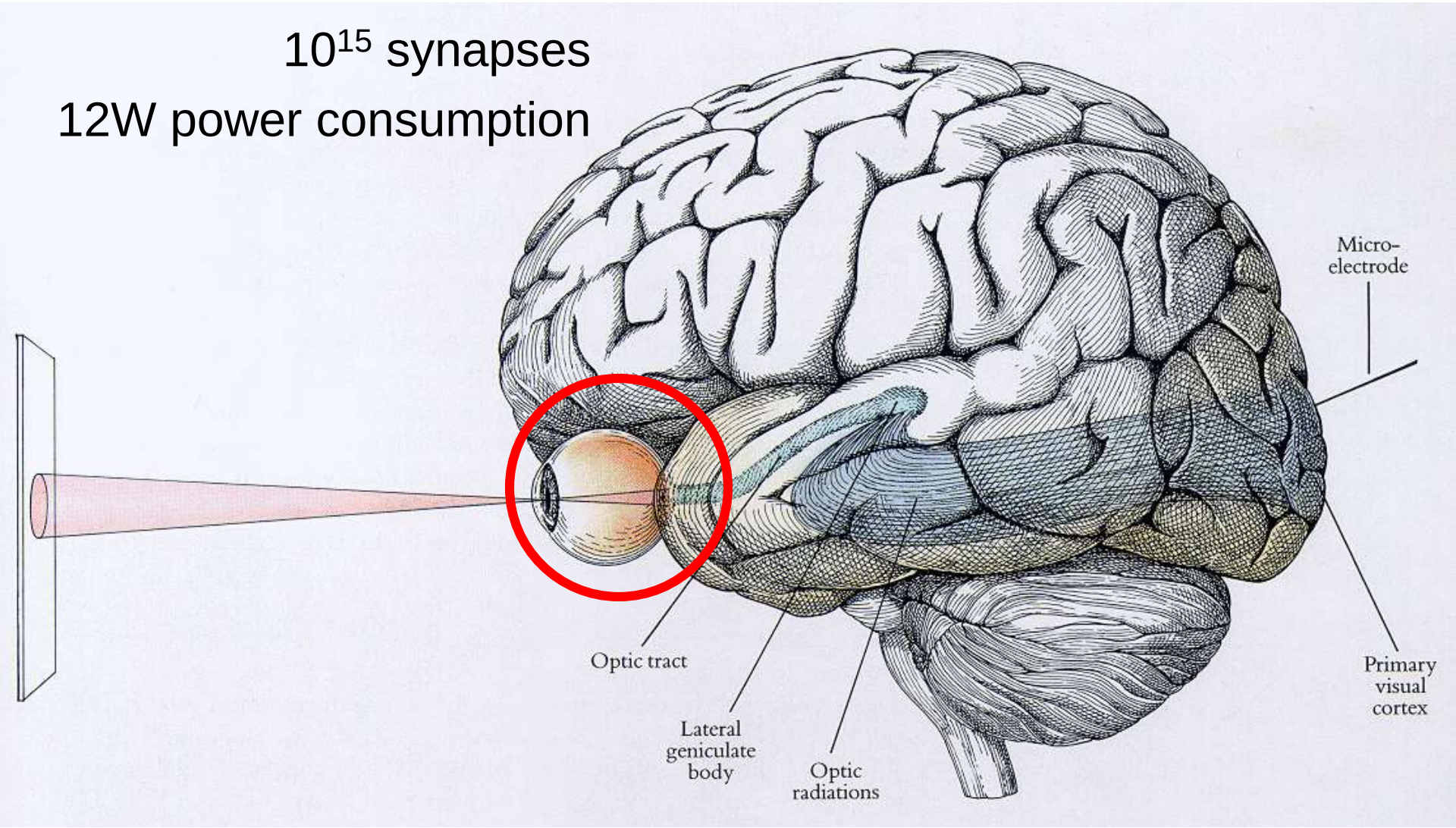
Biological Retinas

How do we see?

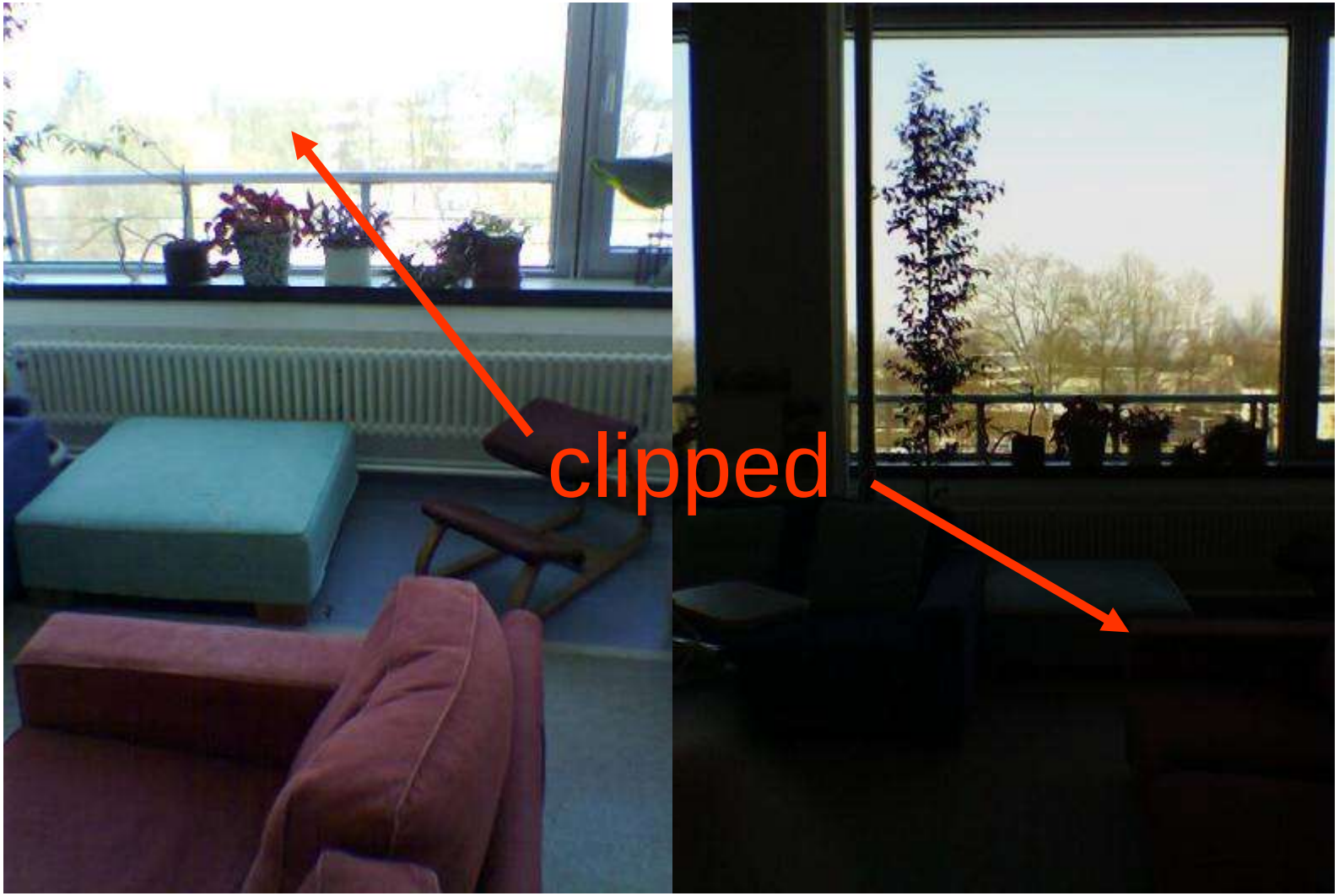
10^{11} neurons

10^{15} synapses

12W power consumption



Is your eye a camera?



Light ranges

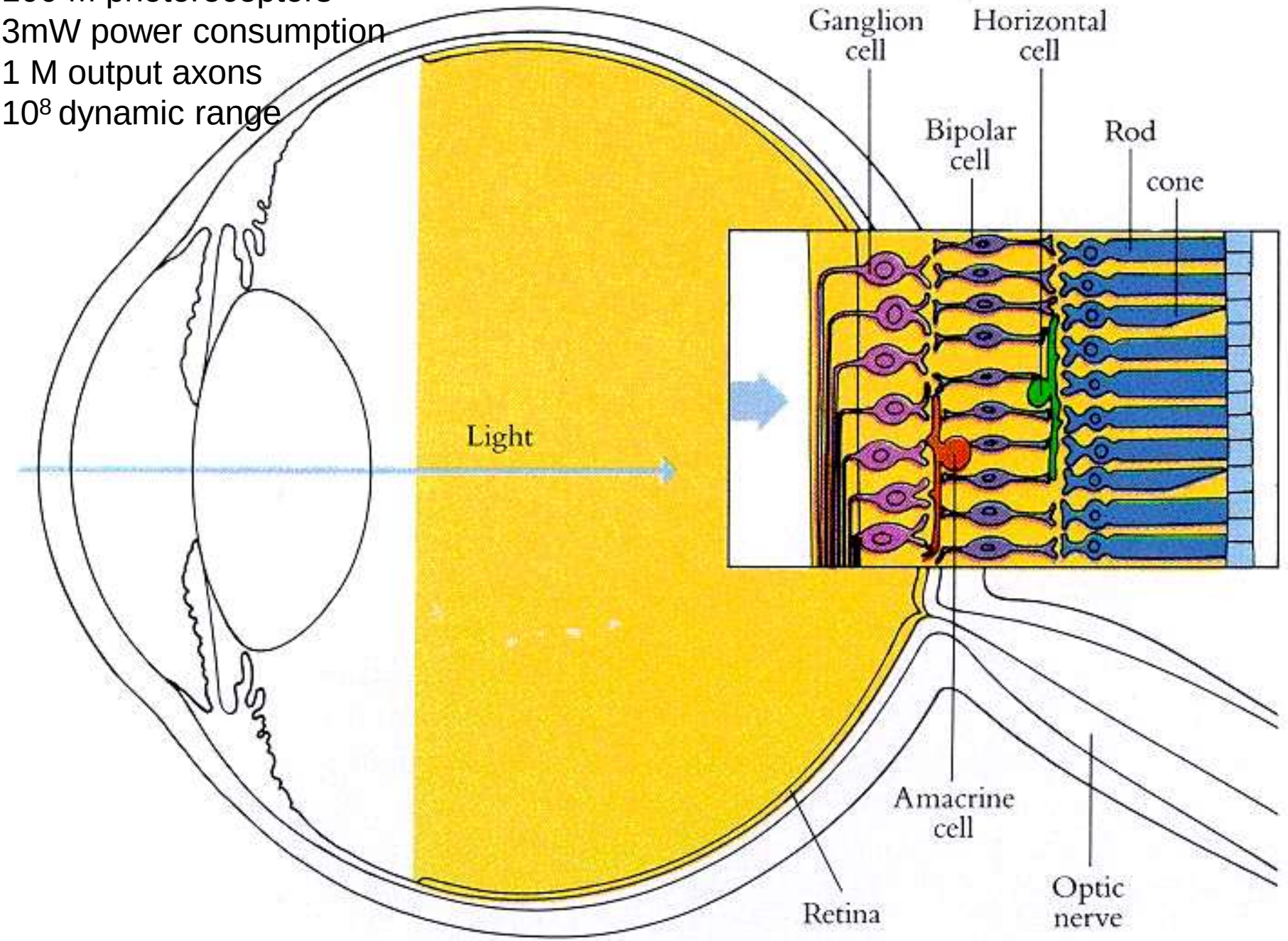
1 lux of sunlight is about 10^4 photons/um^2/sec

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

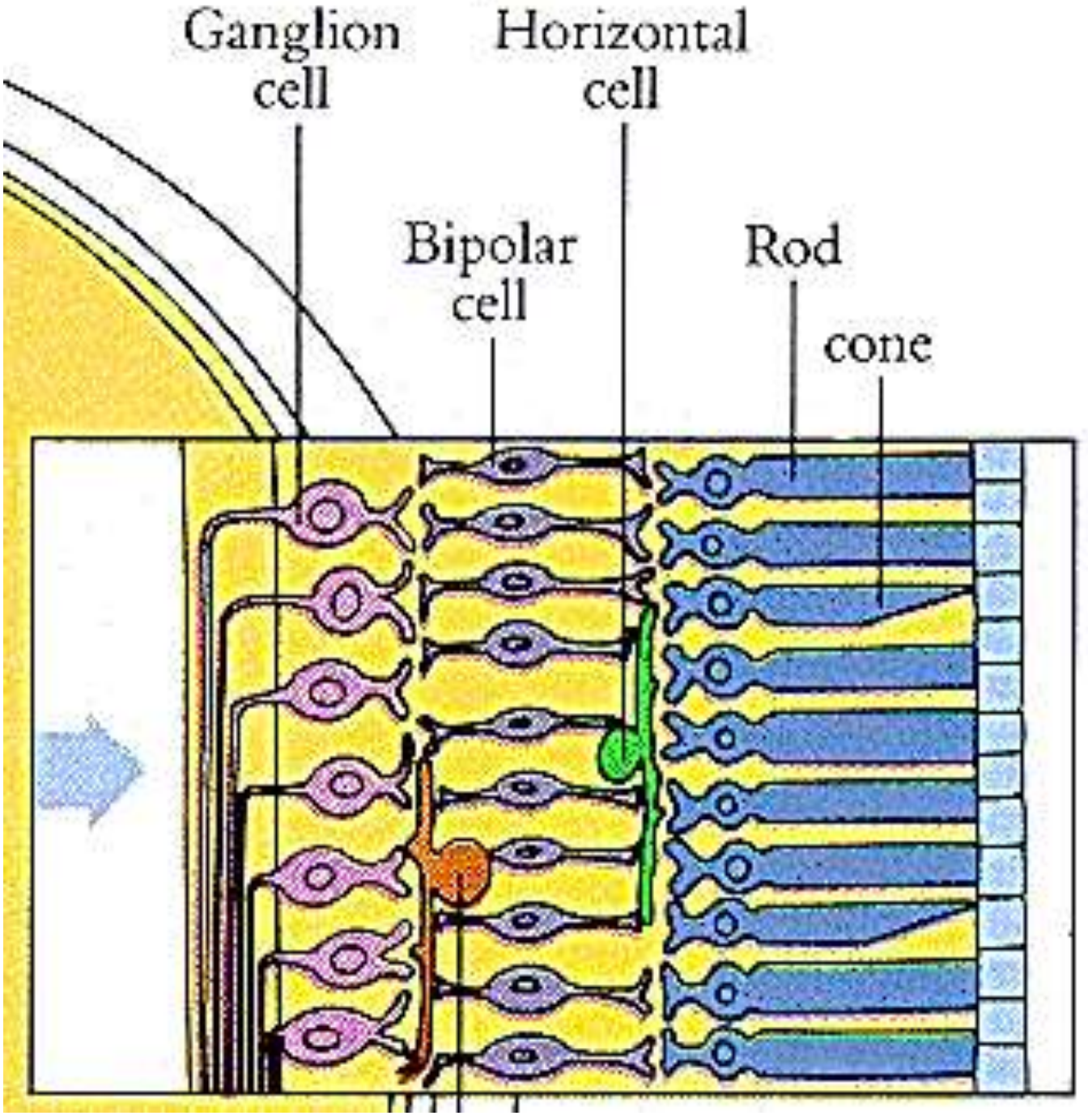
Entire range

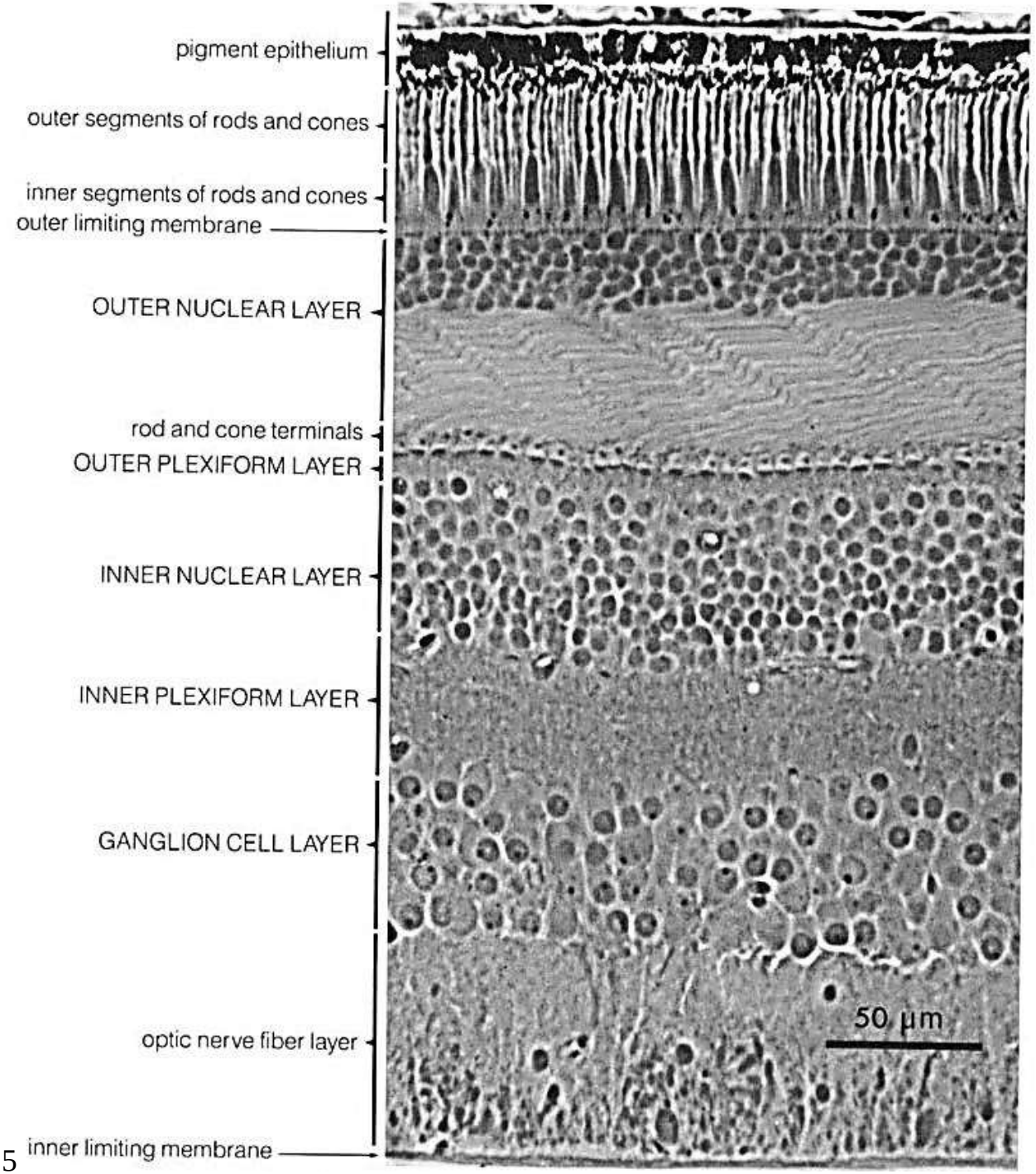
Camera range

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

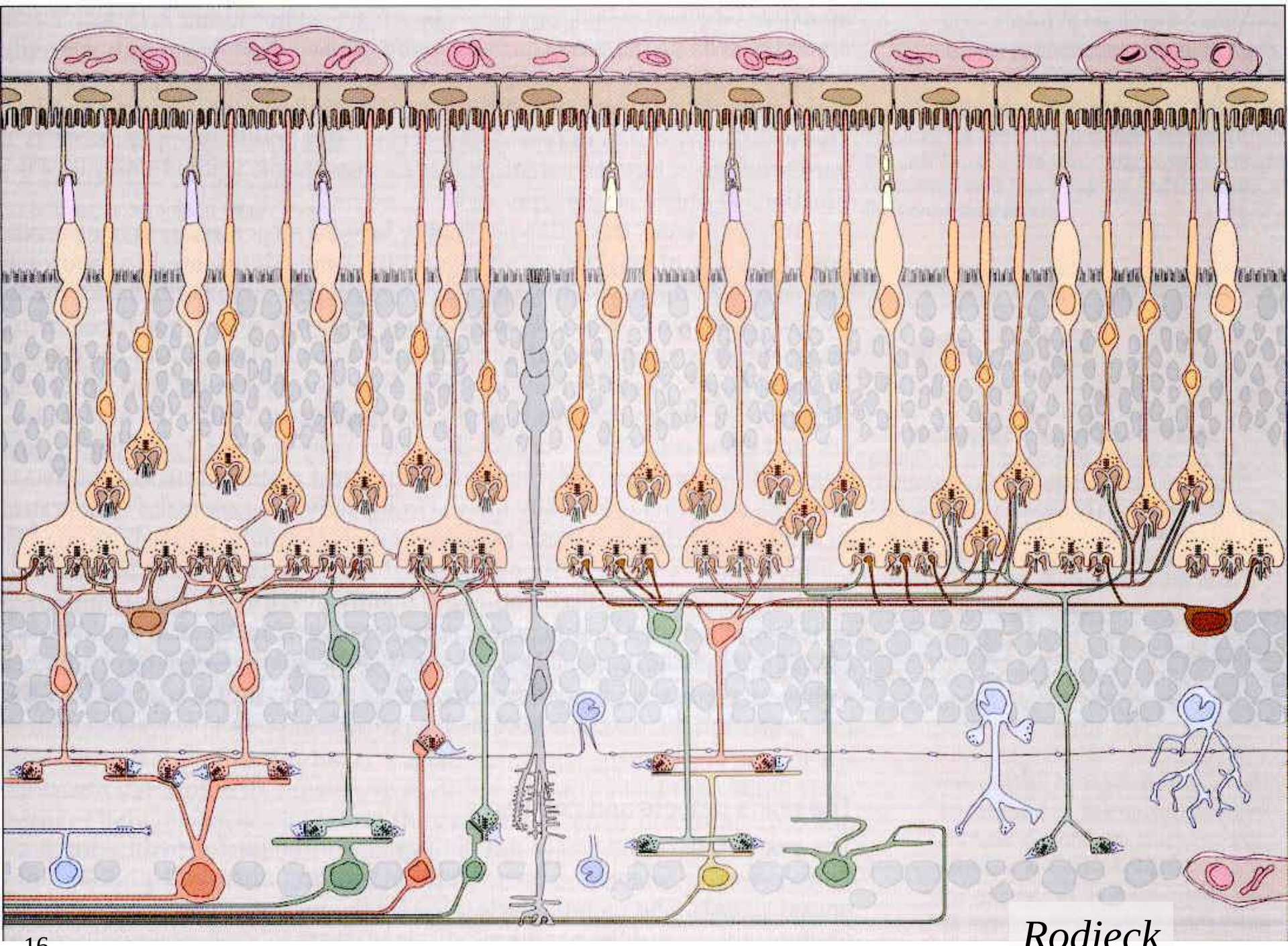


Rodieck, 1998


Ganglion cell
Horizontal cell
Bipolar cell
Rod
cone

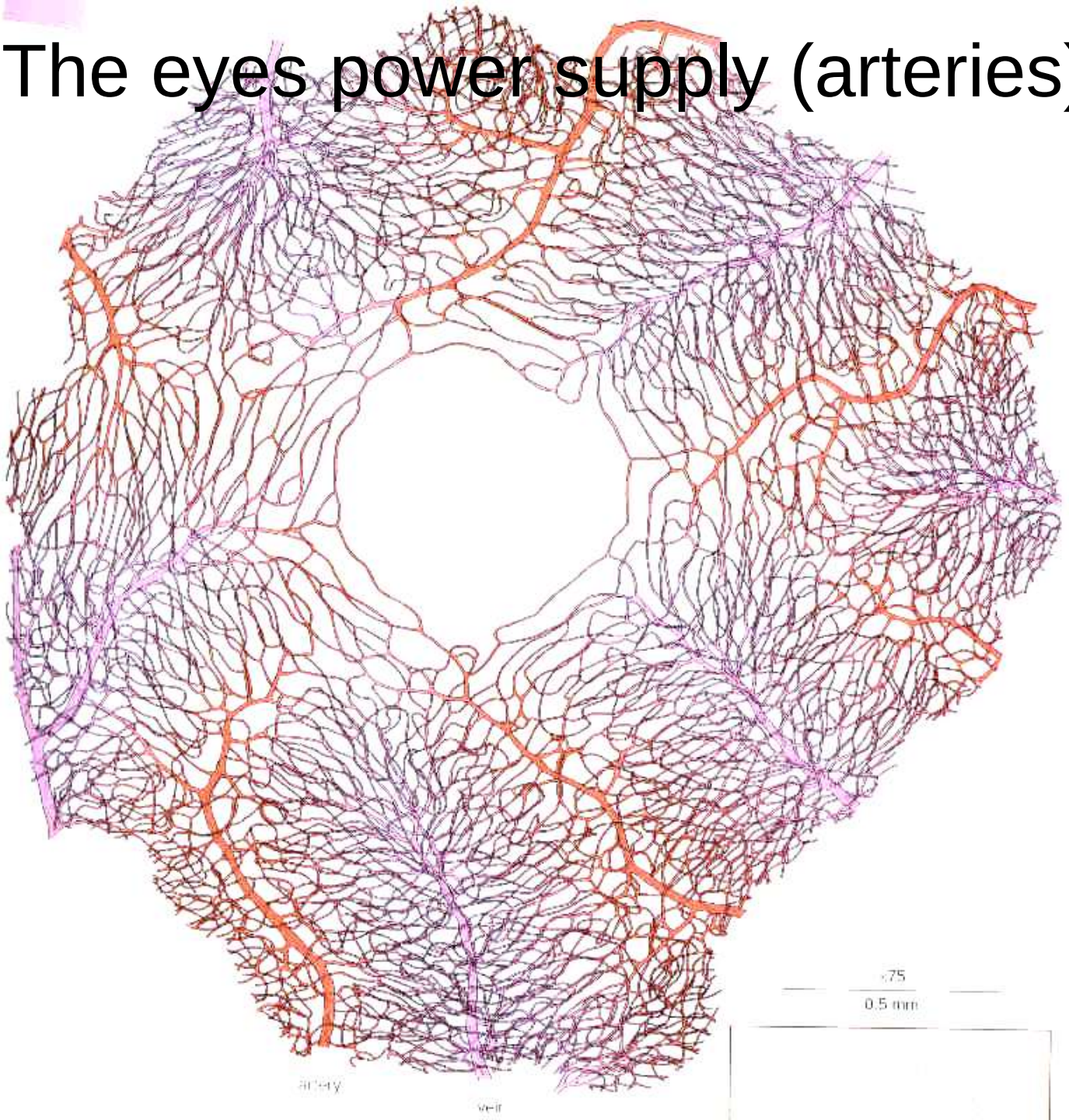


Cross section of human retina



Rodieck

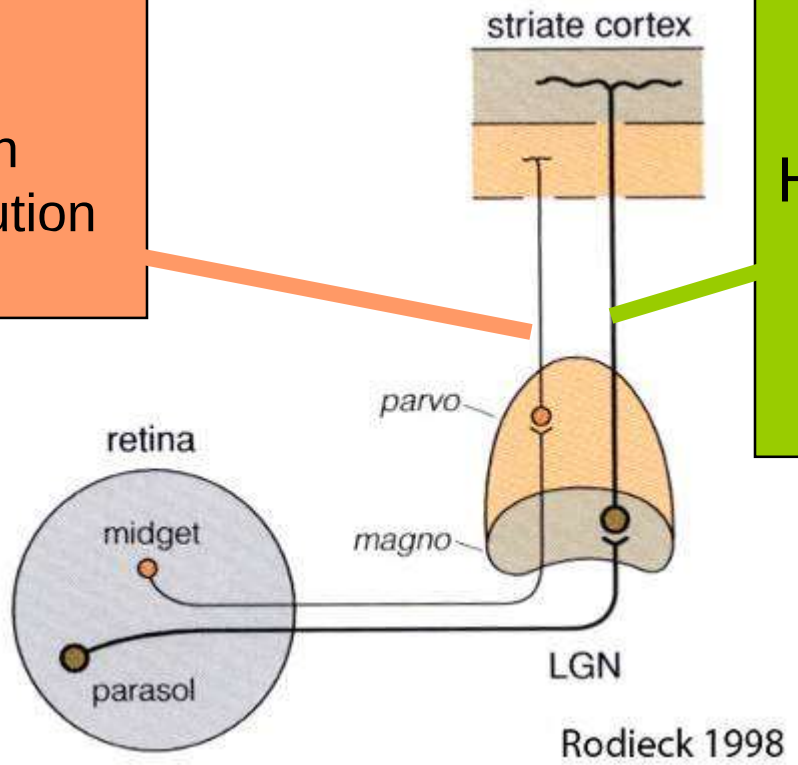
The eyes power supply (arteries)



