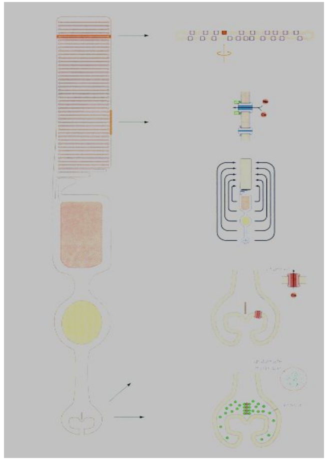
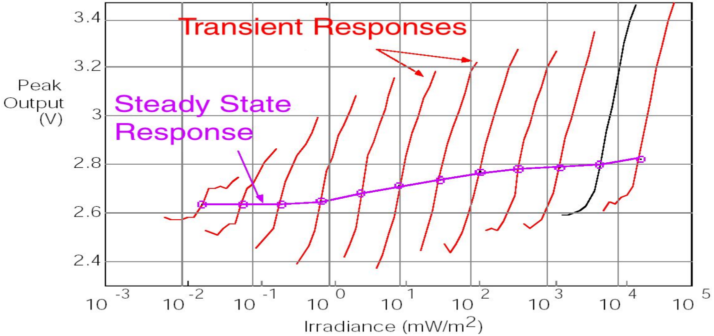