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

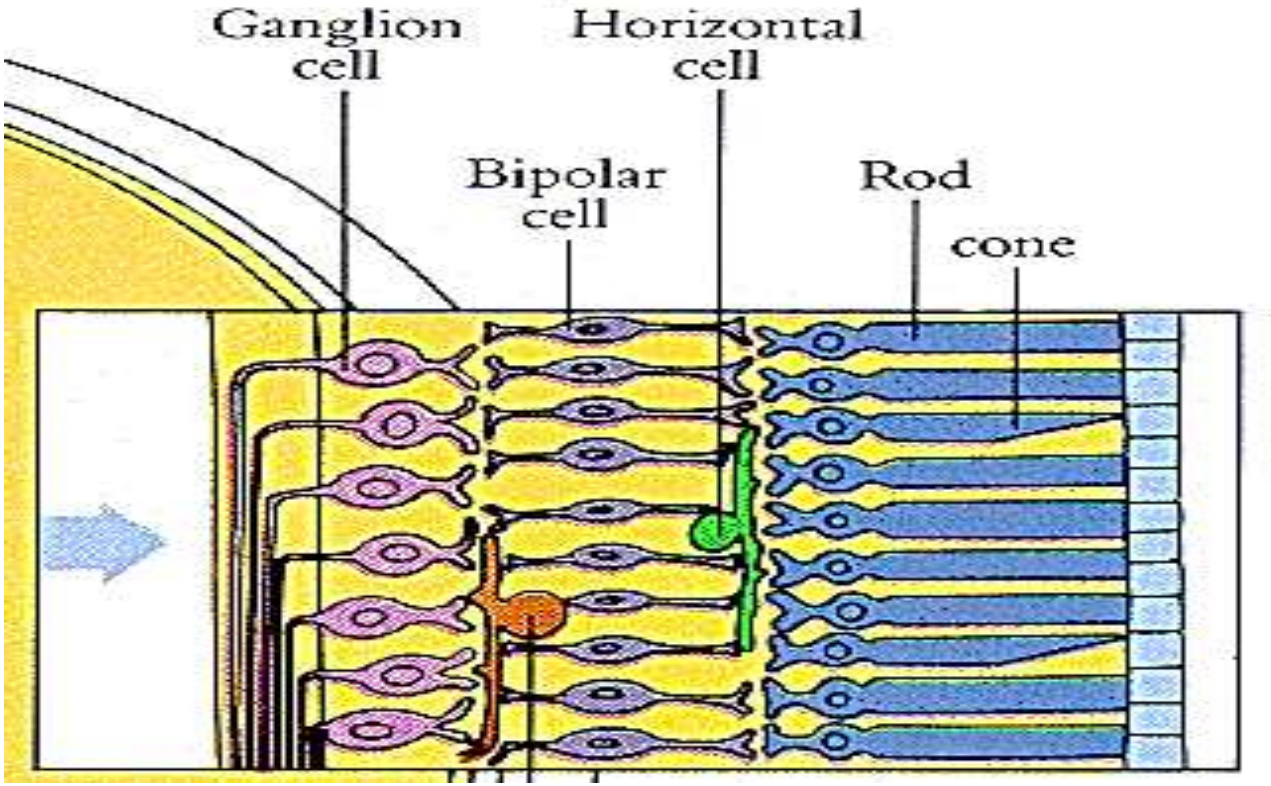


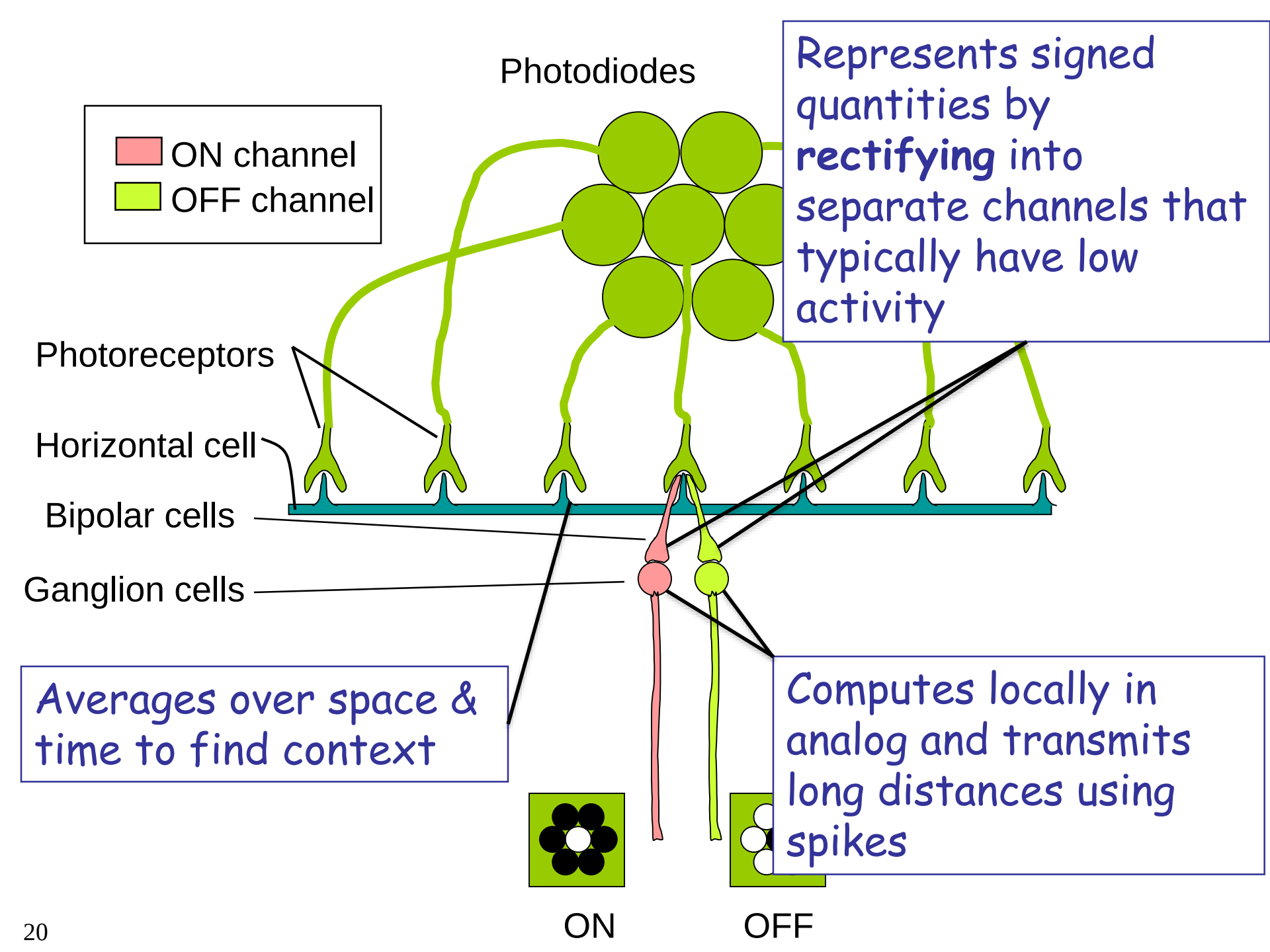
Standard image sensors do this

Temporal contrast sensor does this

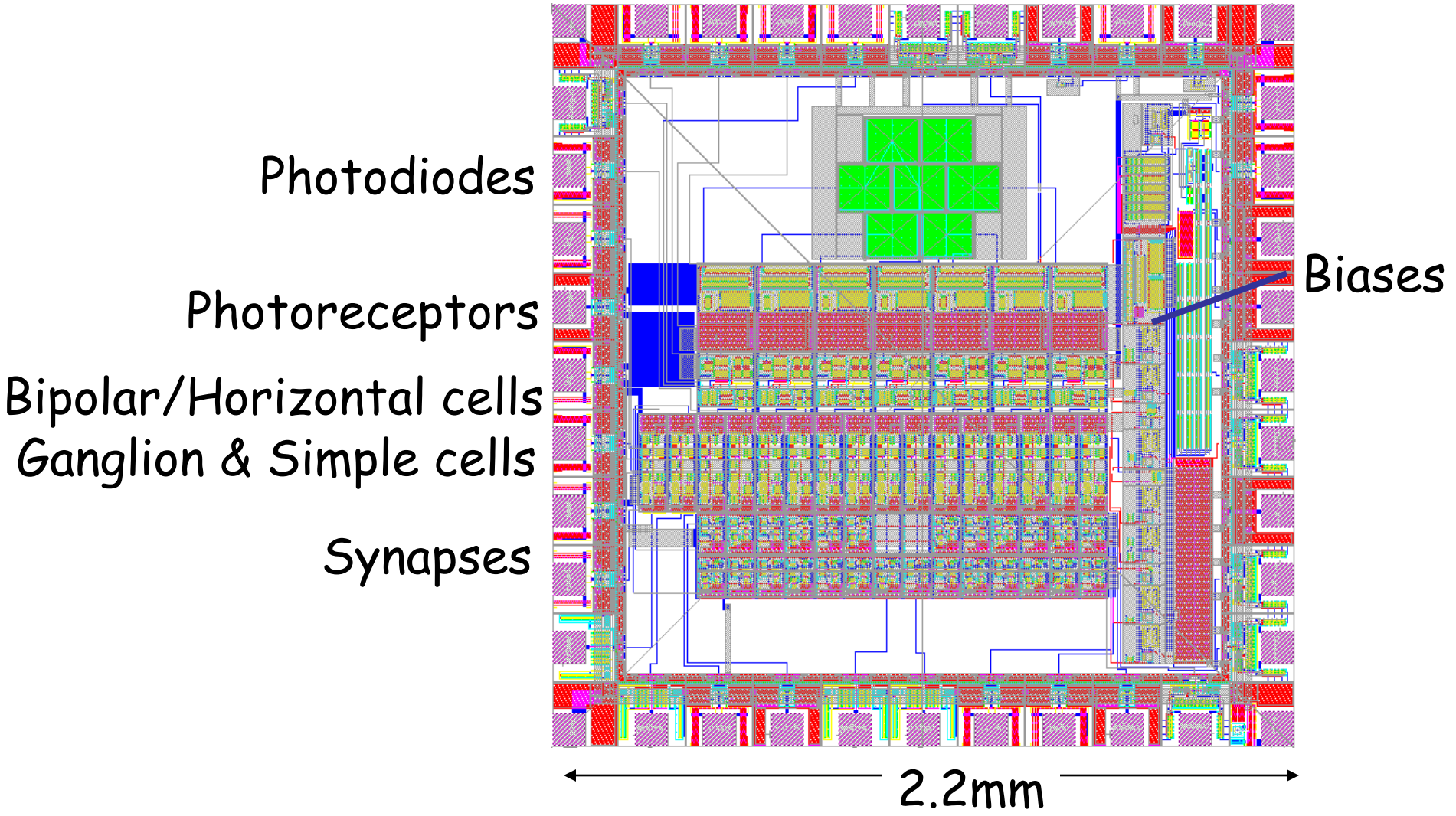
Three layer retina model

Photoreceptors – bipolar cells – ganglion cells

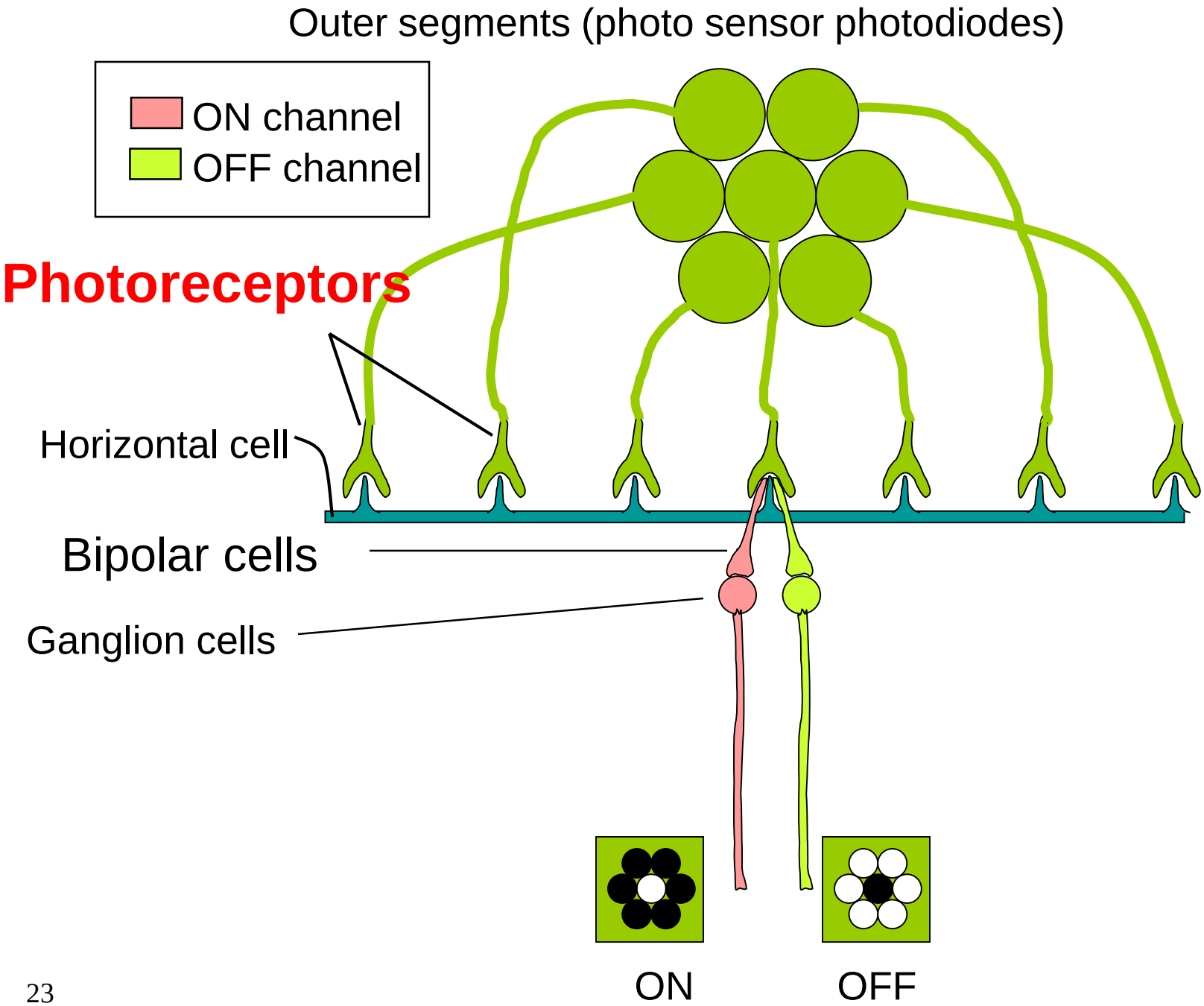



Photodiodes
ON channel
OFF channel
Represents signed quantities by **rectifying** into separate channels that typically have low activity
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
Averages over space & time to find context
Computes locally in analog and transmits long distances using spikes
ON
OFF

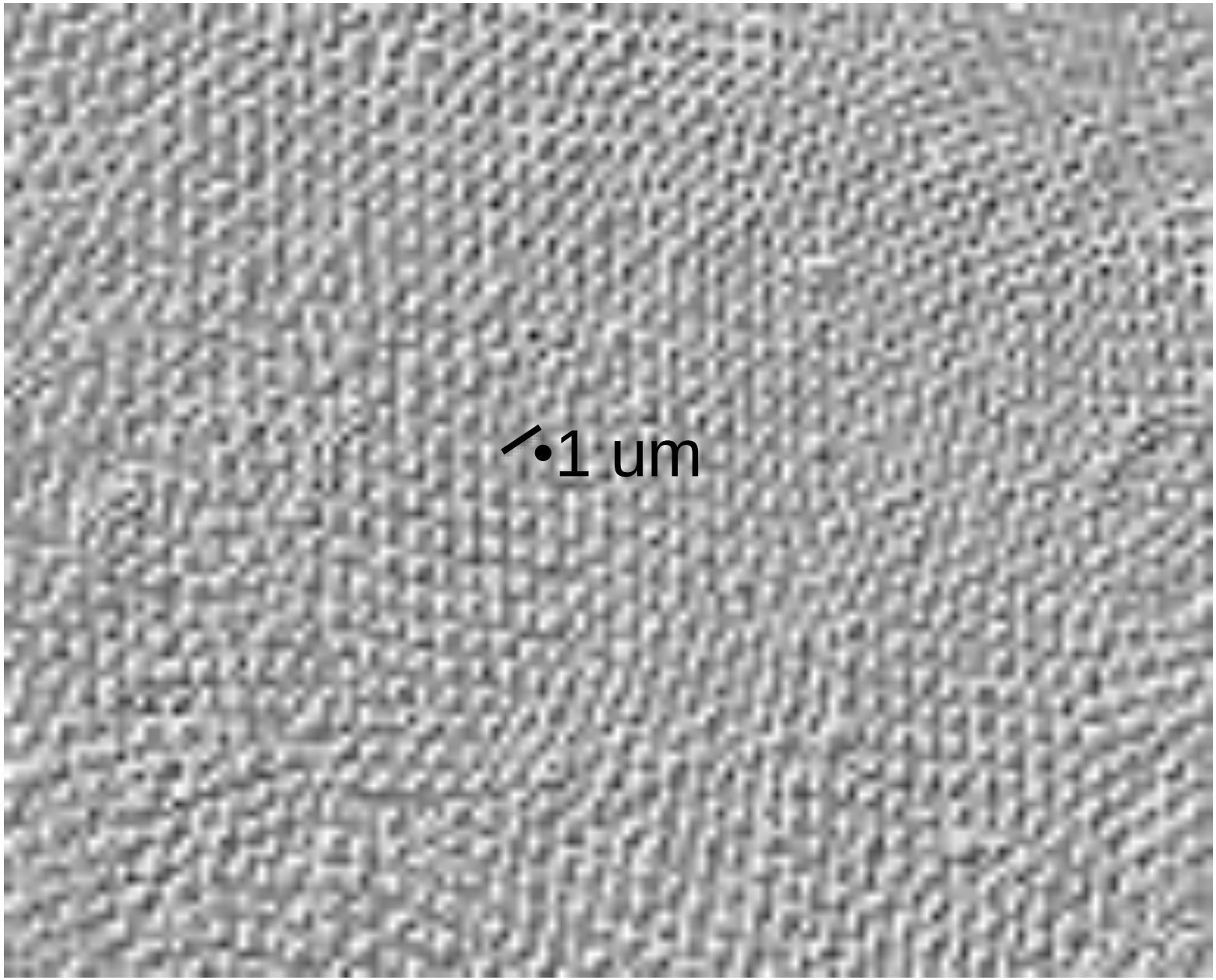
Physio Friend Layout



Photoreceptors


Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF

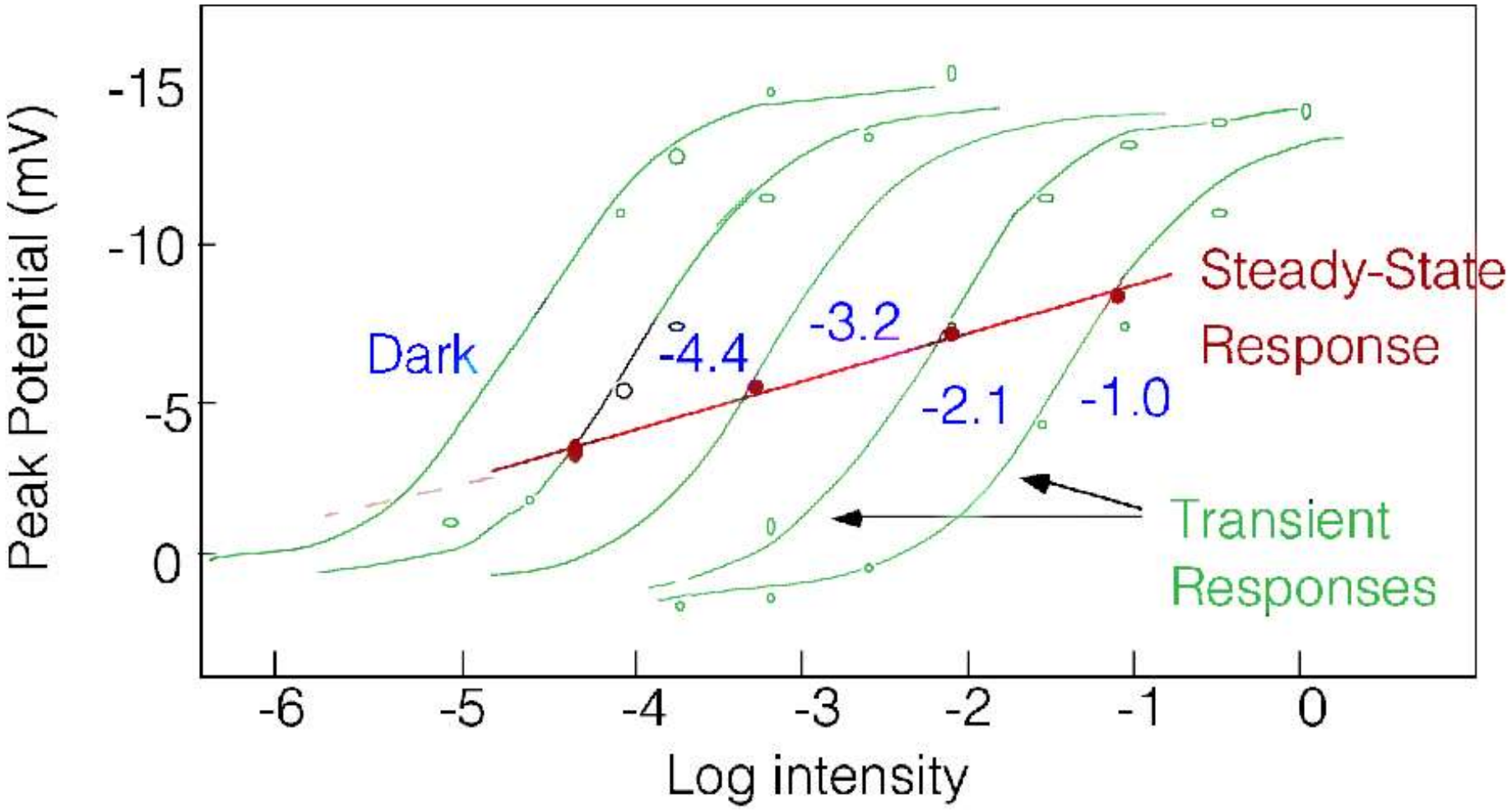
The photoreceptor mosaic in the eye



Rodieck 1998

The first steps in seeing

Biological photoreceptors adapt their operating point and gain

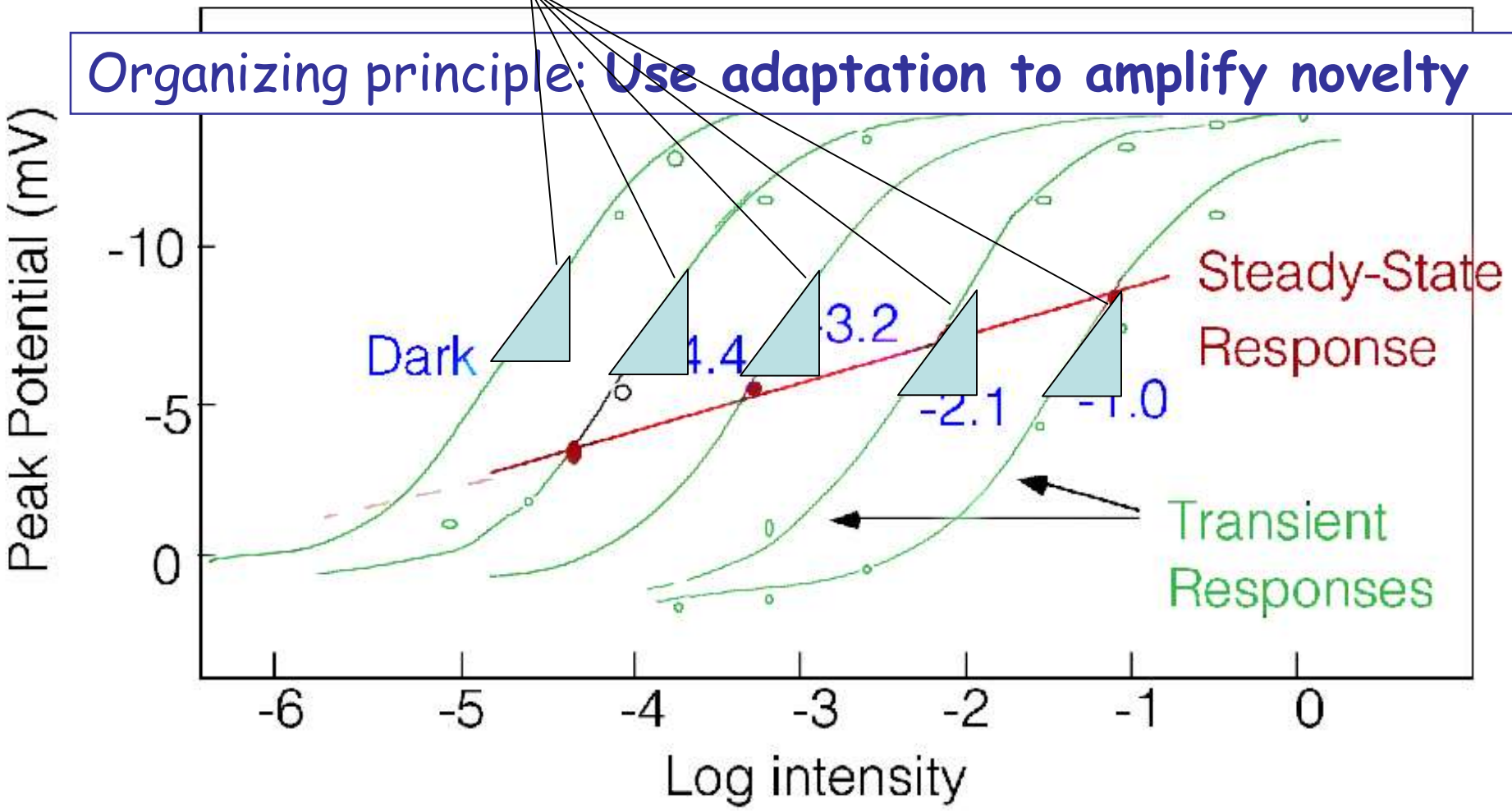


Norman & Perlman 1979

Biological photoreceptors adapt their operating point and gain

Organizing principle: Use **Context** to **Normalize** signal

Organizing principle: **Use adaptation to amplify novelty**



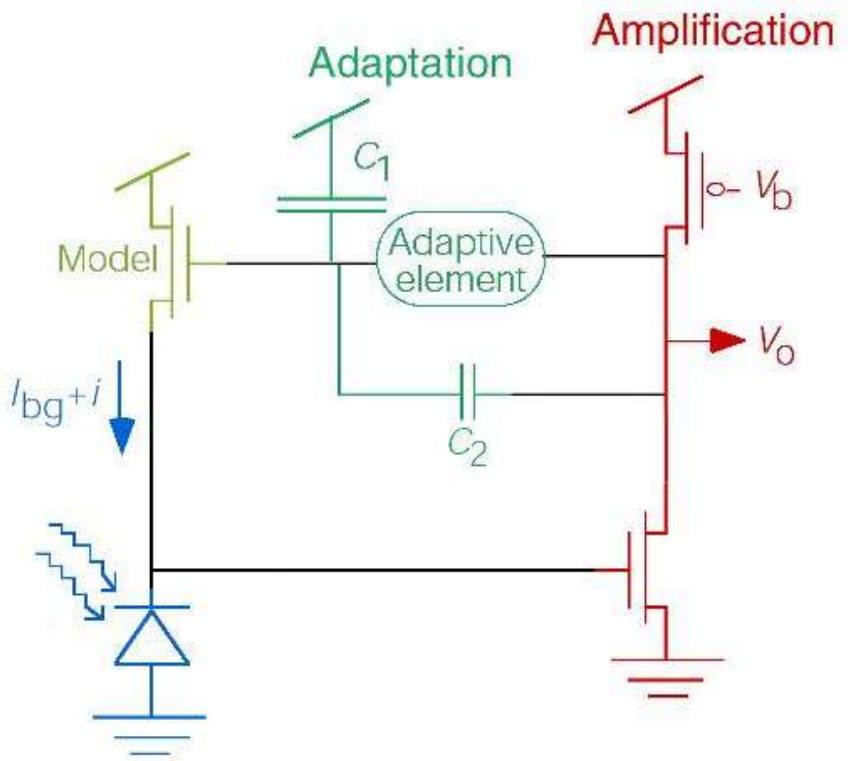
Norman & Perlman 1979

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

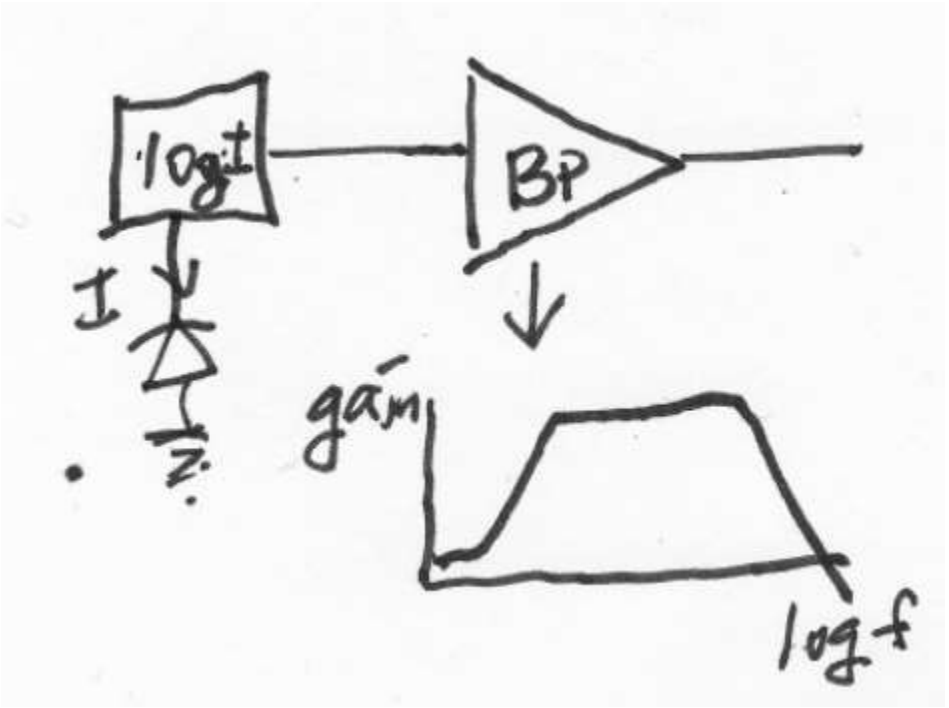
$$d(\log X) = dX/X$$

Adaptive Photoreceptor Circuit

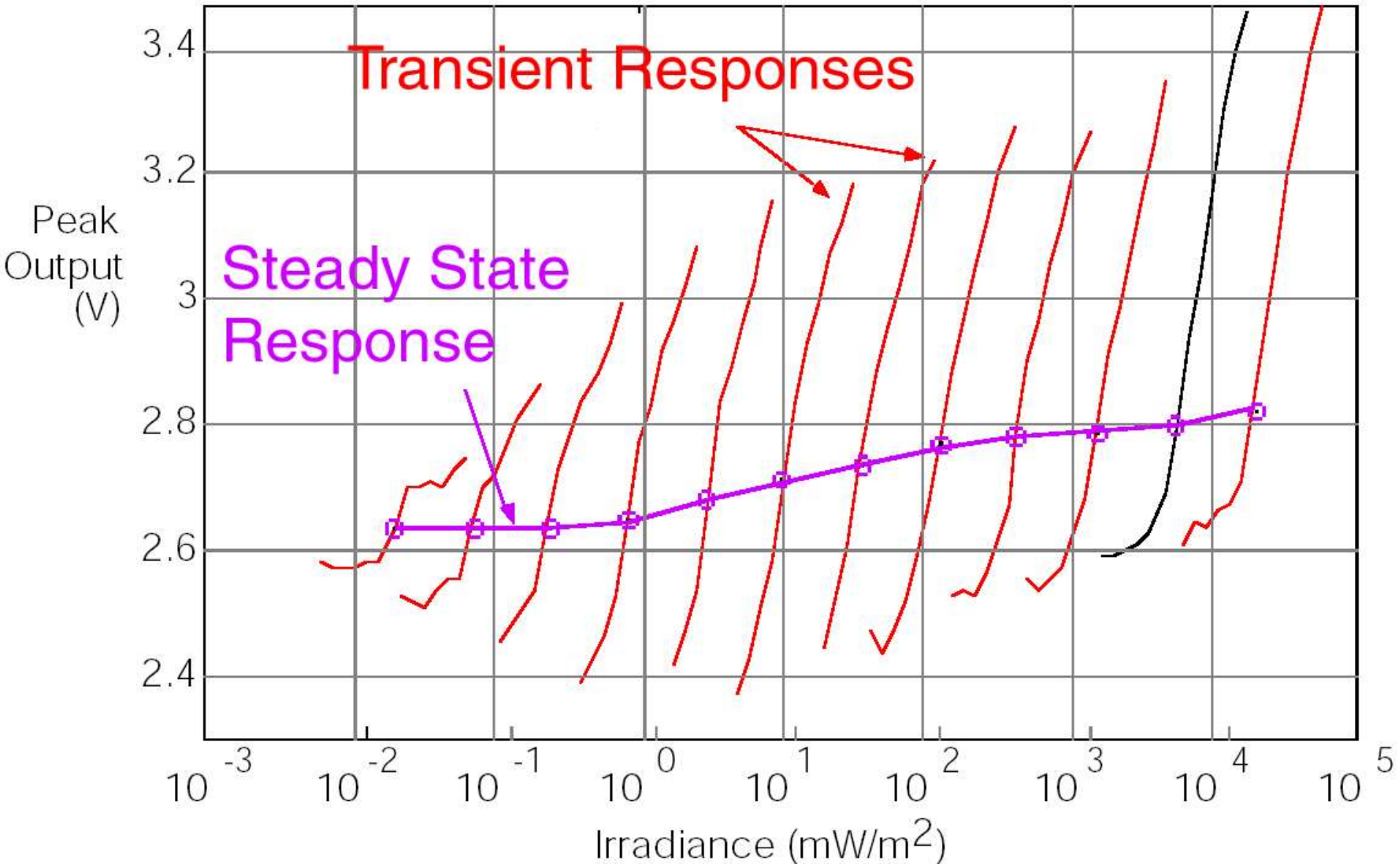
Actual circuit



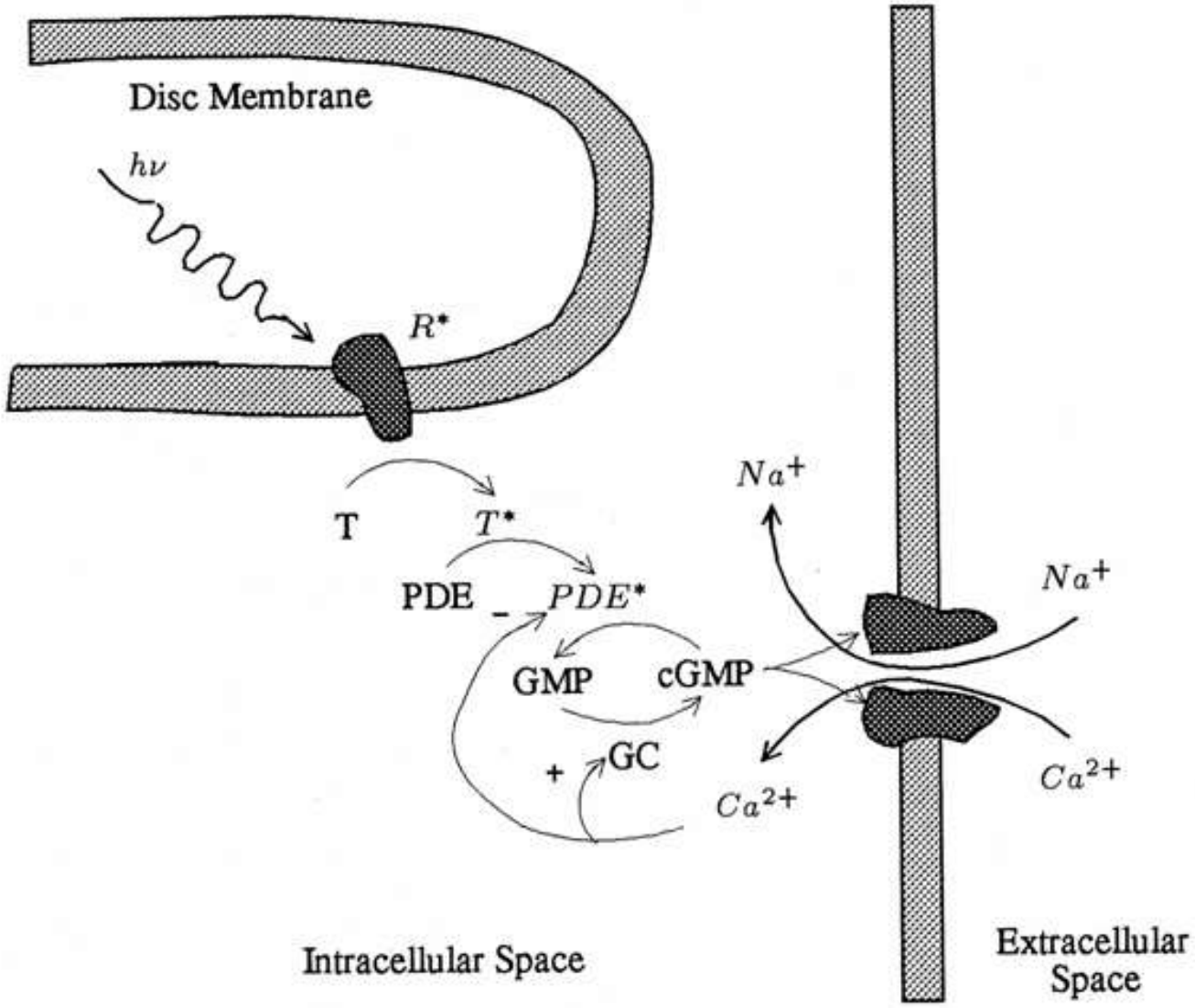
Conceptual circuit



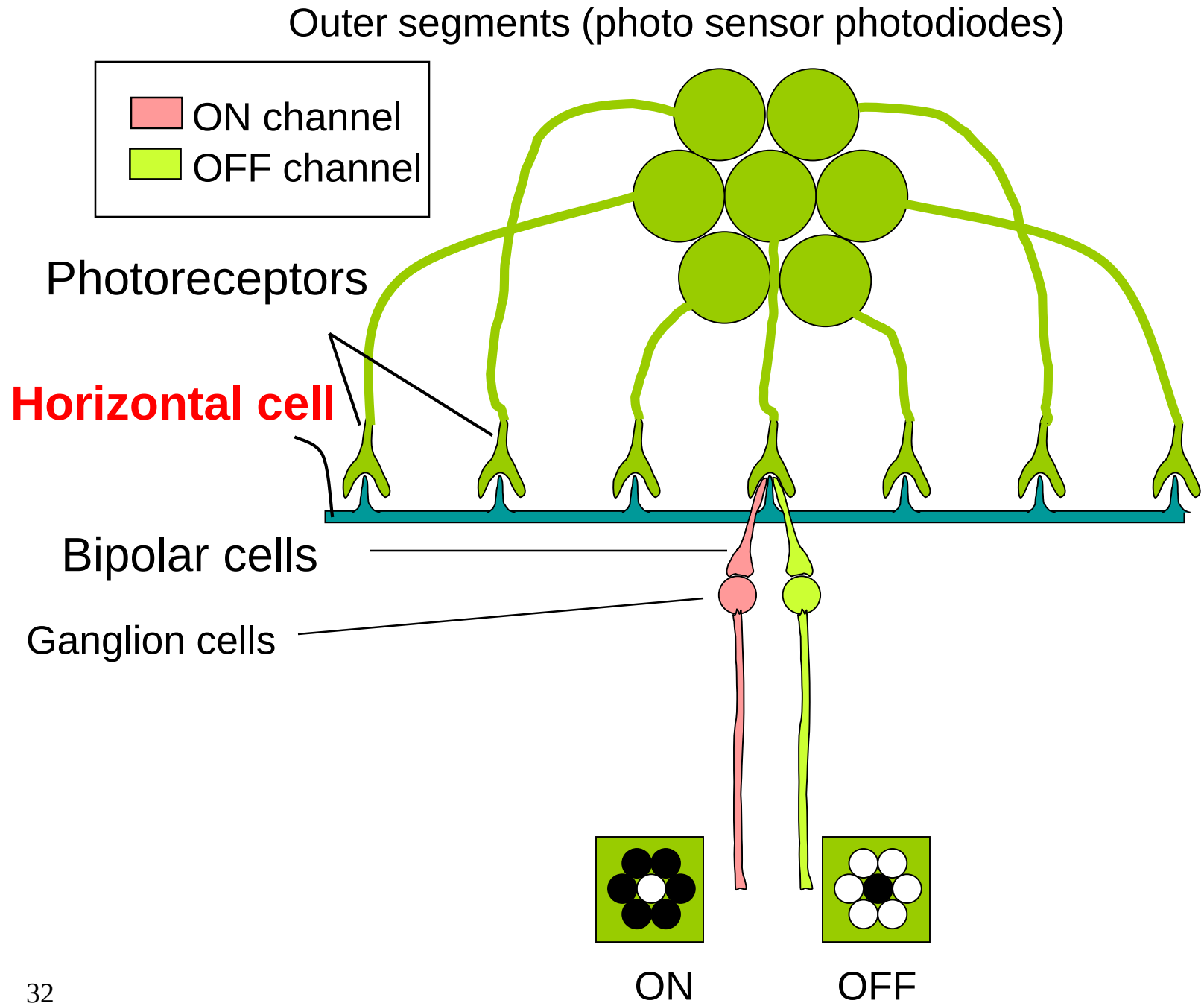
Adaptive photoreceptor responses

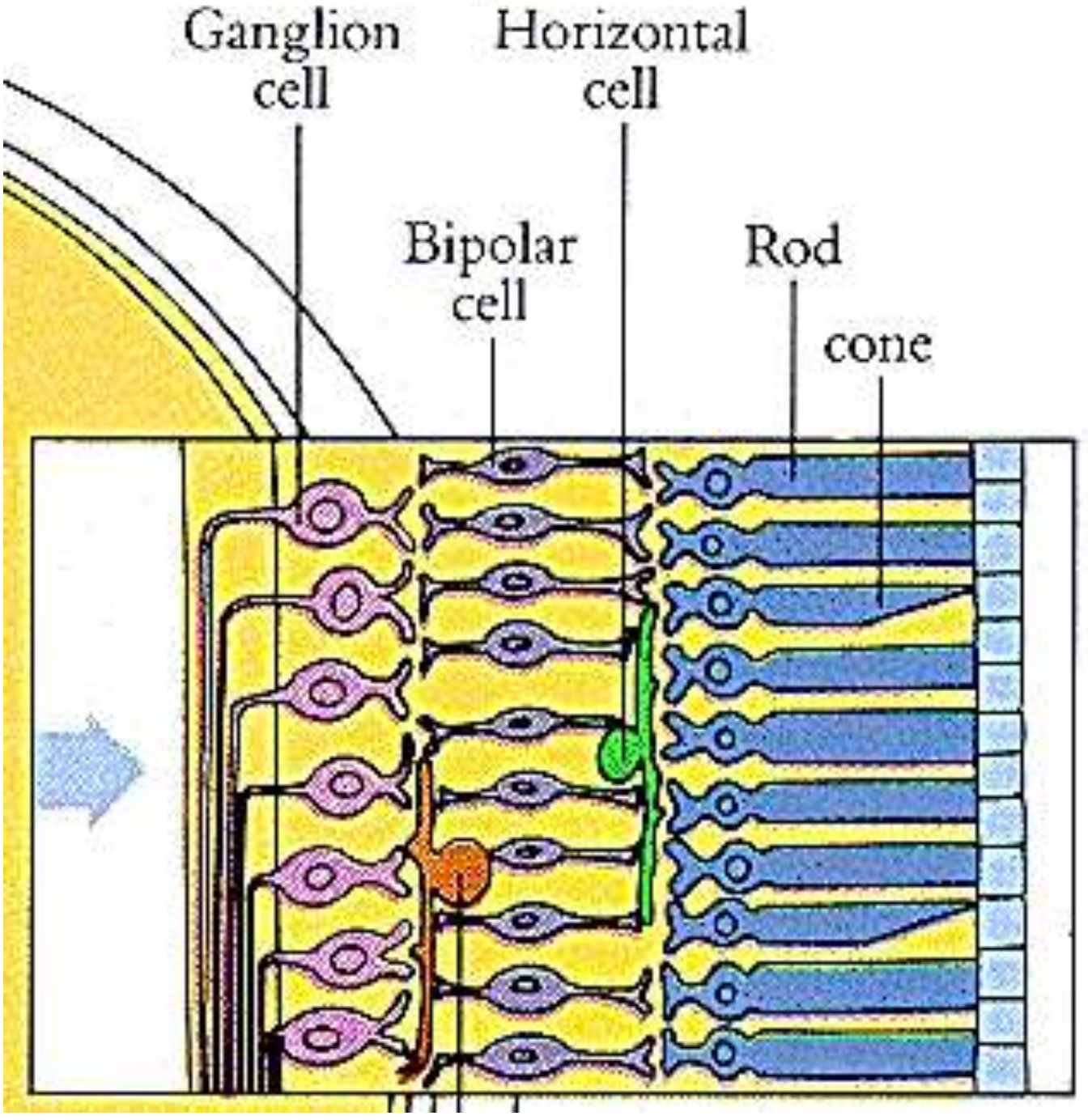


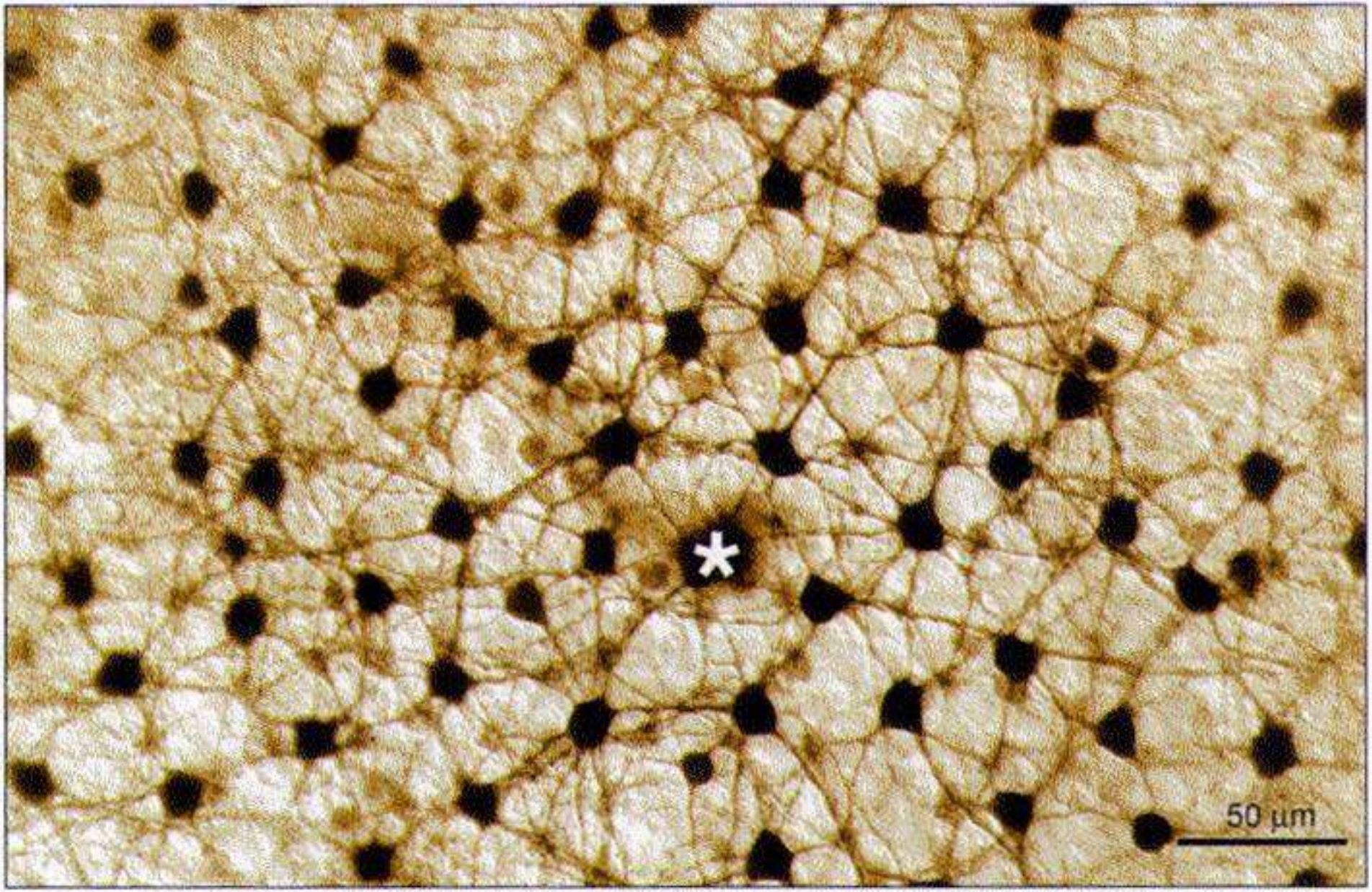
Biological phototransduction uses distributed chain of amplifiers



Mahowald, 1992


Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF


Ganglion cell
Horizontal cell
Bipolar cell
Rod
cone



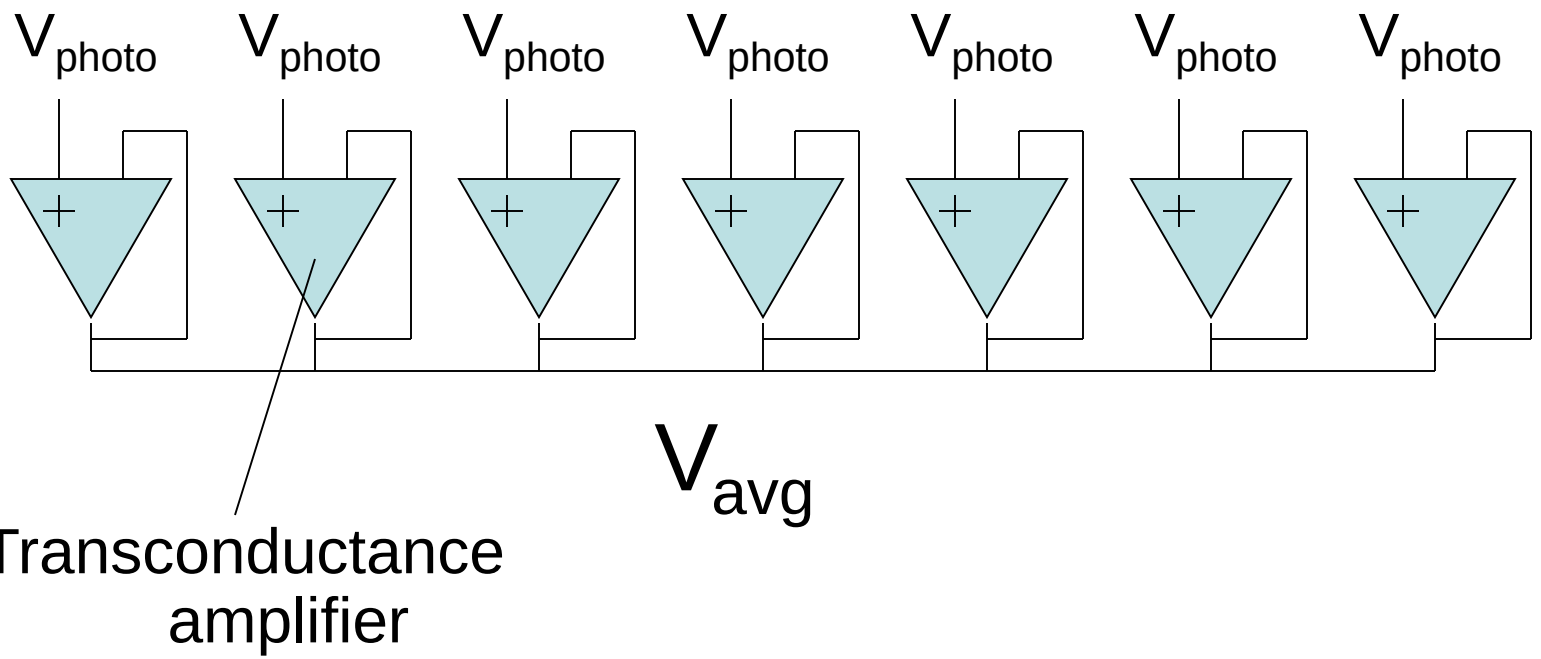
HI horizontal cells labeled following injection of one HI cell (*)

×300

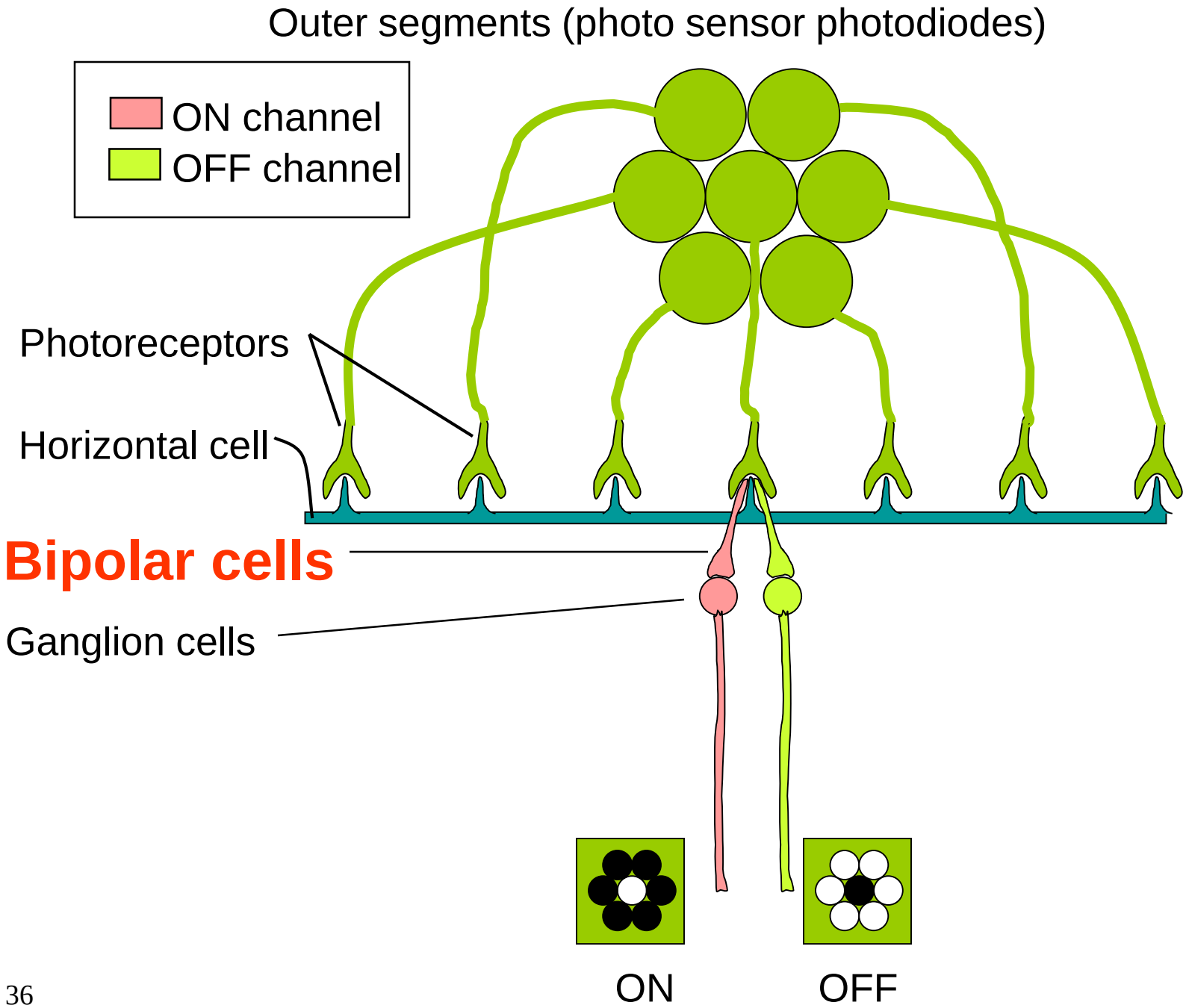
after Dacey, Lee, and Stafford, 1996

Horizontal cell

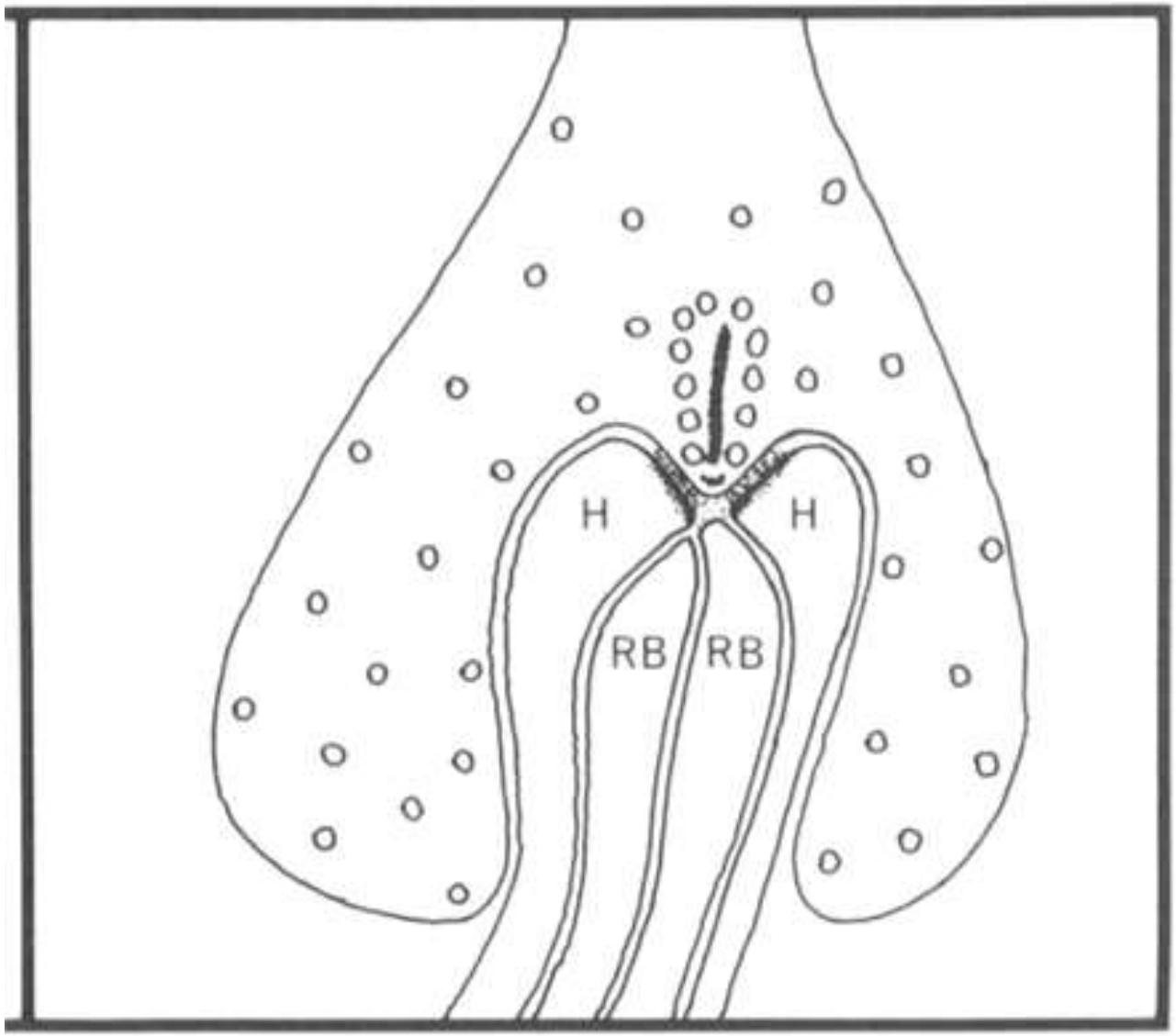
A *Follower-Aggregator* averages the photoreceptor outputs to compute the average of the inputs. This average is the *context* which is compared to the photoreceptor.



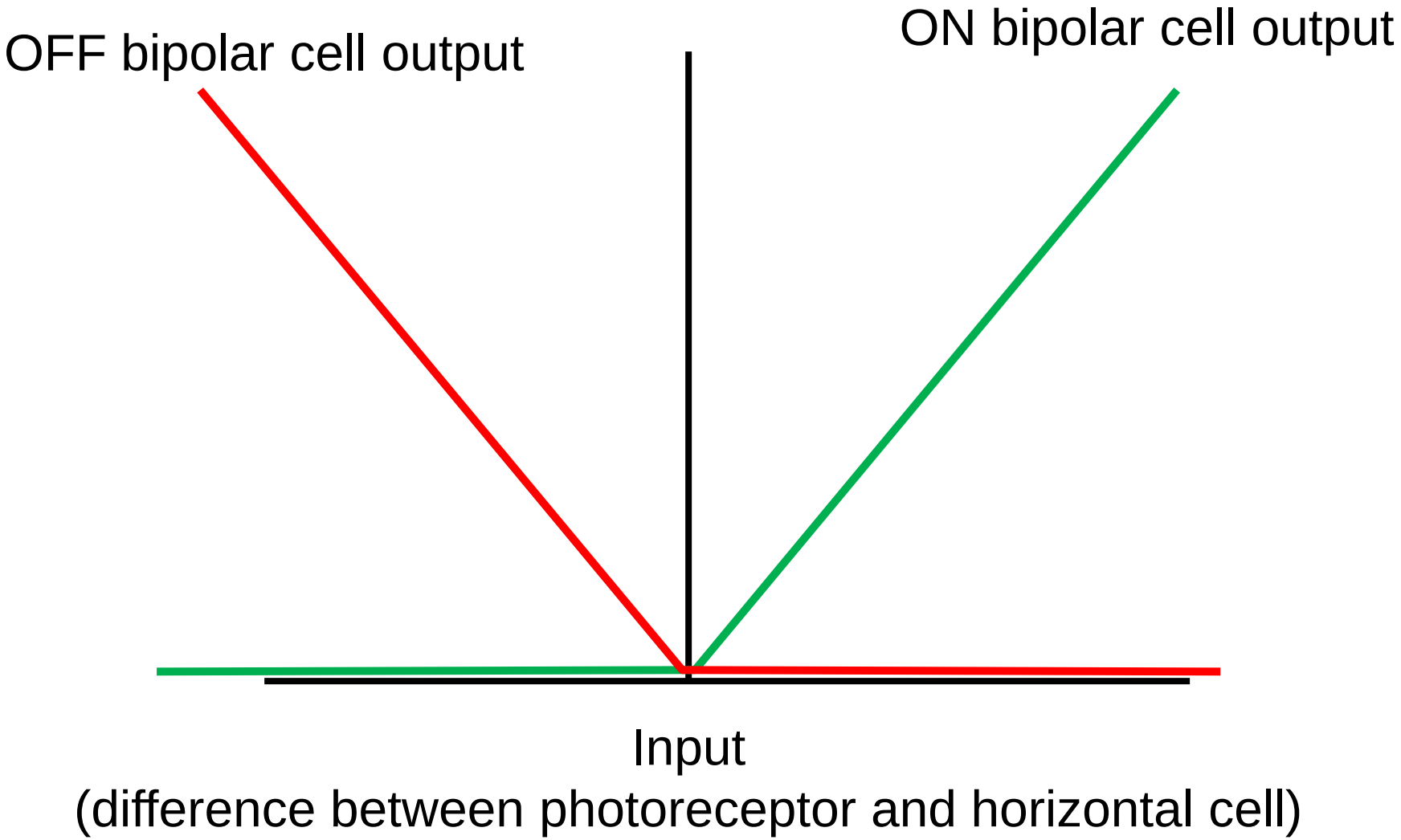
Because the follower output current saturates, the follower-aggregator computes **mean** for small signals and **median** for large signals


Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF

Rod-Horizontal Cell-Bipolar cell junctions

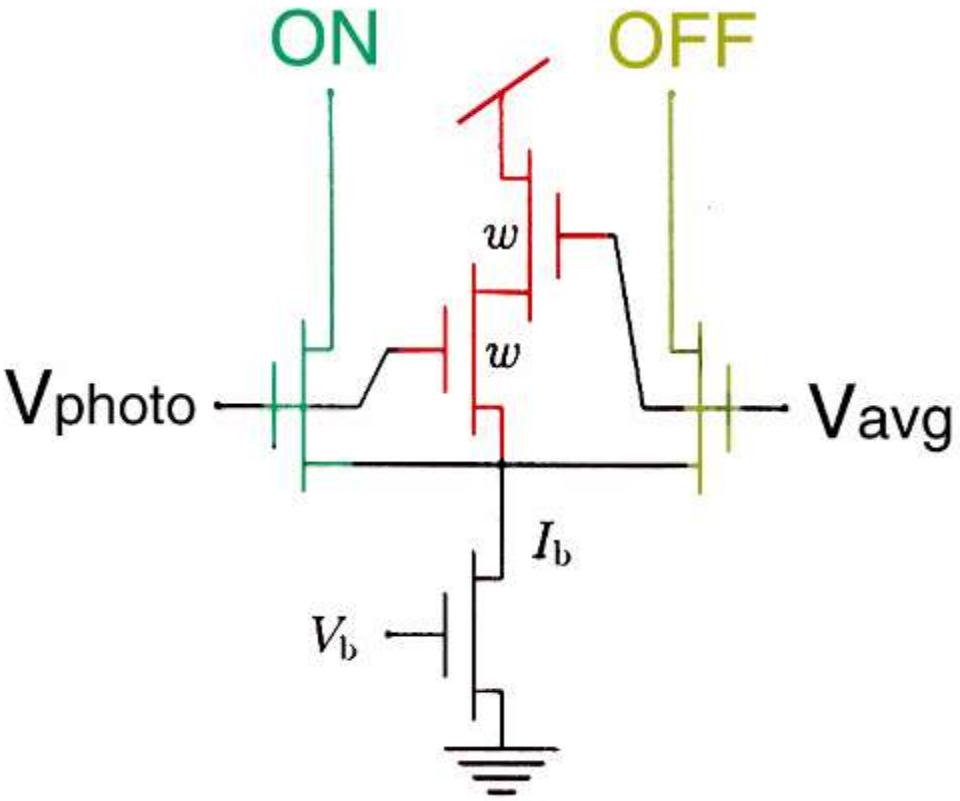


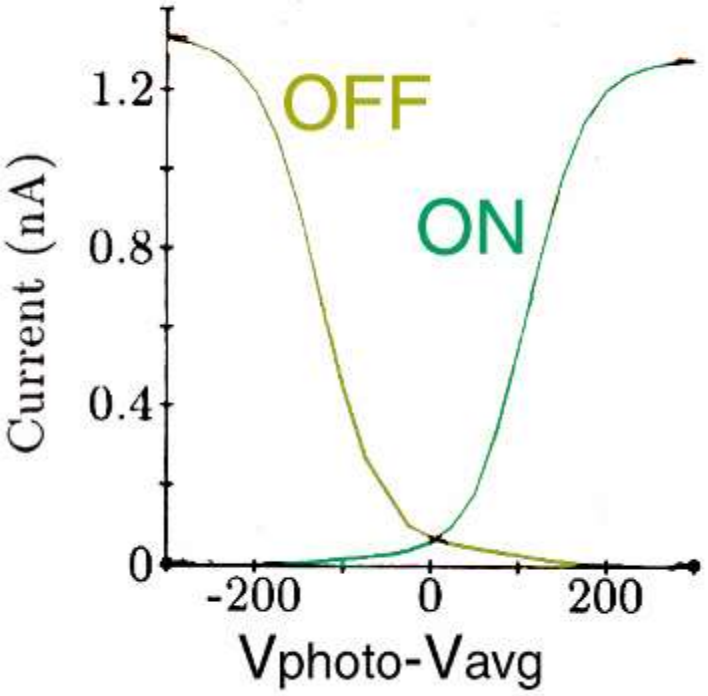
Rectification at the photoreceptor-horizontal cell-bipolar cell synapse

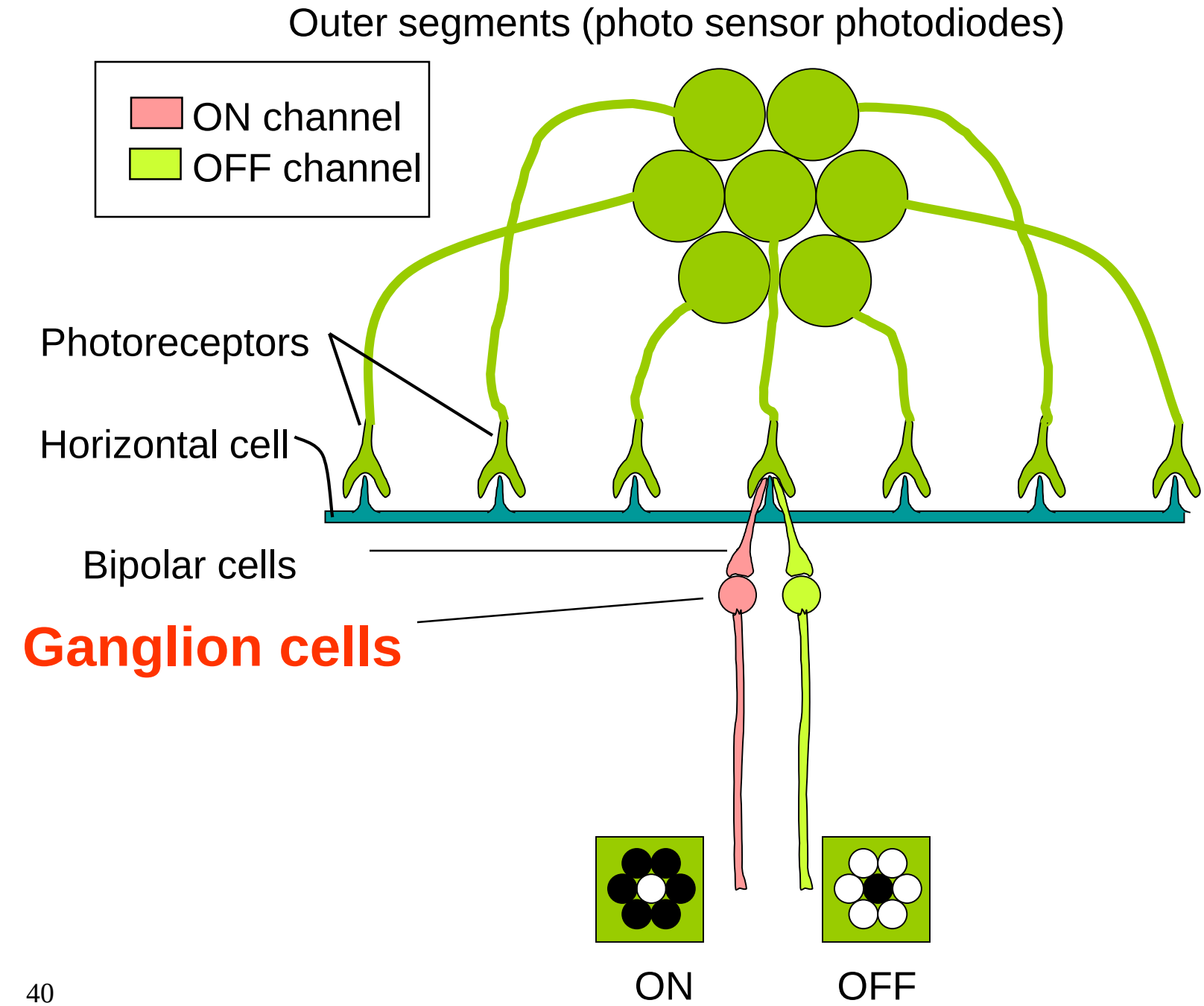


Bipolar Cell (Anti-bump circuit)

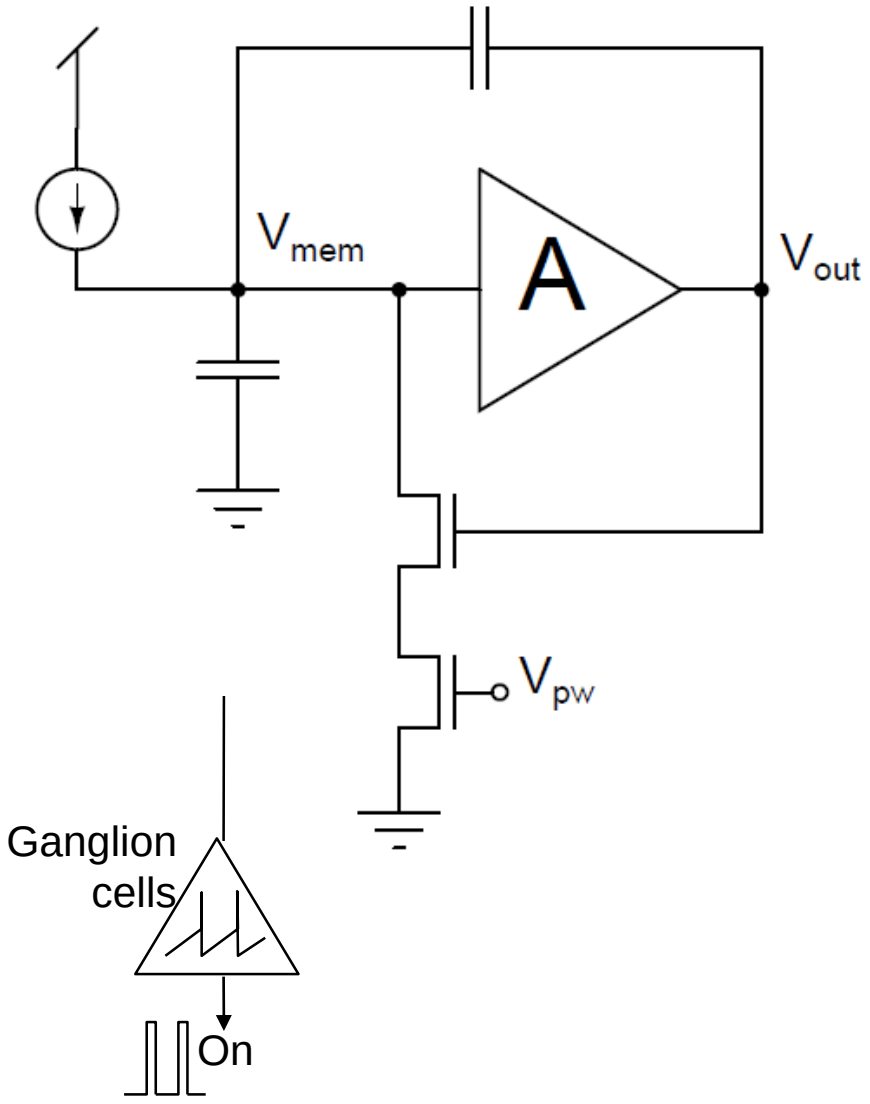
Rectifies into ON and OFF currents

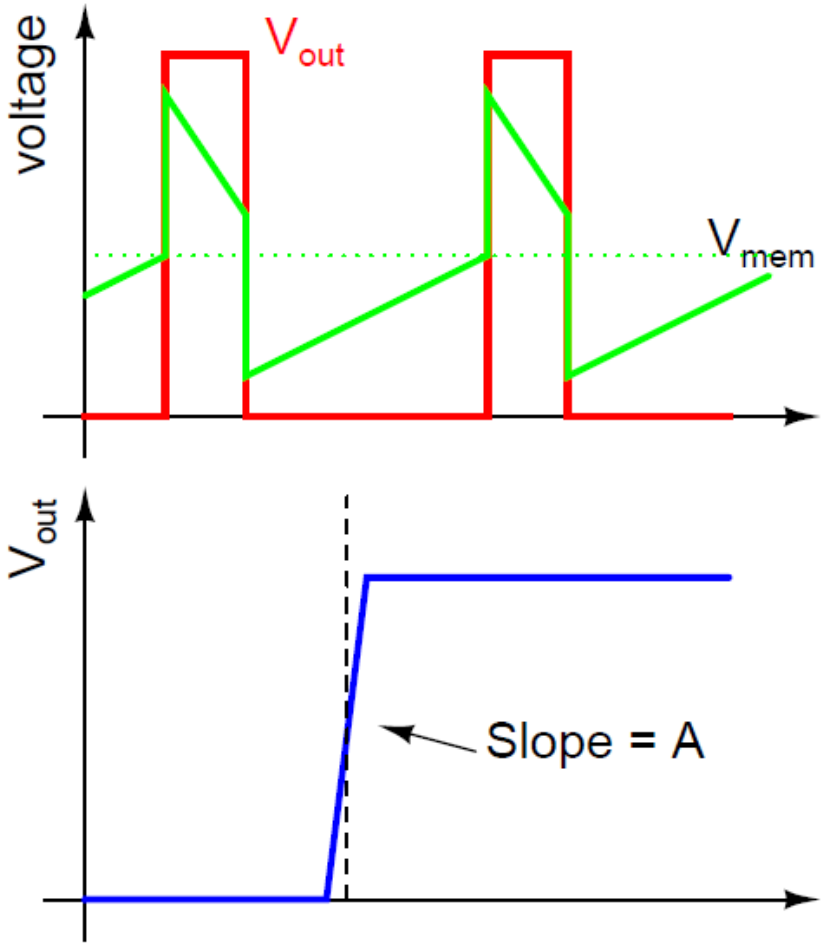




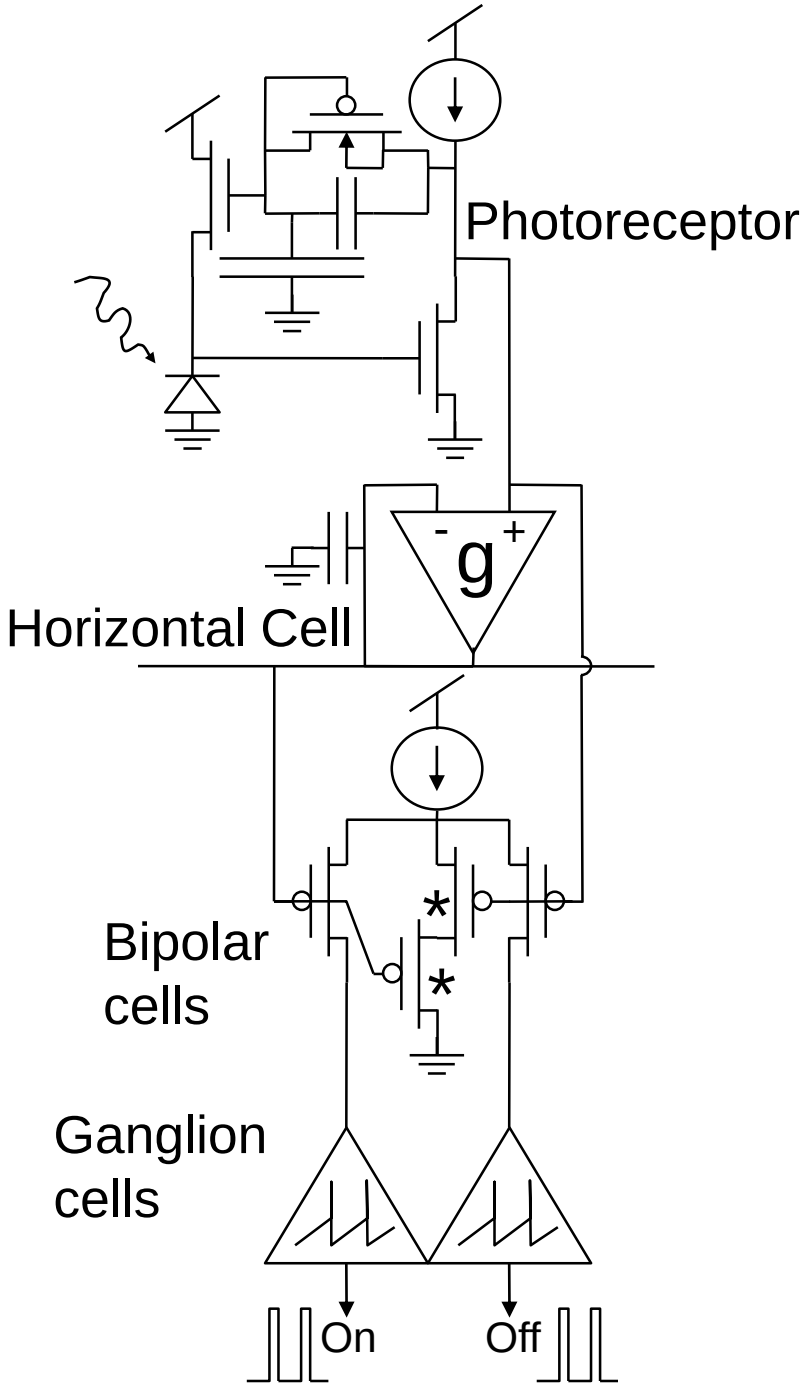

Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF

“Axon-hillock” spiking soma circuit turns the graded bipolar cell outputs into ganglion cell spikes





Complete circuit for retina part of Physiologist's Friend circuit

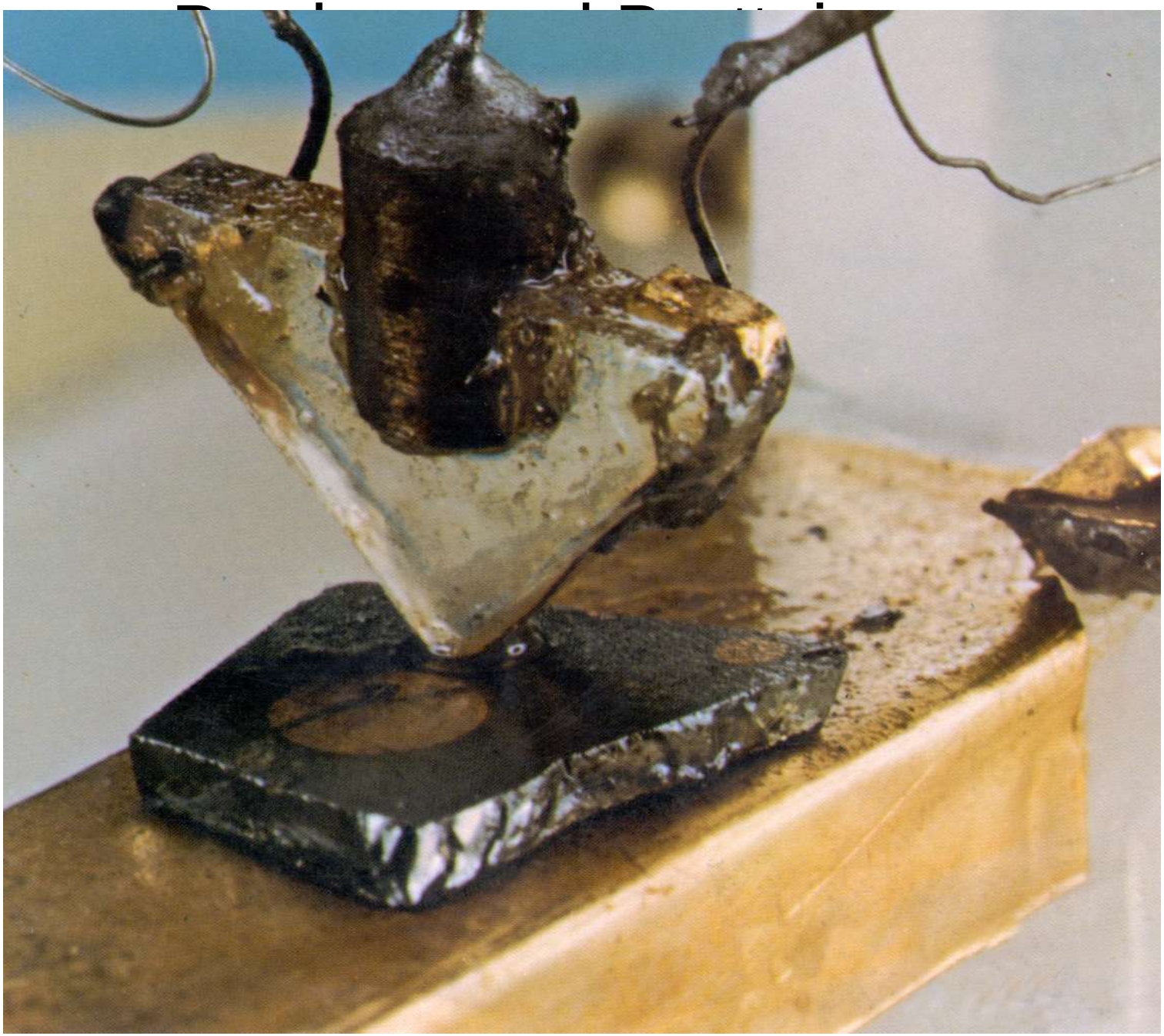


Neuromorphic Electronics?

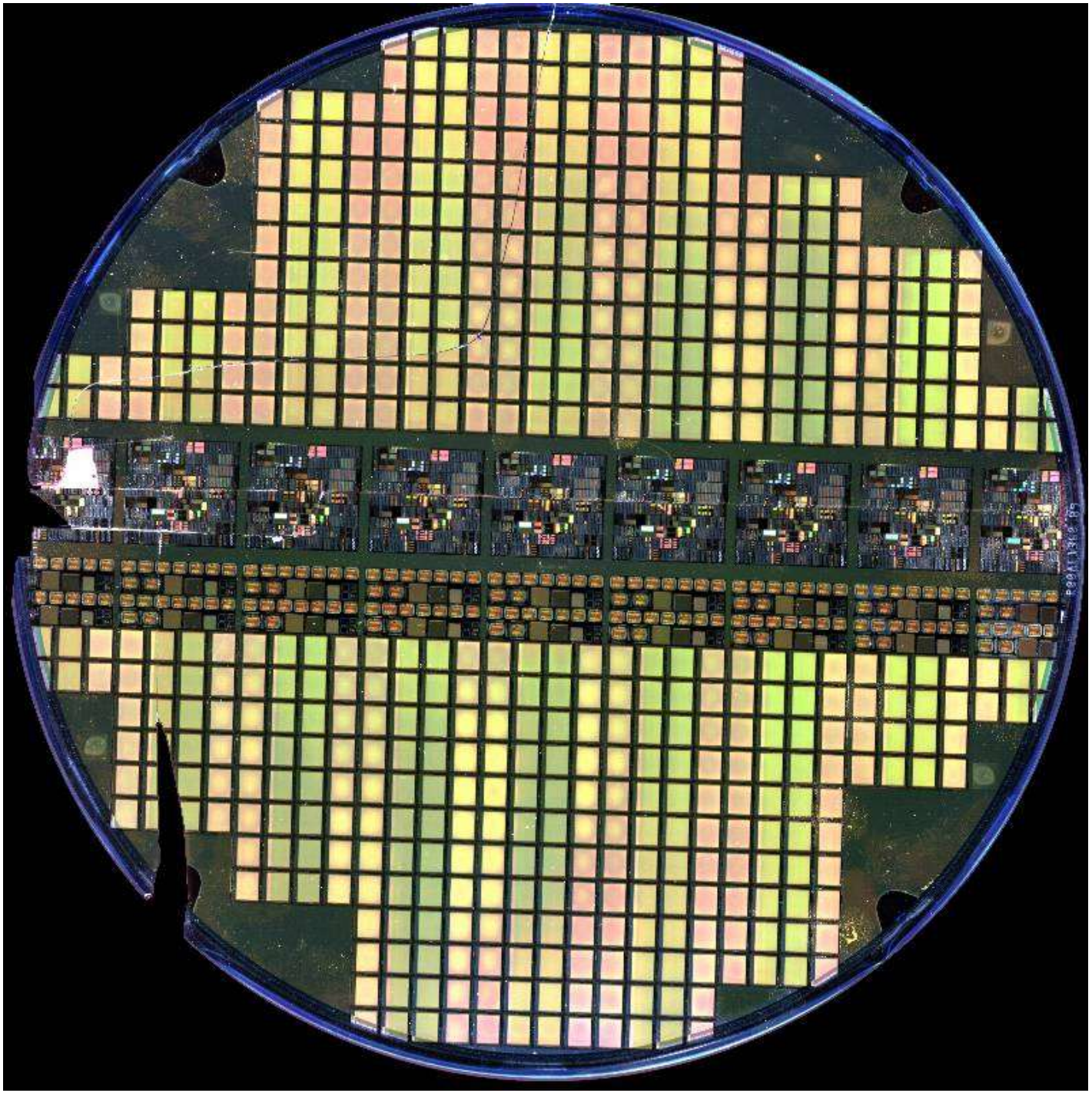
What is it all about?

The context, of silicon electronics with synchronous logic

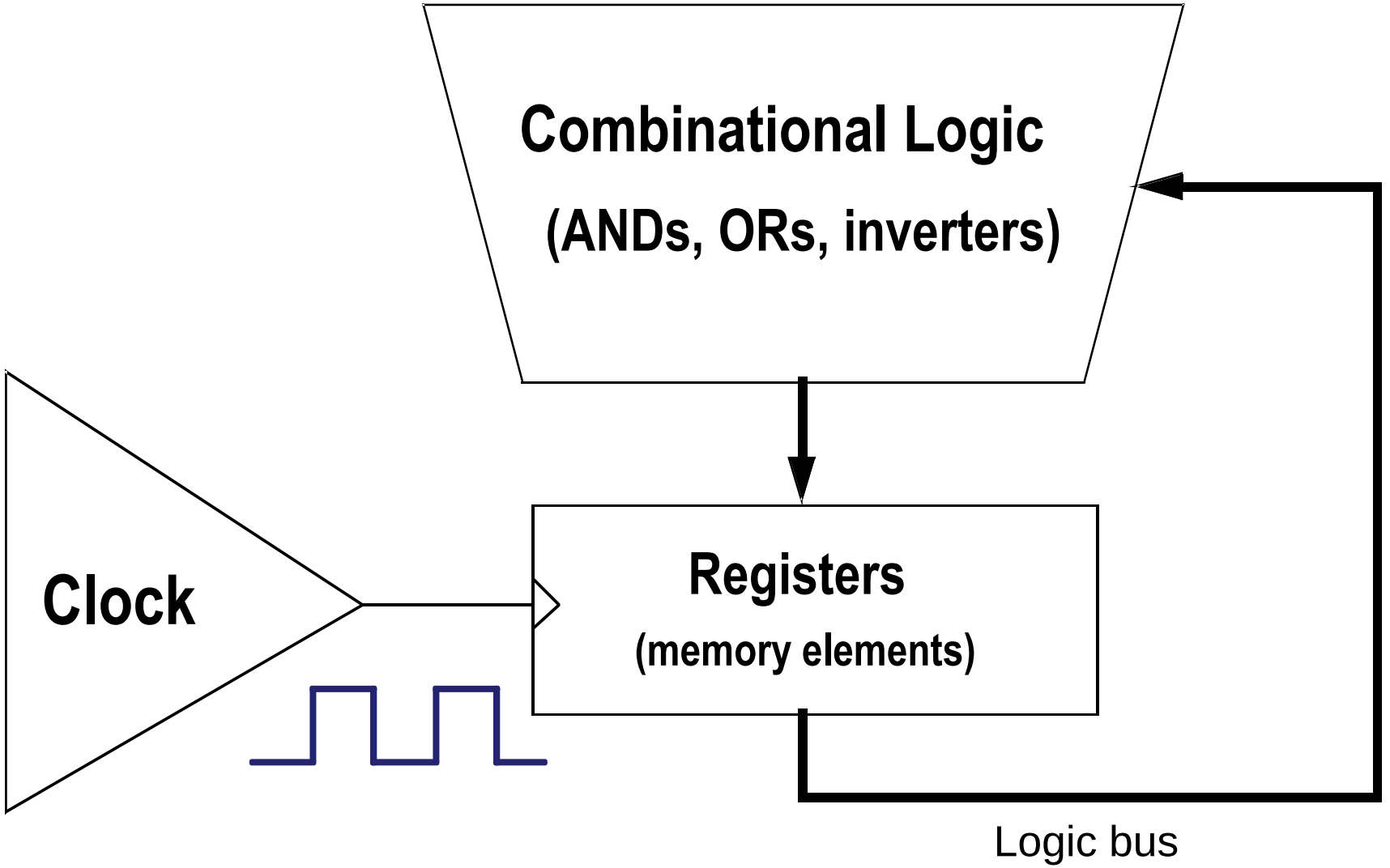
•1947

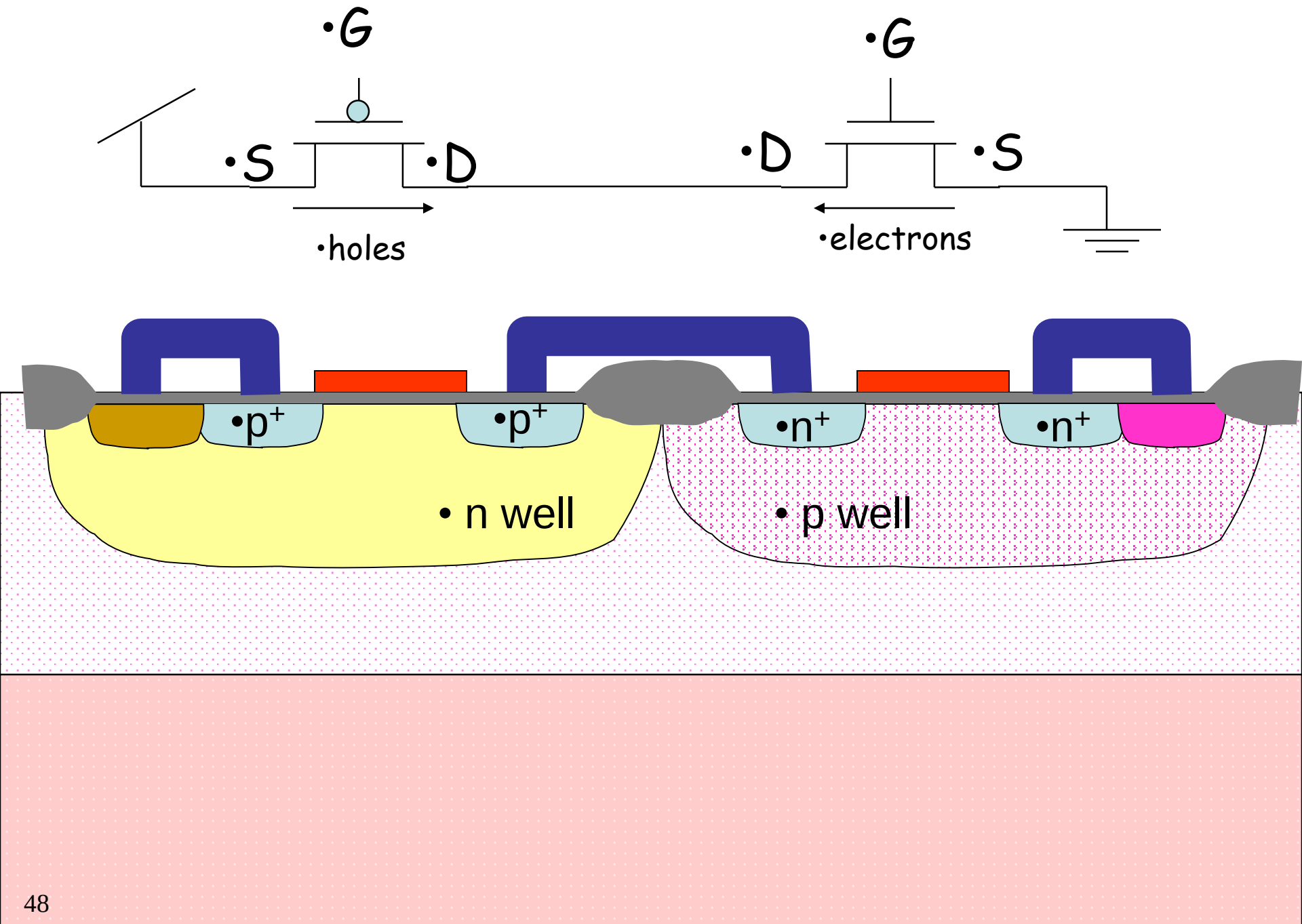


- 2000

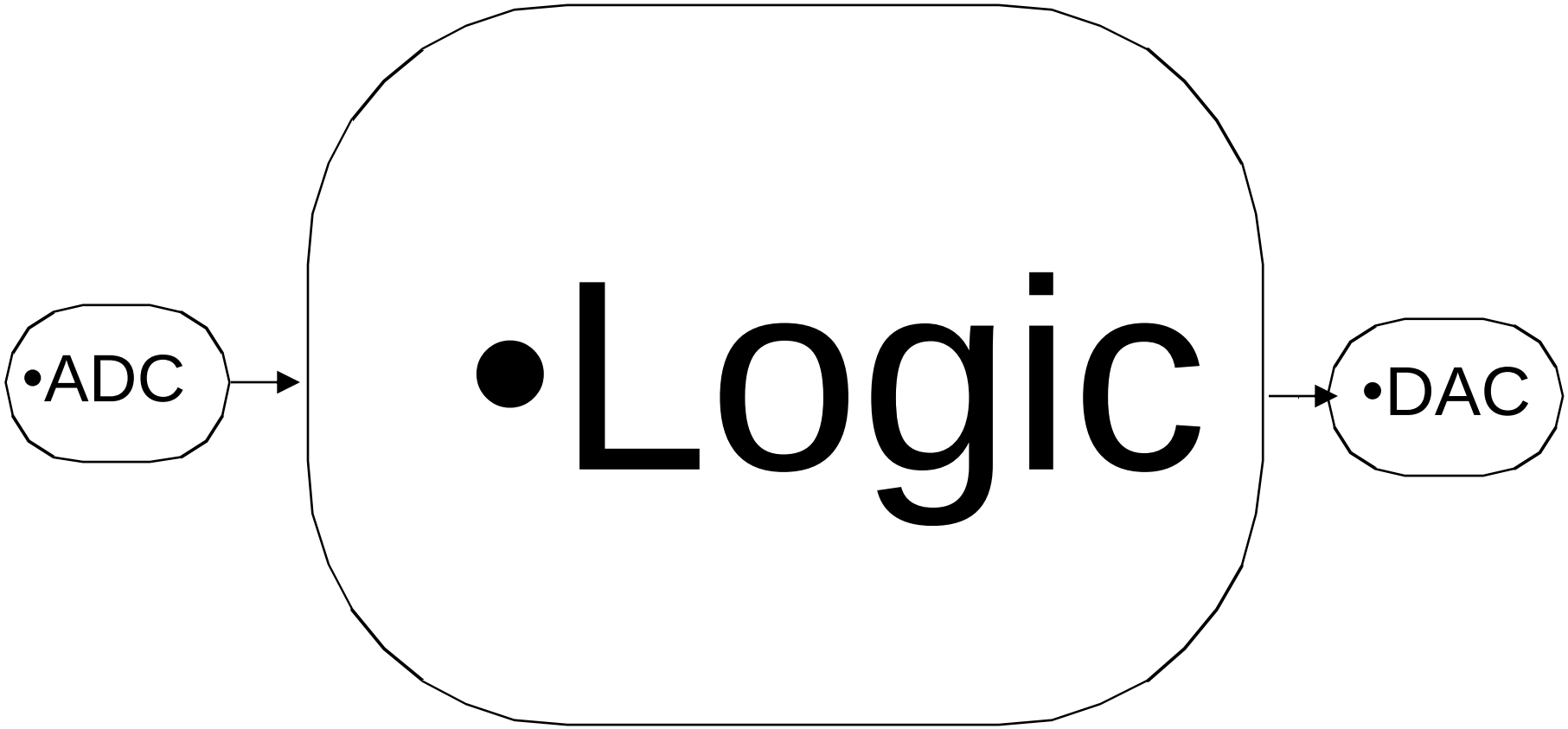


Synchronous logic is ubiquitous



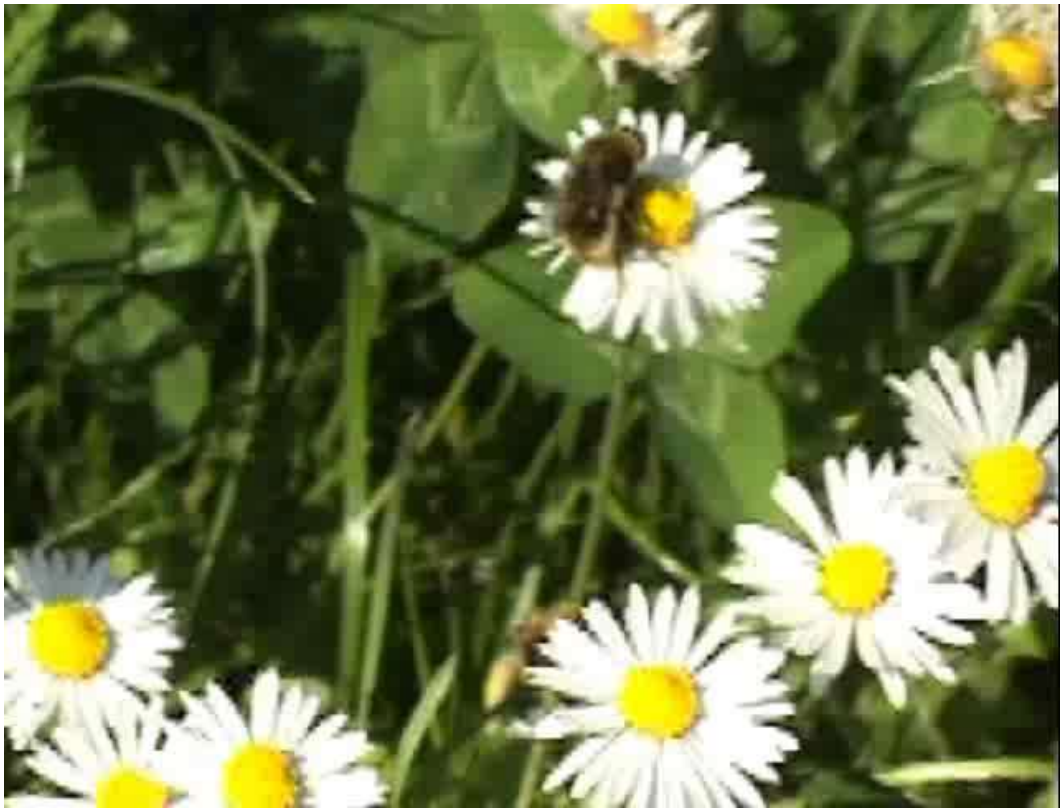

•G
•S
•D
•holes
•G
•D
•S
•electrons
•p+
•p+
•n+
•n+
• n well
• p well

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



The motivation

•Natural computation



- Flies acrobatically
- Recognizes patterns
- Navigates
- Forages
- Communicates

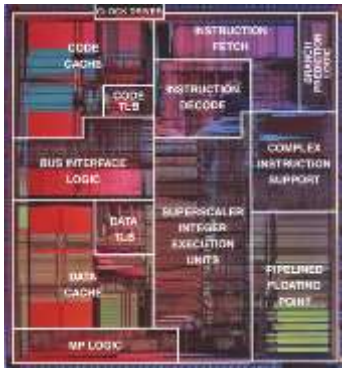
- 10^{-15} J/op

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

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

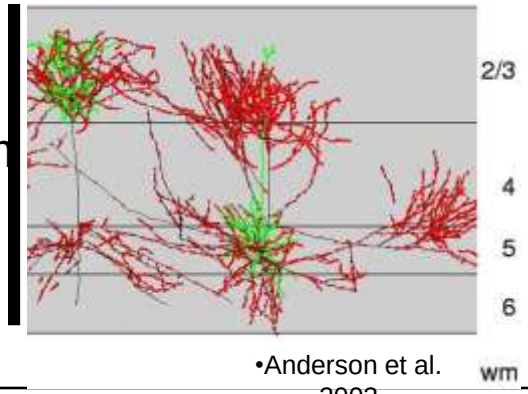
•Computer vs. Brain

•Pentium 4



•Cortex

•1mm



•Anderson et al. 2003

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

•1967

•P. Mueller

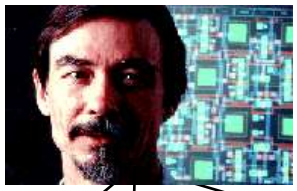
•E. Vittoz

•C. Mead

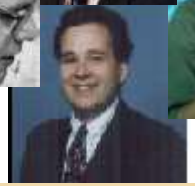
•M. Delbruck

•CSEM

•1980 s

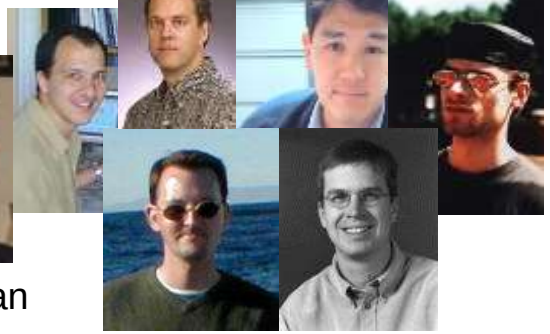


•C. Koch



Van Schaik

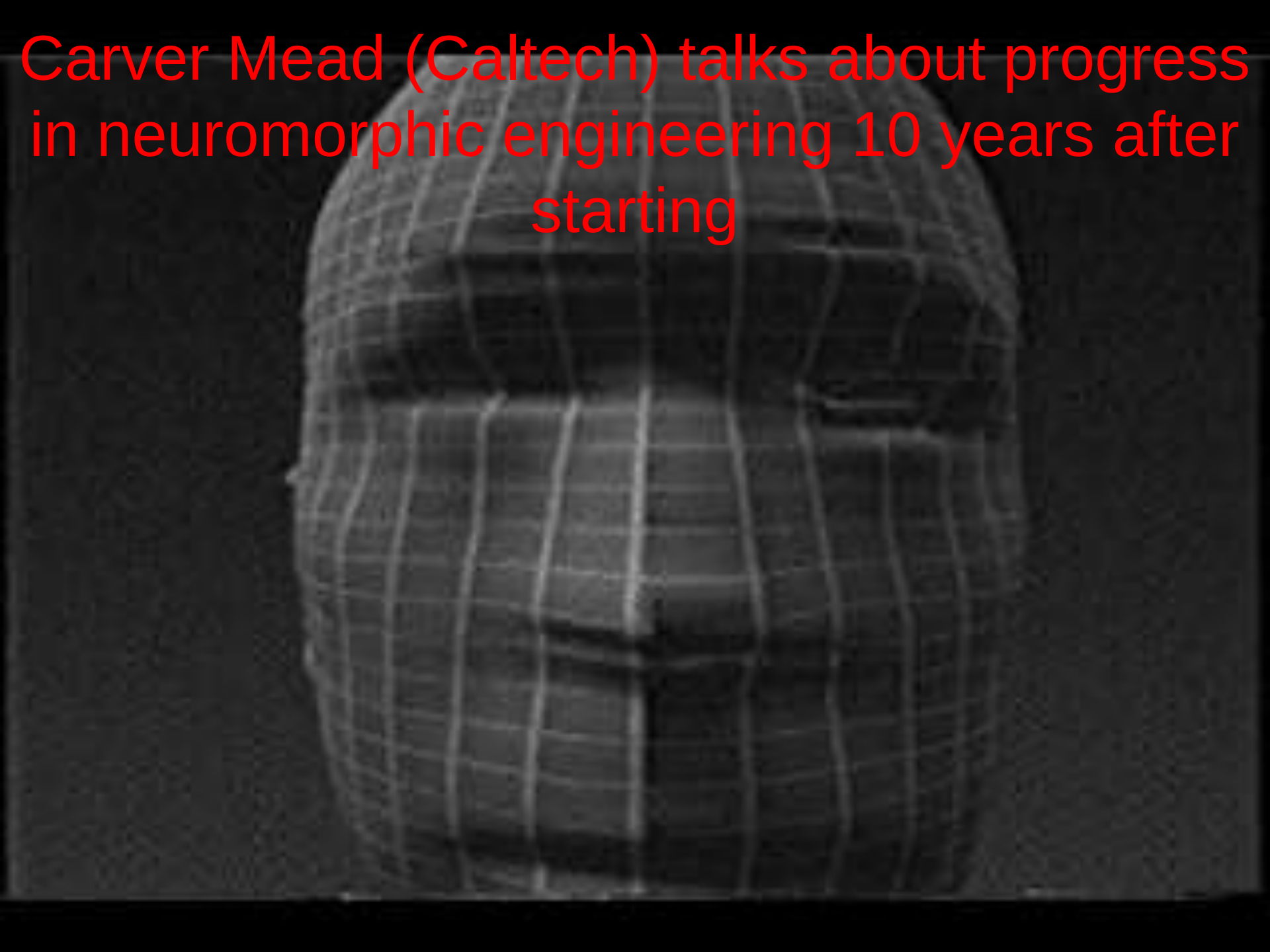
•Mid to late 1990s



•R. Sarpeshkar •B. Minch •C. Diorio •P. Hasler •S-C. Liu •K. Boahen •P.Julian

•Liu, 2005

Carver Mead (Caltech) talks about progress in neuromorphic engineering 10 years after starting



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

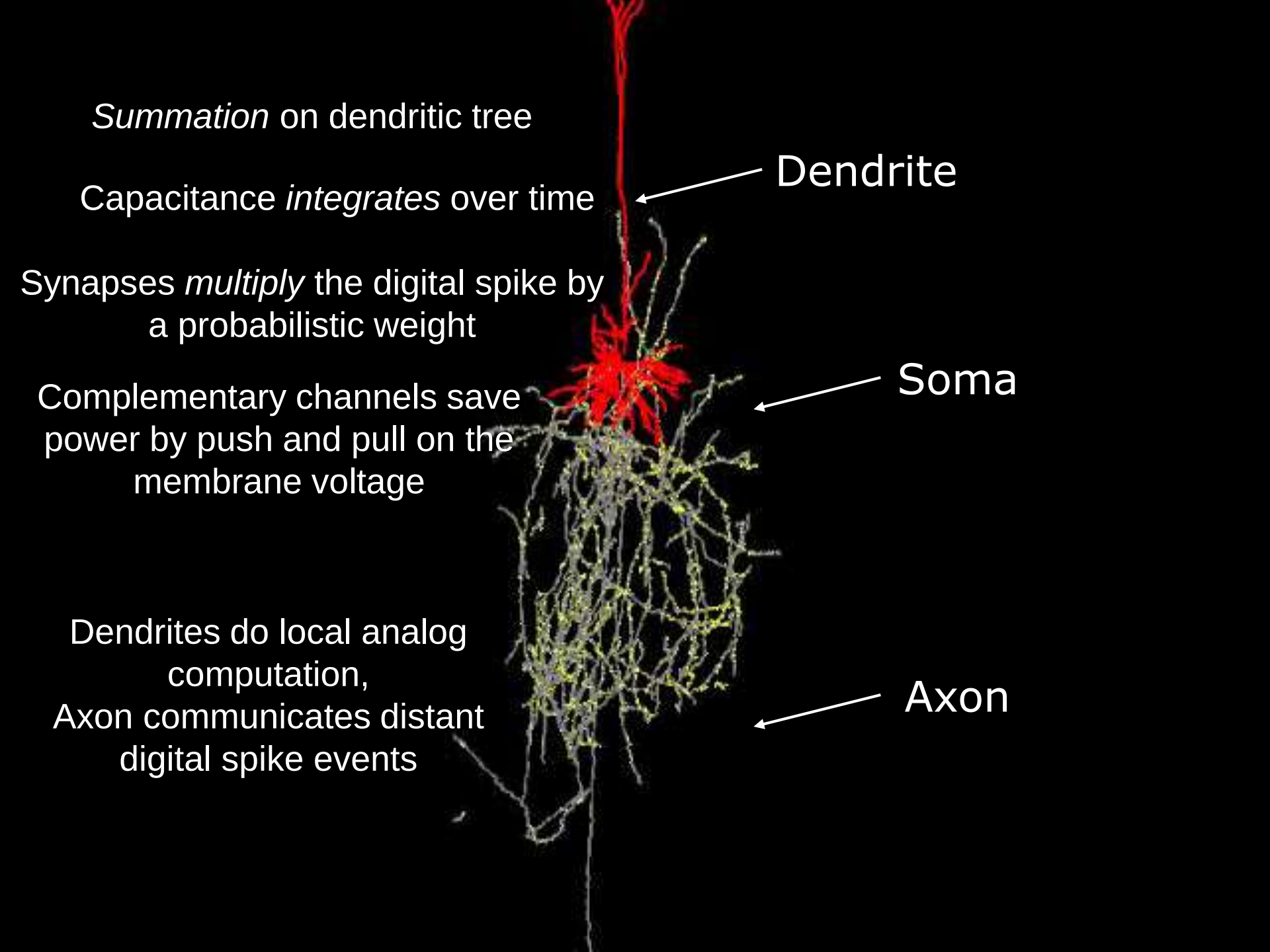
Summation on dendritic tree

Capacitance *integrates* over time

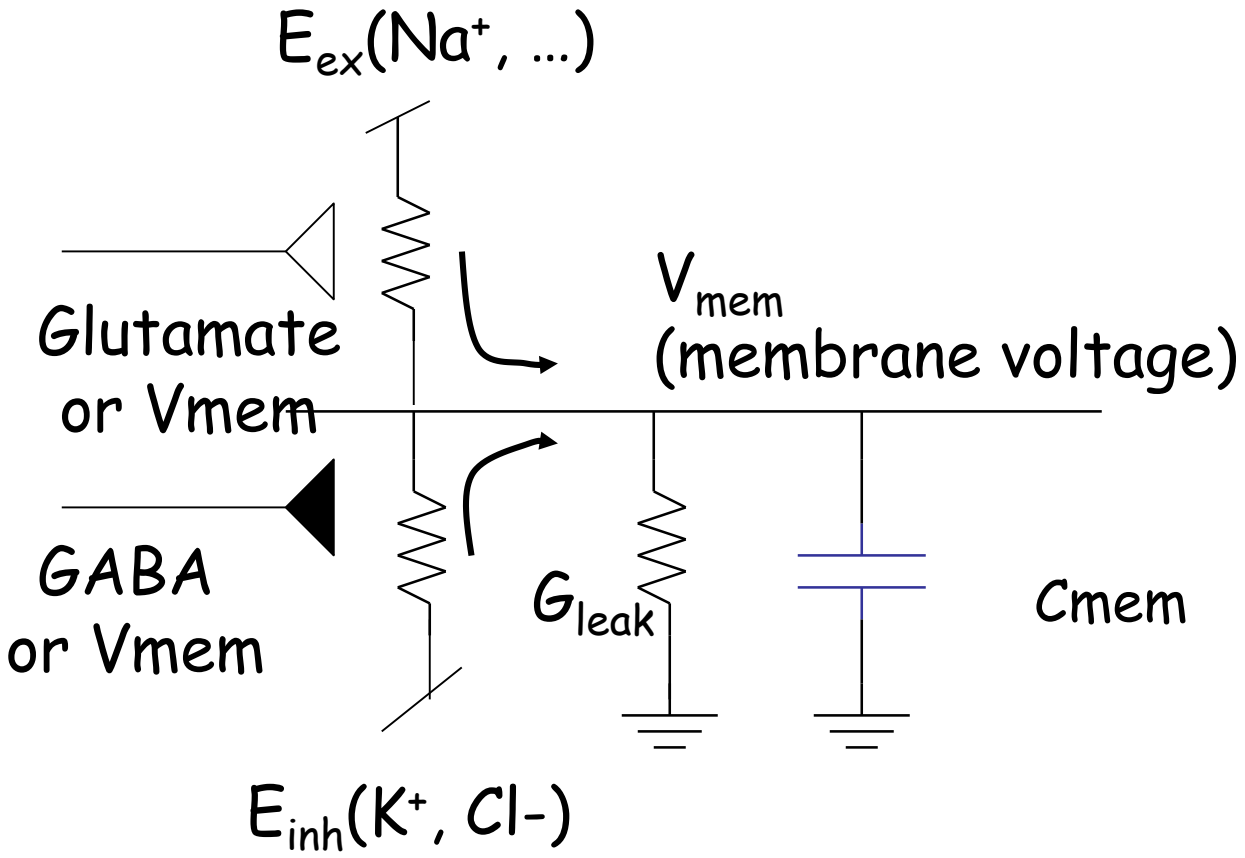
Synapses *multiply* the digital spike by a probabilistic weight

Complementary channels save power by push and pull on the membrane voltage

Dendrites do local analog computation,
Axon communicates distant digital spike events



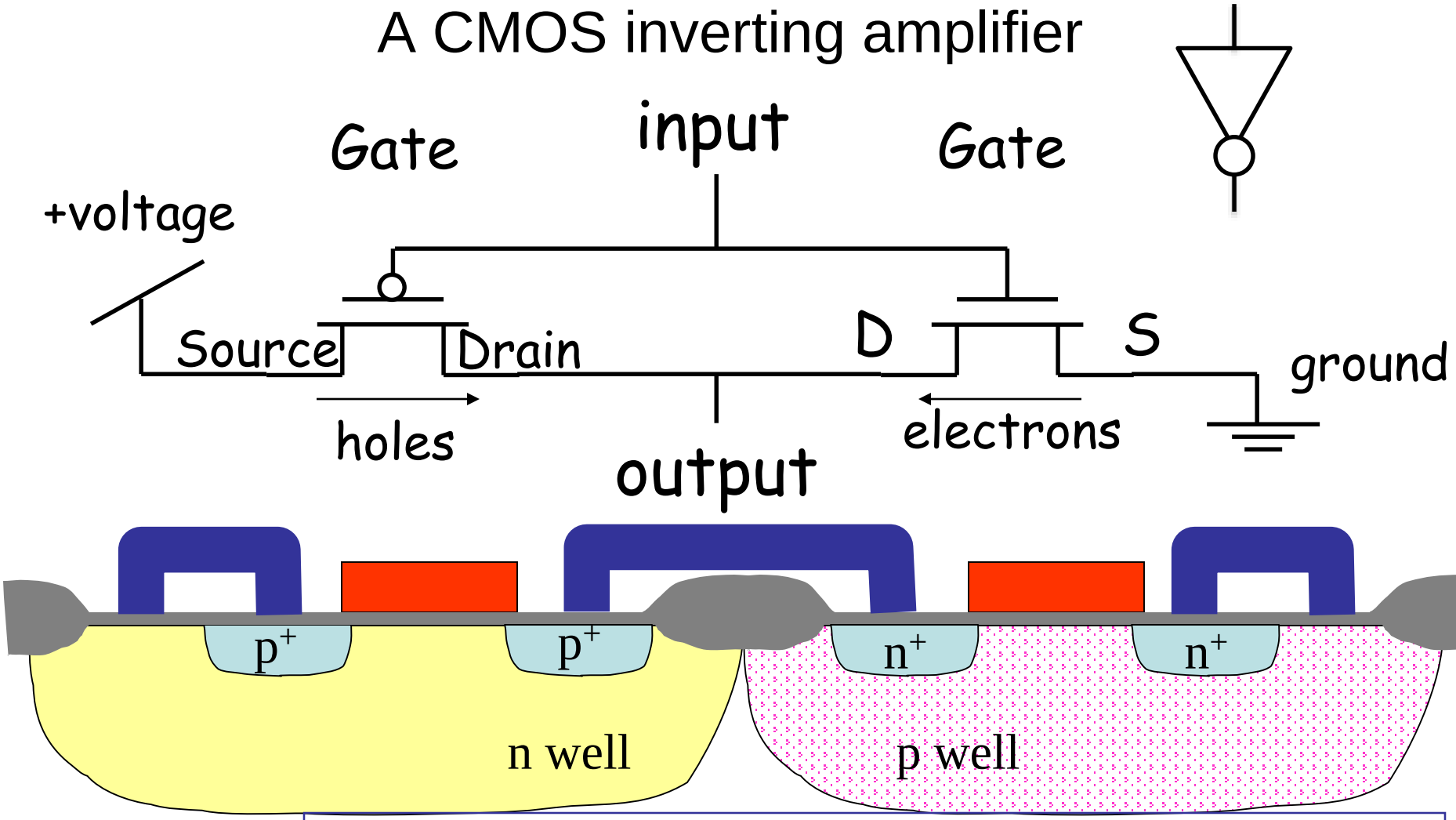
The membrane voltage is controlled by complementary transmitter or voltage gated channels



Almost no power is burned when both channels are off!

CMOS (complementary metal oxide semiconductor)

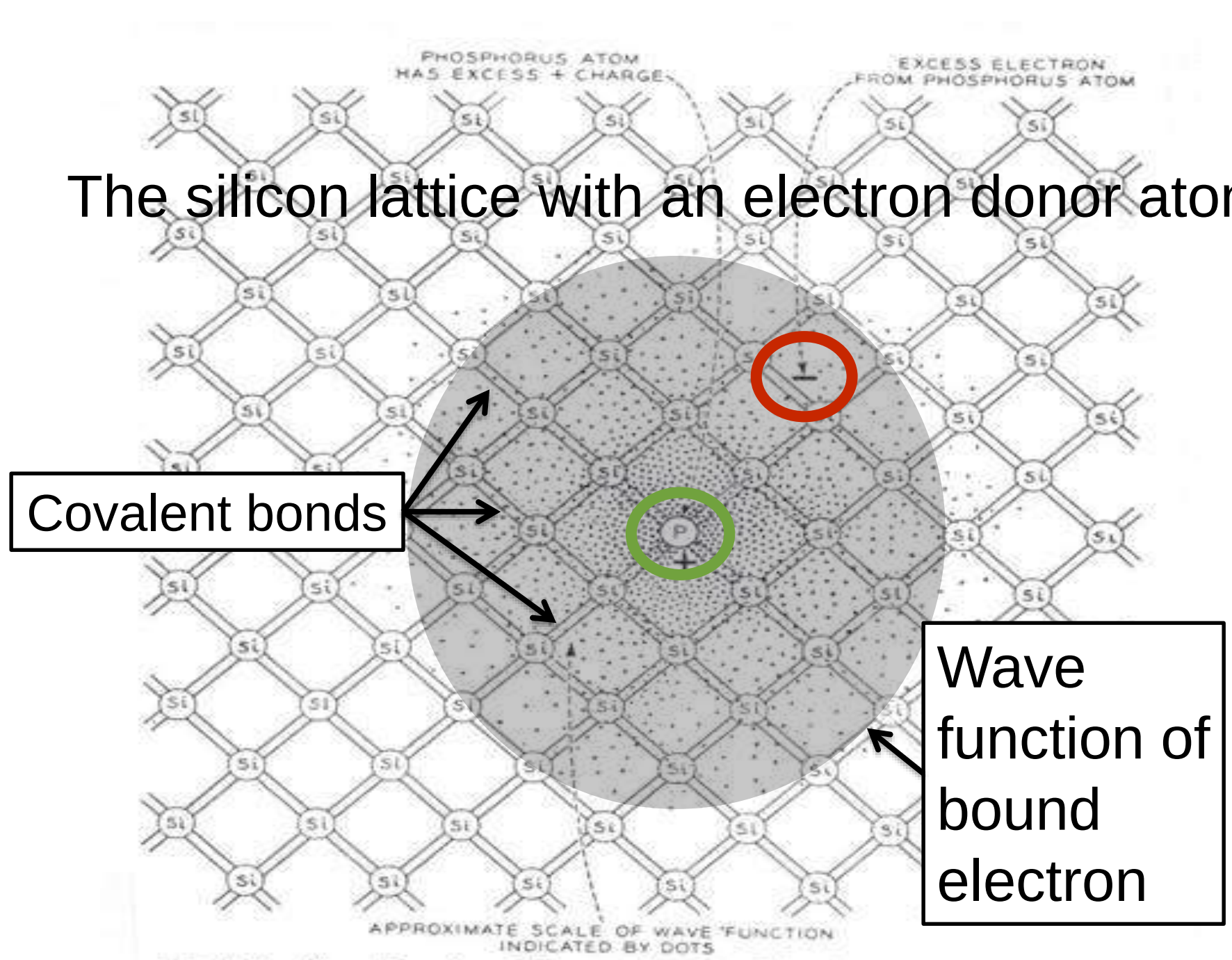
A CMOS inverting amplifier



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

Interlude on semiconductors and transistors

The silicon lattice with an electron donor atom



Covalent bonds

Wave function of bound electron

FIG. 1–14—Wave Function of Electron Bound to Phosphorous Atom in Silicon.

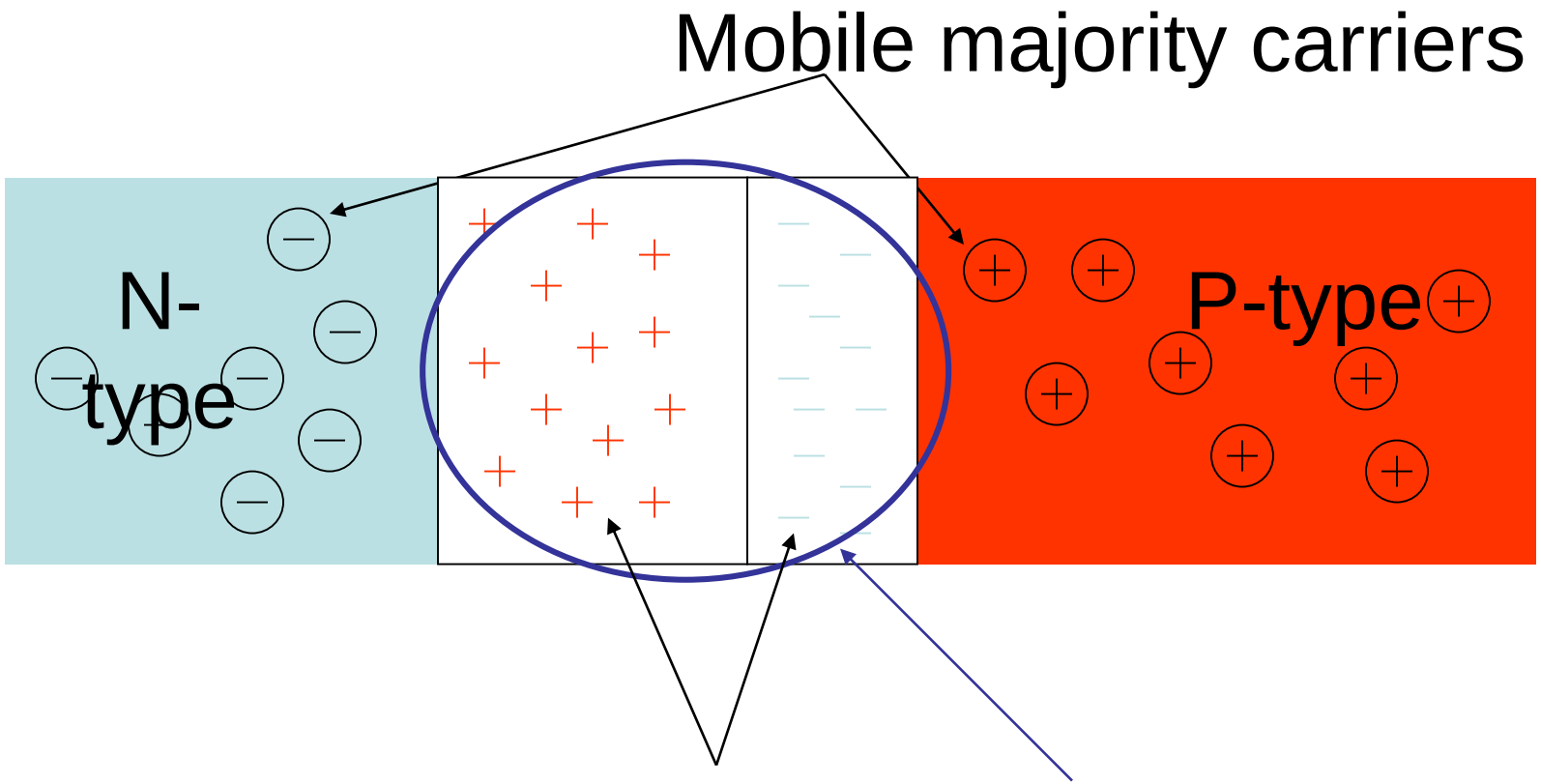
Donors and Acceptors in the periodic table

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

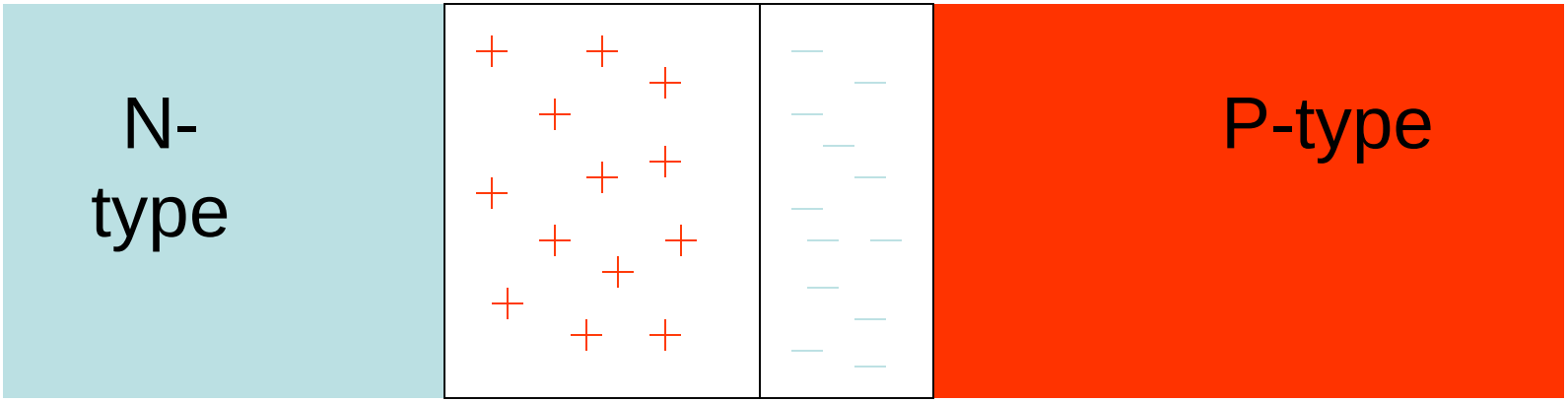
Acceptors
1 missing electron

Donors
1 extra electron

A P-N junction



A P-N junction



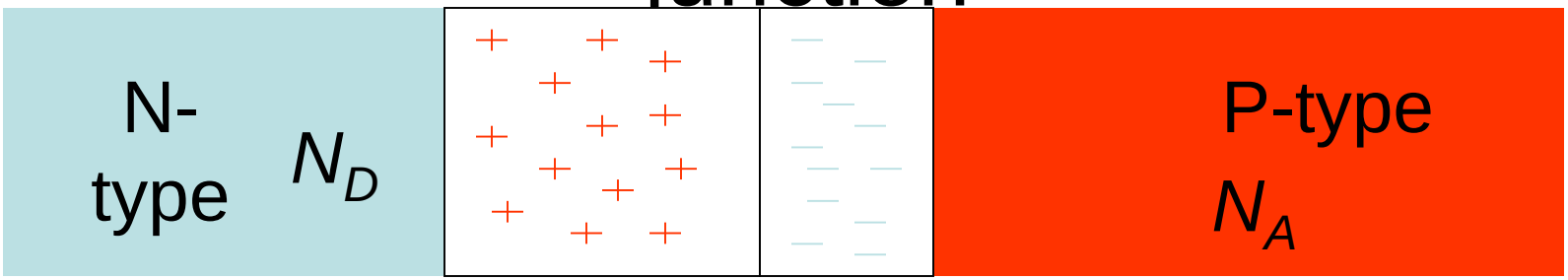
Electric field

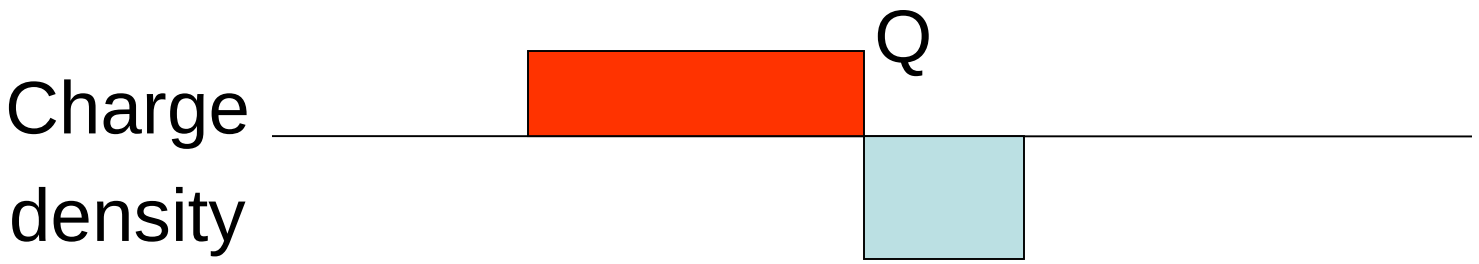
Diffusion of holes from *p* region

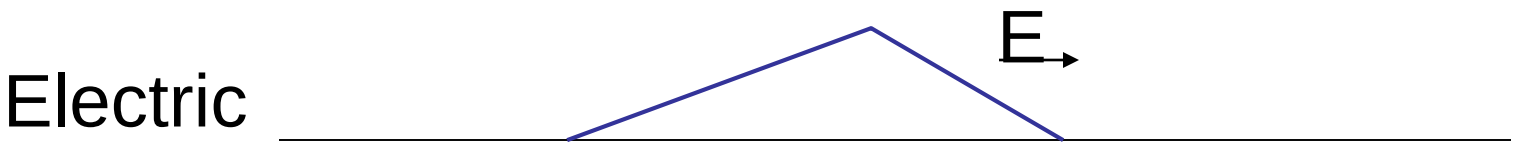
Diffusion of electrons from *n* region

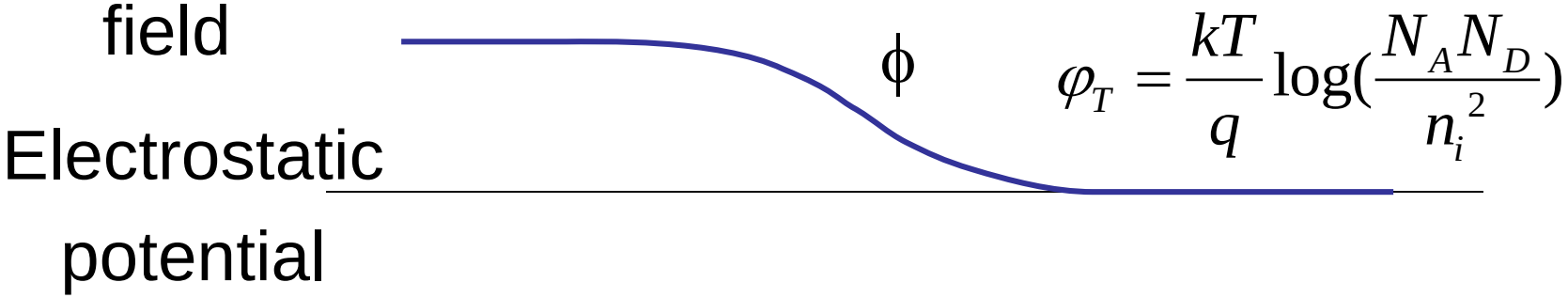
In equilibrium, *Drift* = *Diffusion* for electrons *and* holes

Charges, fields, and potentials in a PN junction





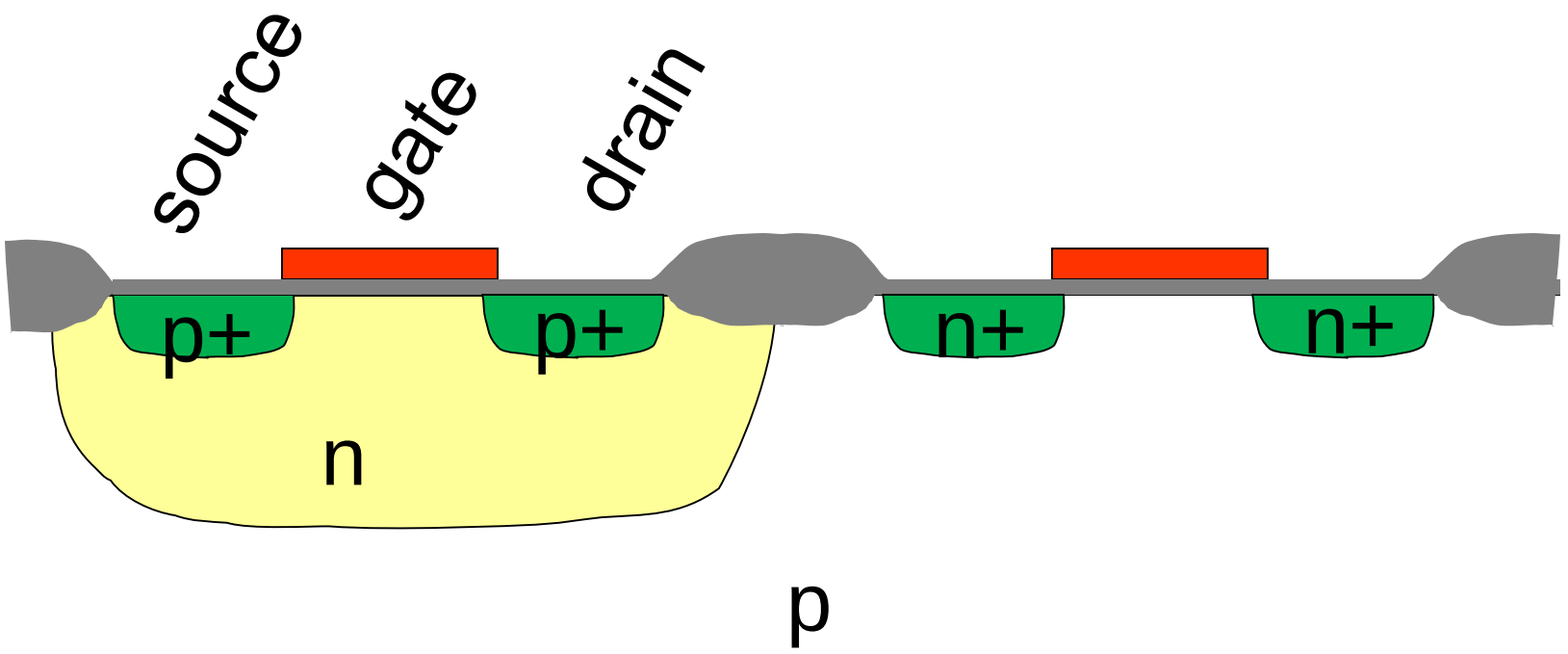


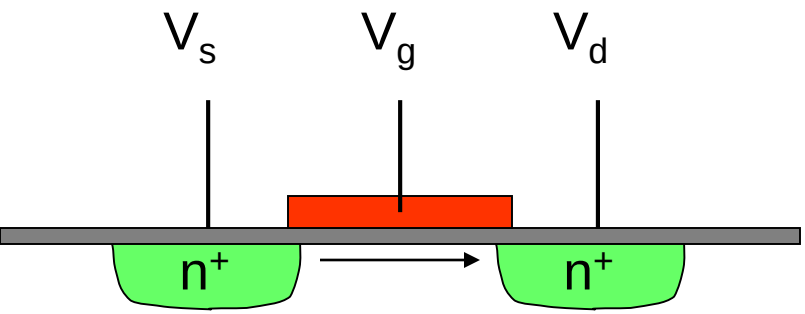


$$\varphi_T = \frac{kT}{q}\log\left(\frac{N_A N_D}{n_i^2}\right)$$

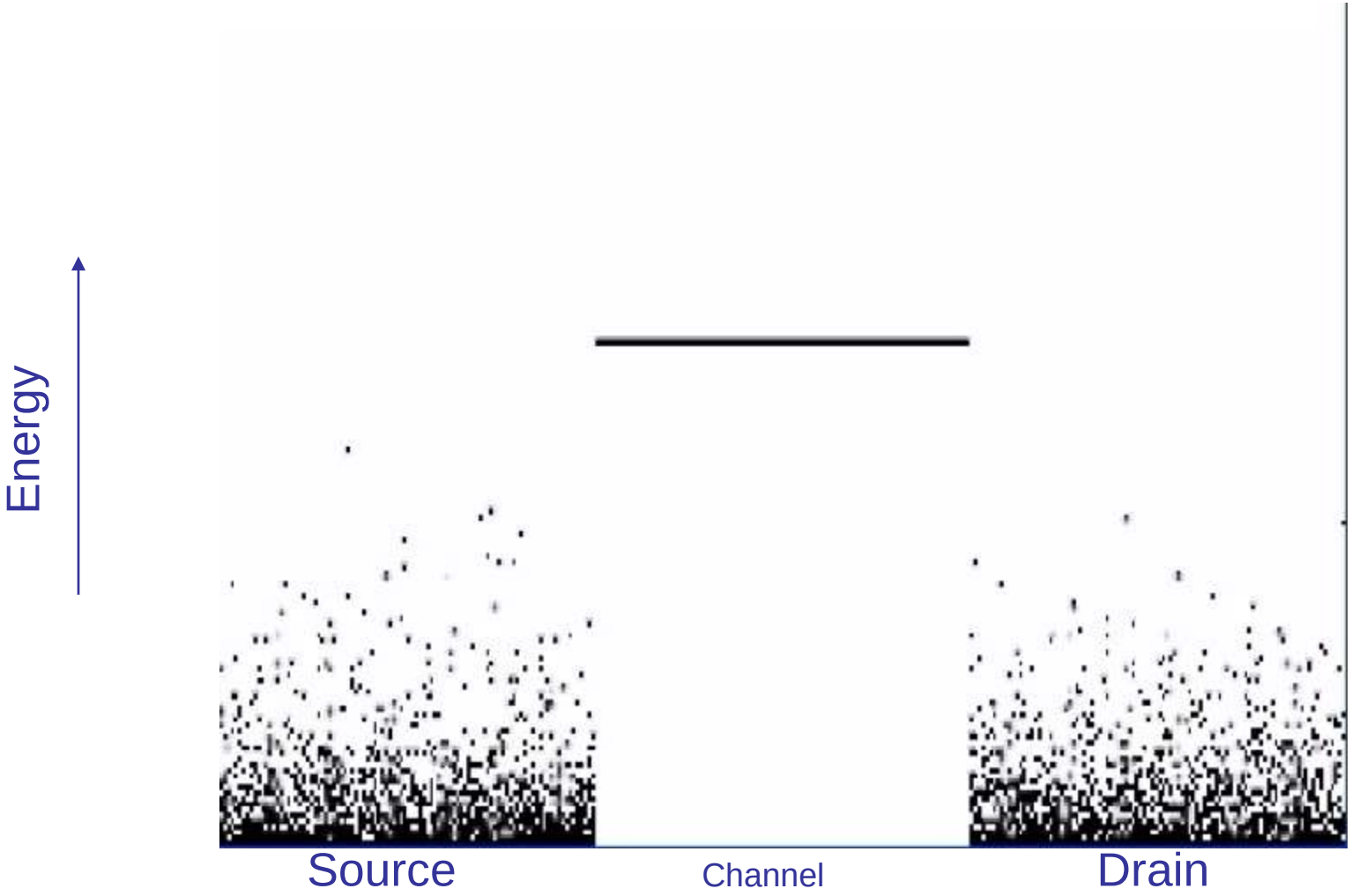
Typically, the *built-in voltage*, φ_T, is about 0.75V

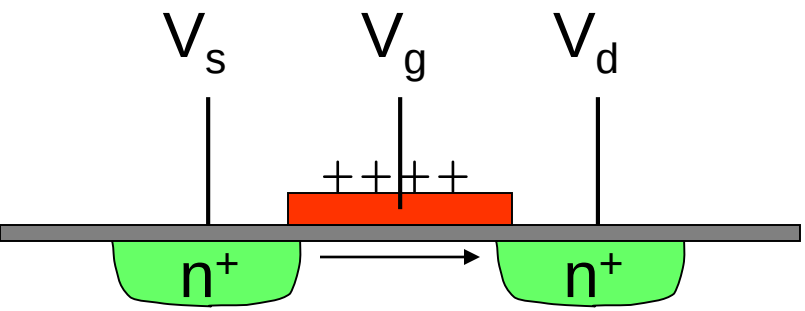
MOS transistors use insulated gates to control barrier energies at PN surface junctions at source and drain



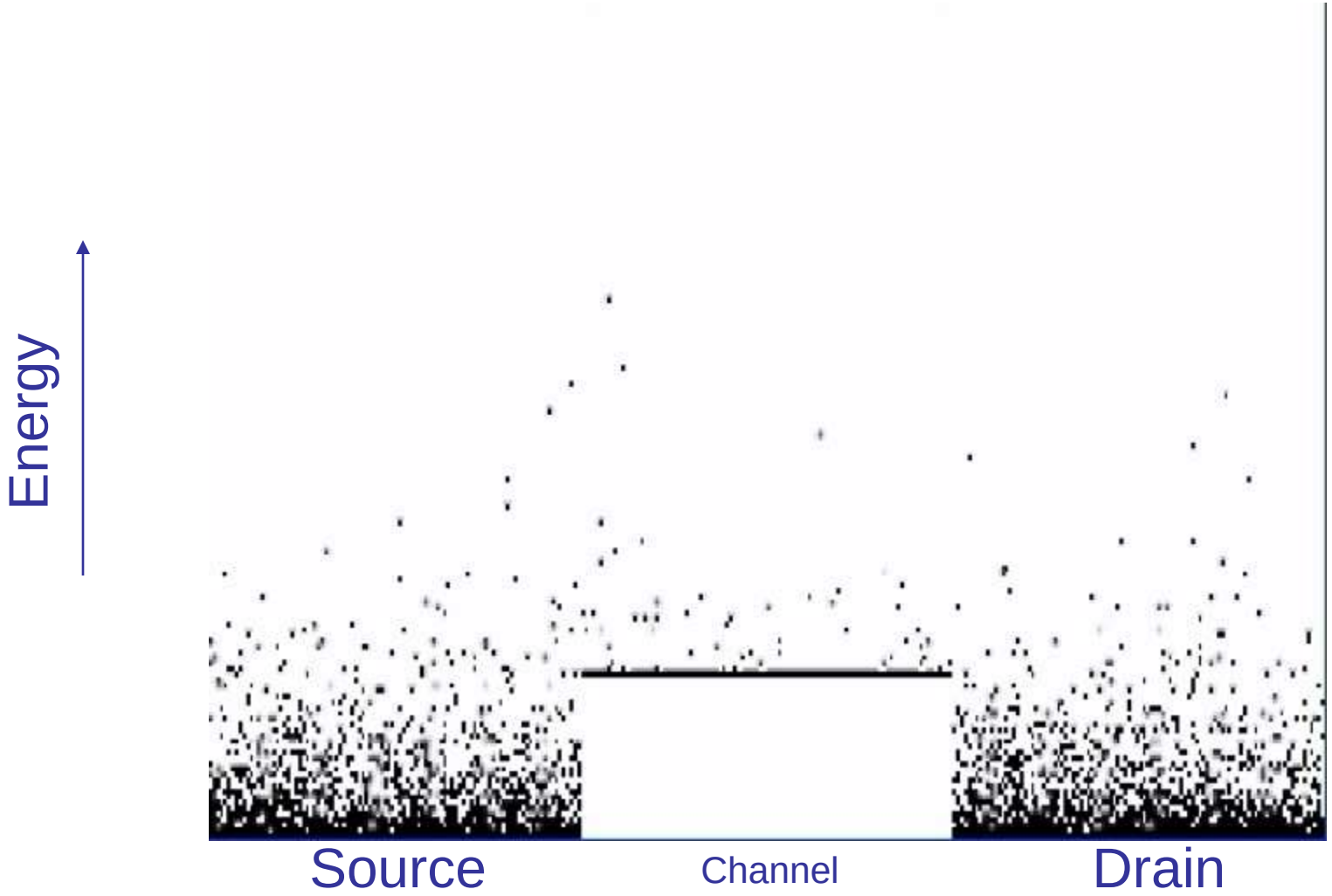


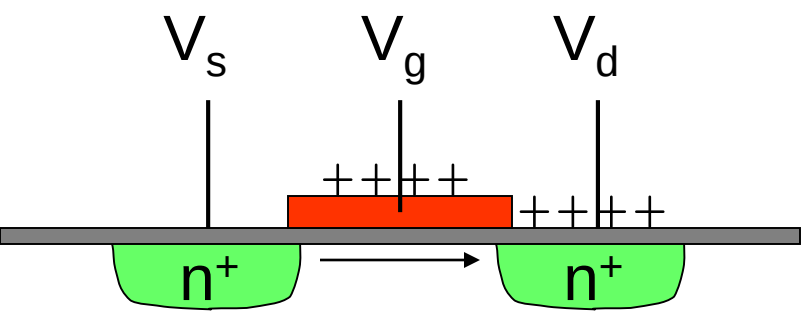
Small Vgs, Vds=0



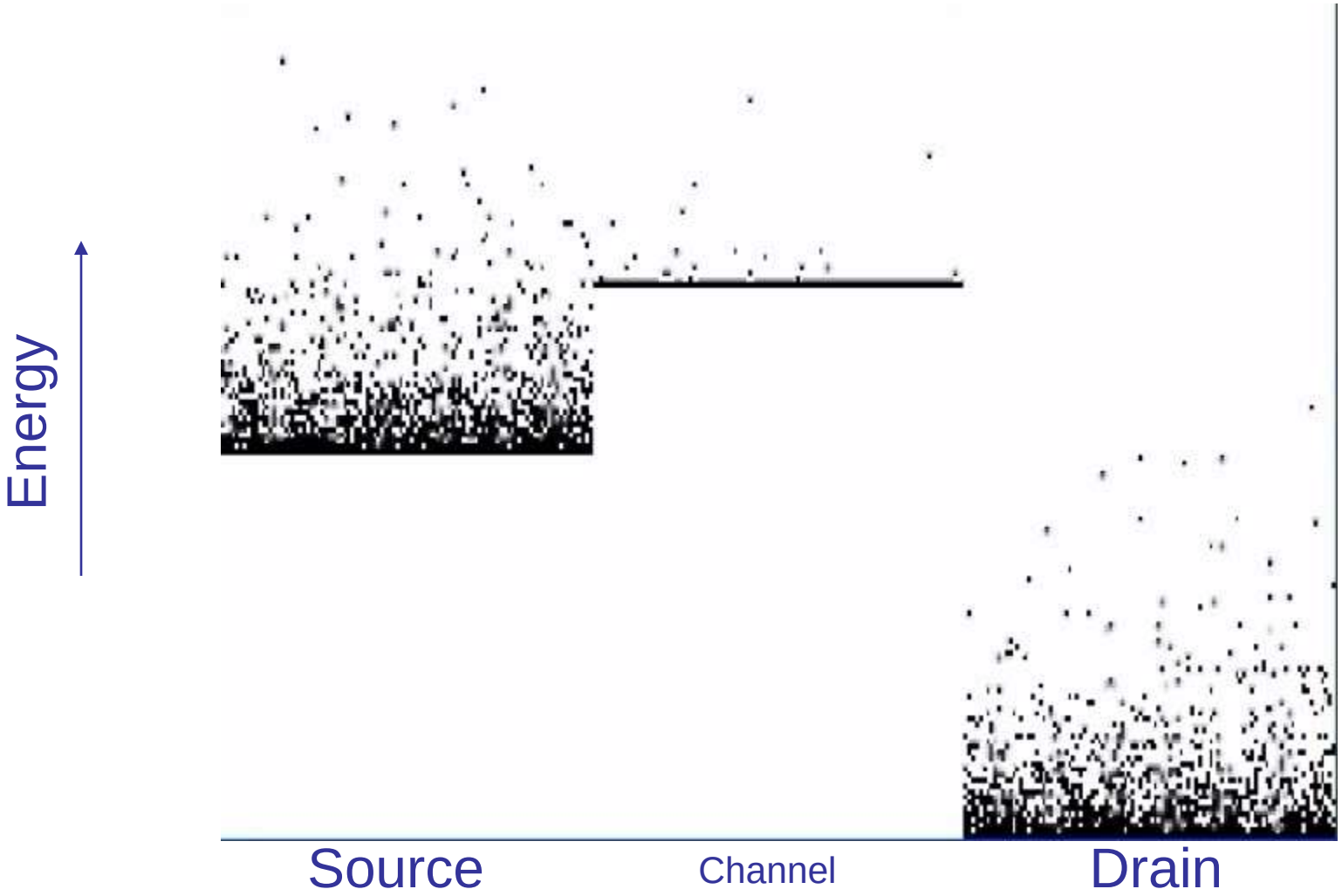


Larger Vgs, Vds=0

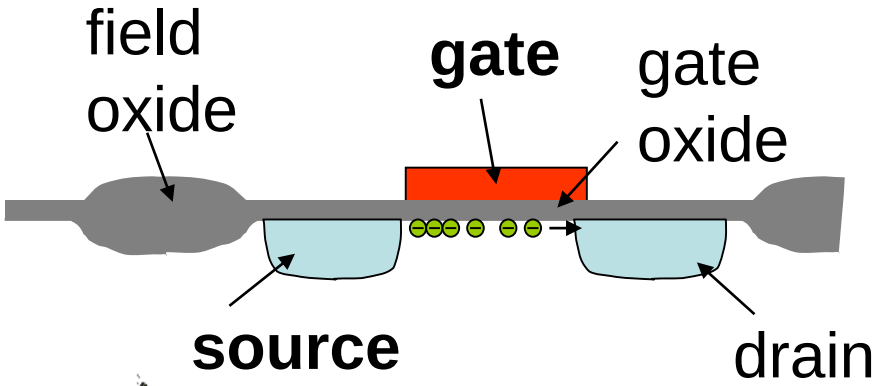


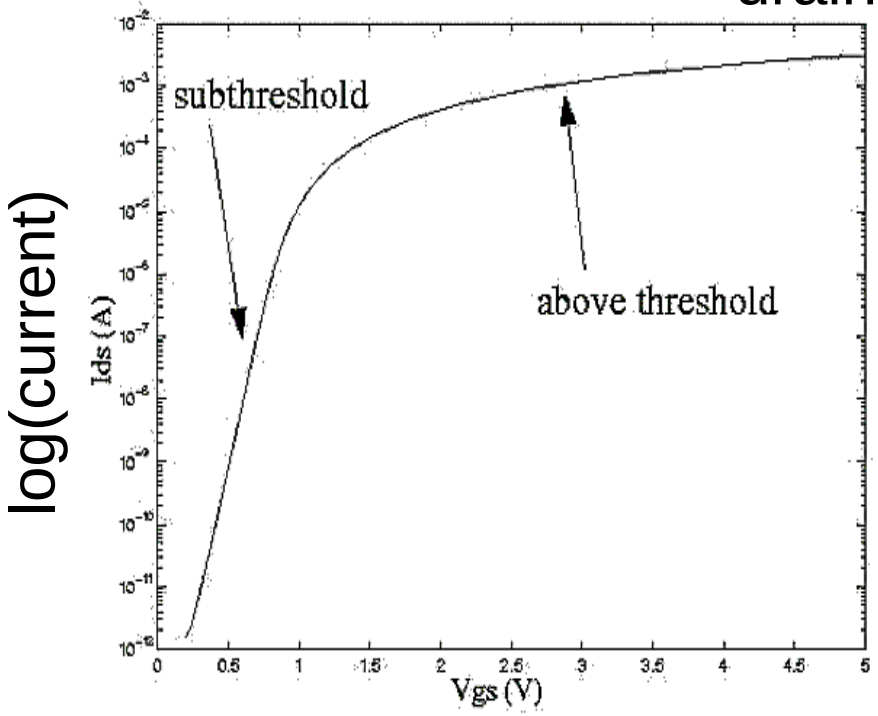


Larger Vgs,
Large Vds



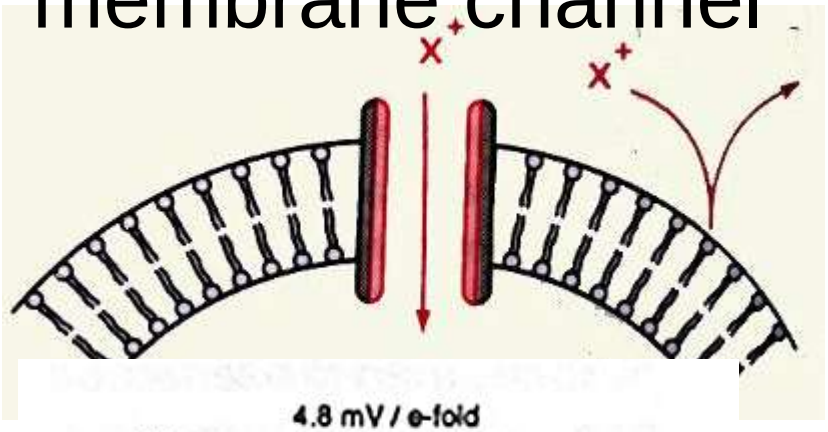
Transistor

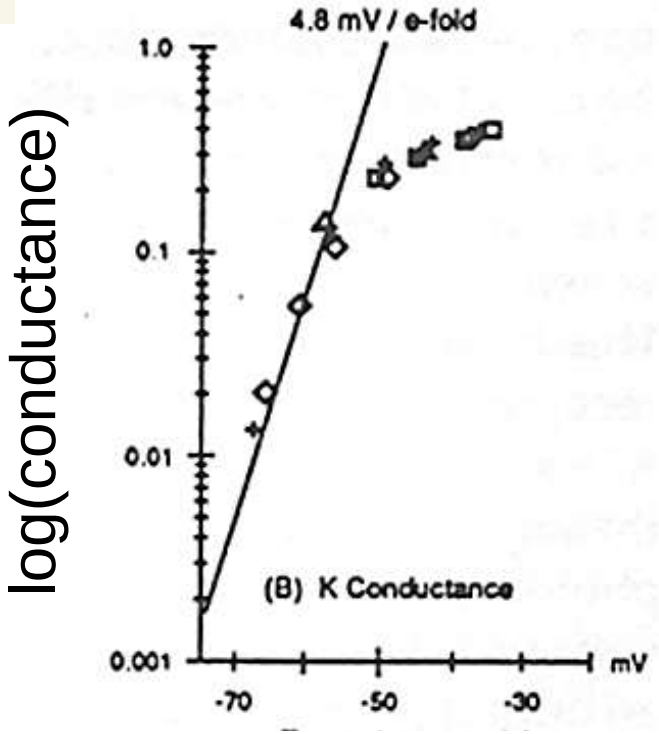




gate-source voltage

Voltage activated membrane channel





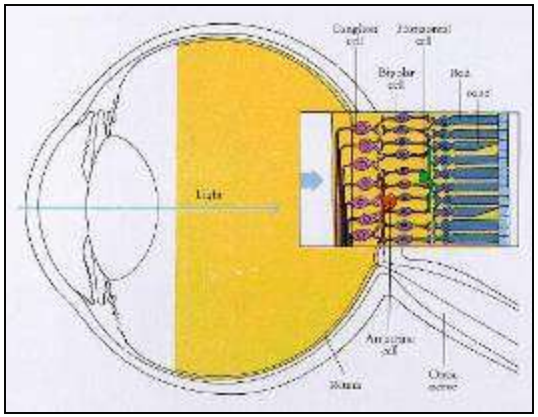
membrane voltage

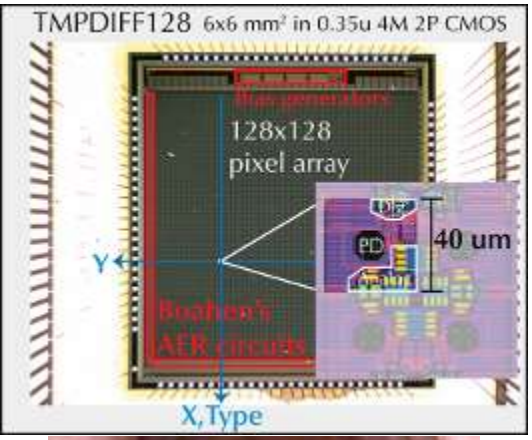
Mechanism of gain

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

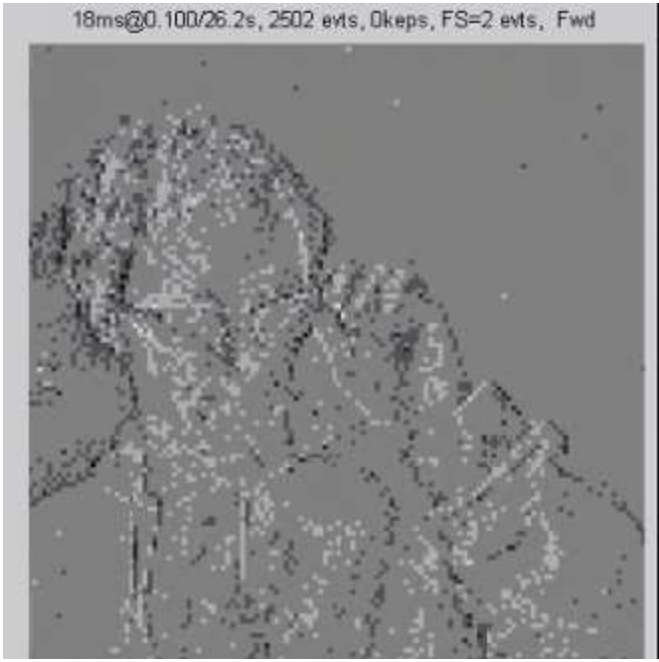
Temporal Contrast Dynamic Vision Sensor

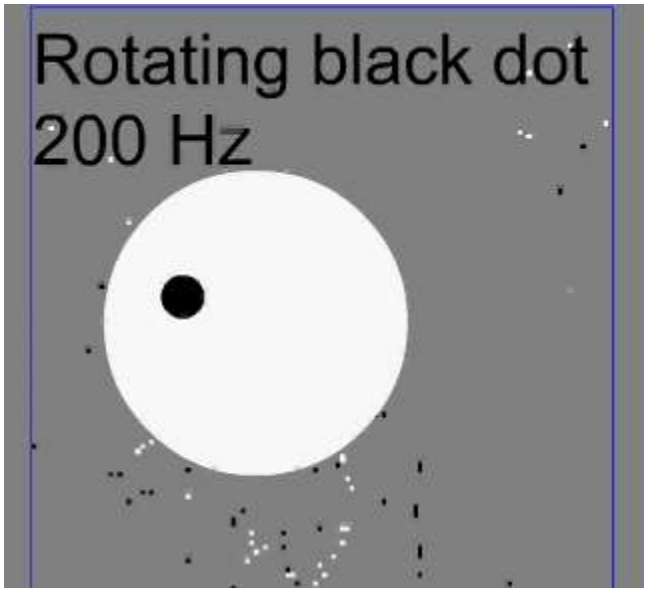




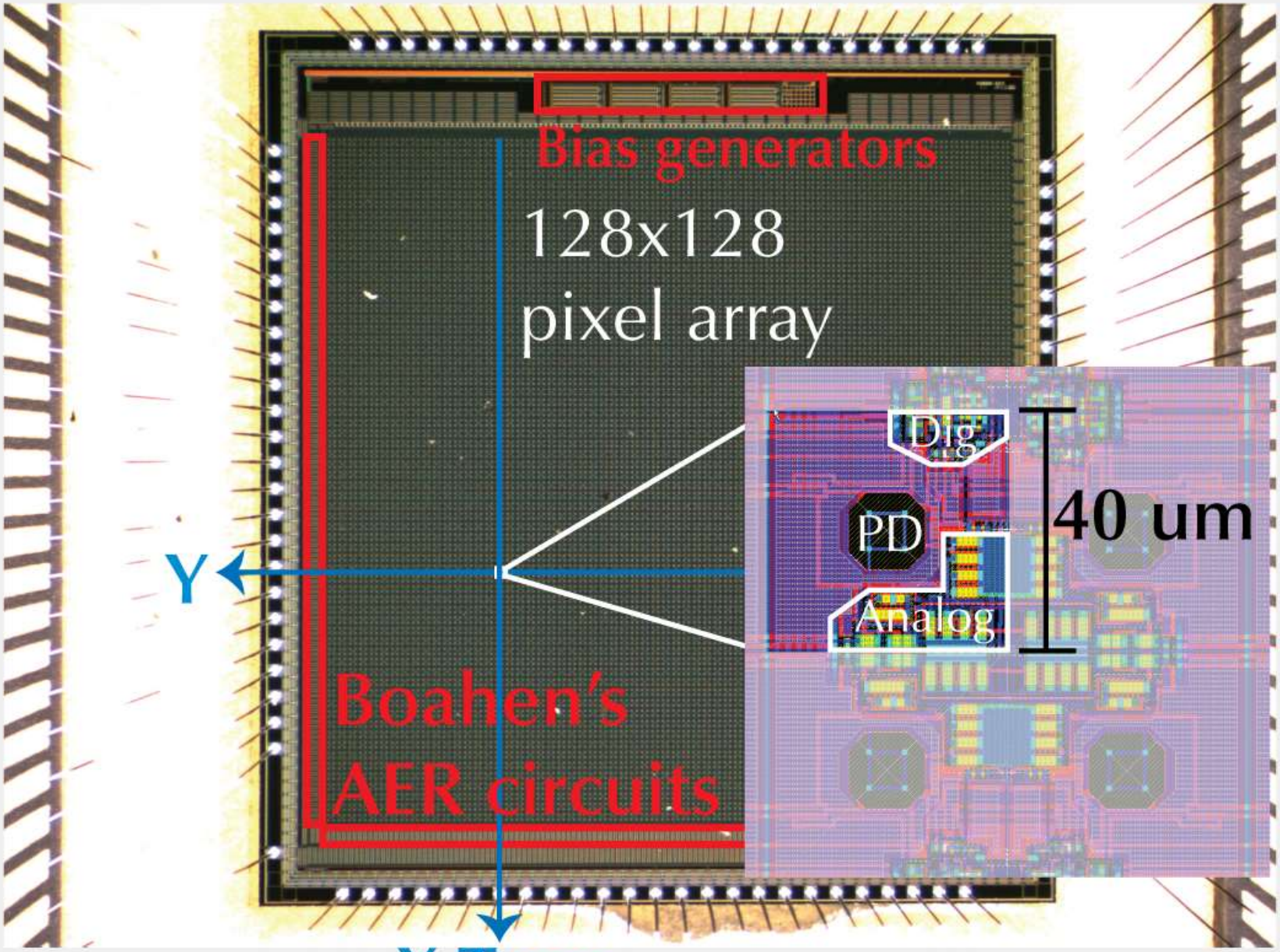
1. This silicon retina **asynchronously** outputs **spiking pixel identities**.
2. Each spike represents a fixed ***temporal contrast*** (ΔlogI), corresponding to change in scene reflectance.

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

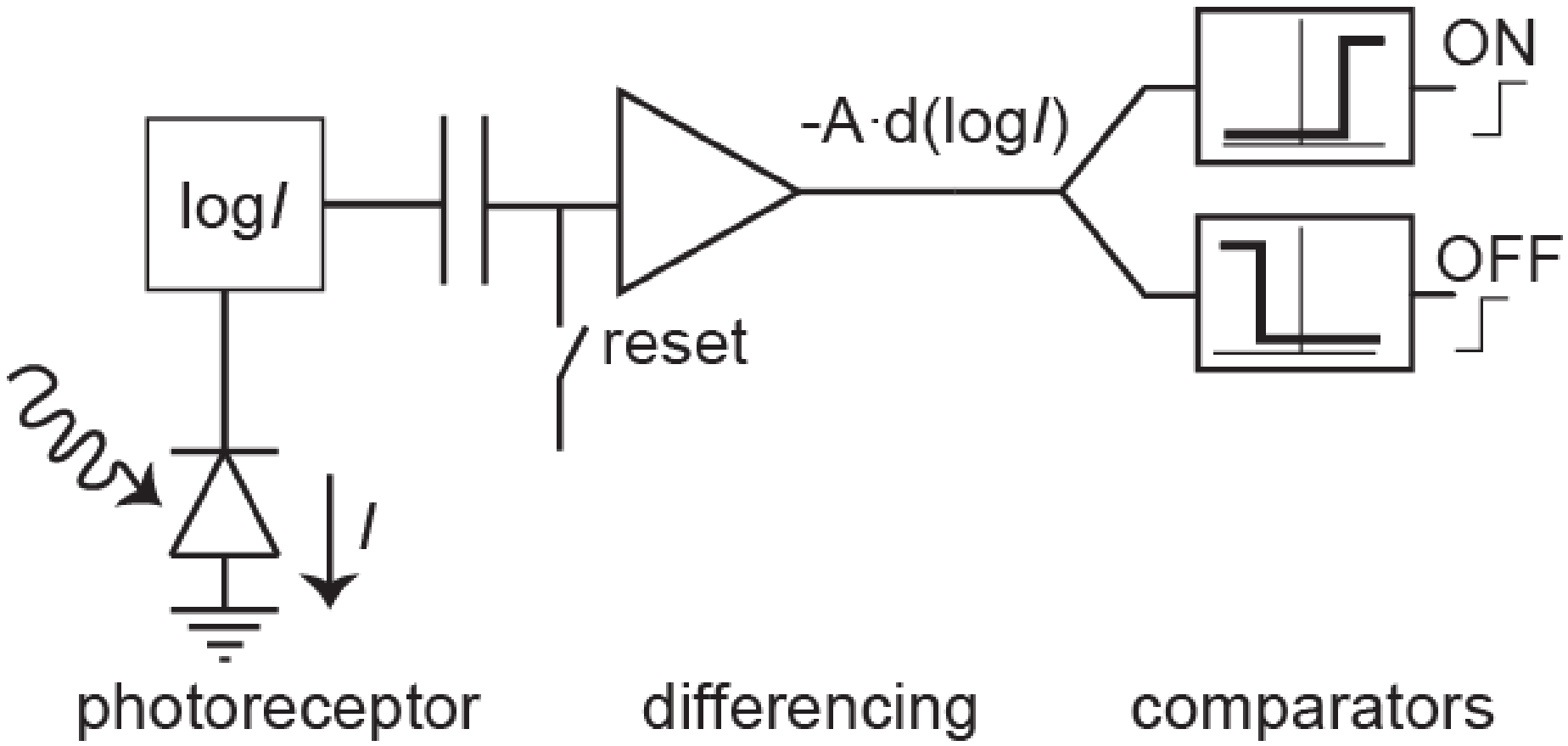


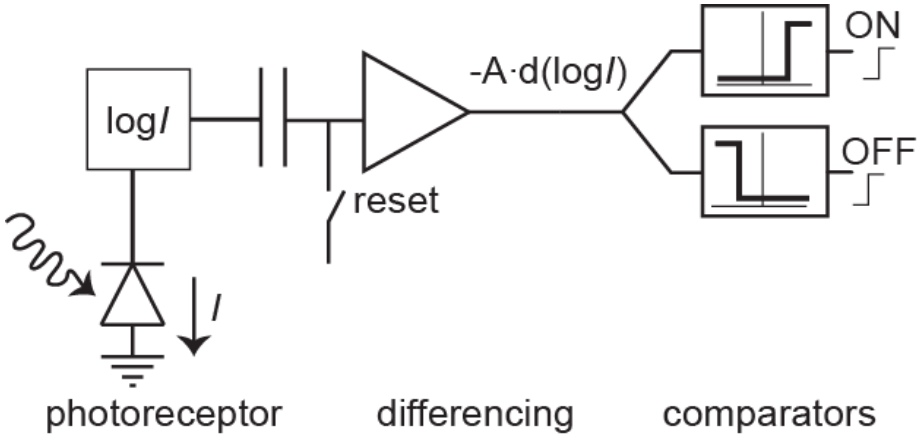


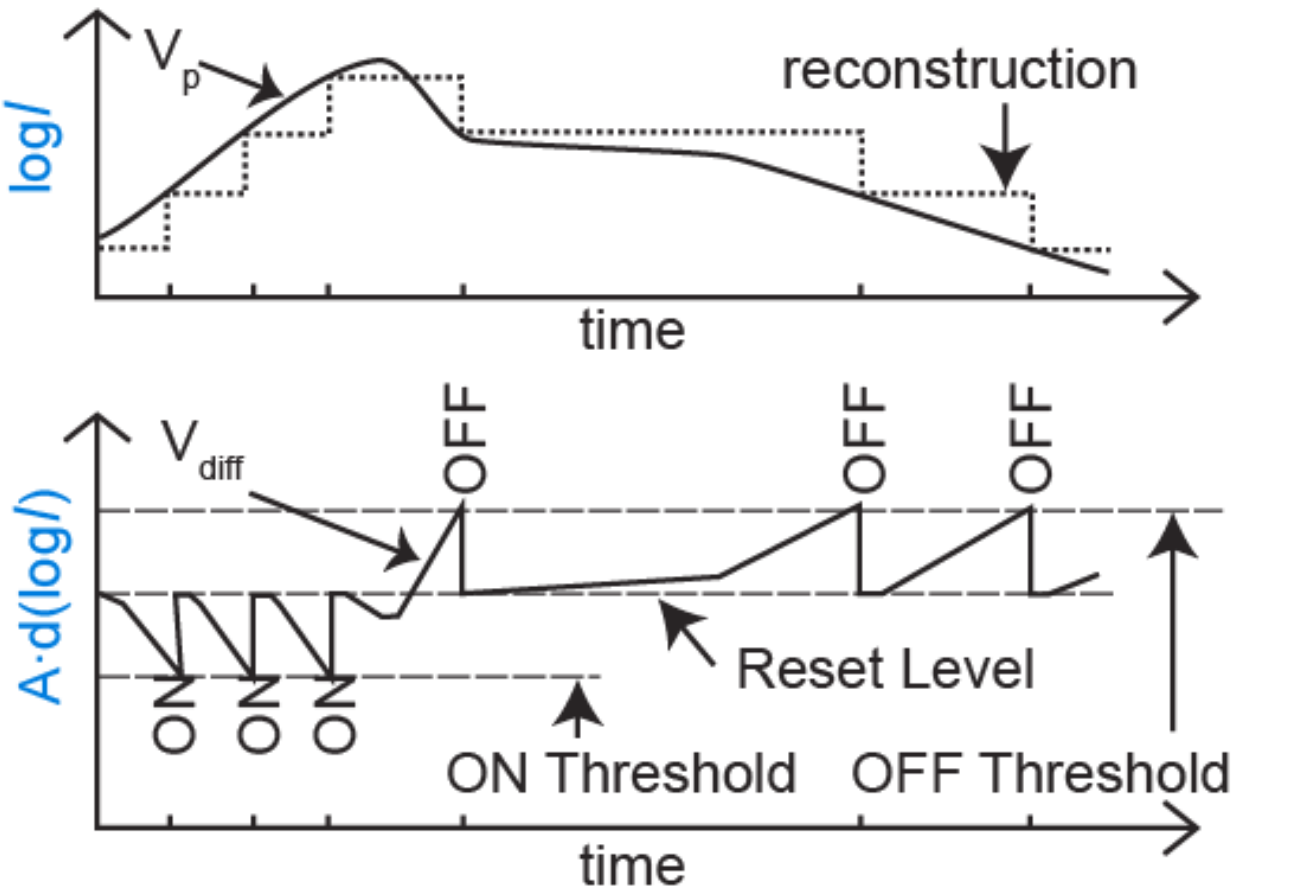
TMPDIFF128 6x6 mm² in 0.35u 4M 2P CMOS



DVS pixel architecture




log I
-A·d(log I)
ON
OFF
reset
I
photoreceptor
differencing
comparators


log I
V p
reconstruction
time
A·d(log I)
V diff
OFF
OFF
OFF
ON
ON
ON
Reset Level
ON Threshold
OFF Threshold
time

Embedded DVS Pencil Balancer

Jorg Conradt, Matt Cook

3 microcontrollers, 600mW

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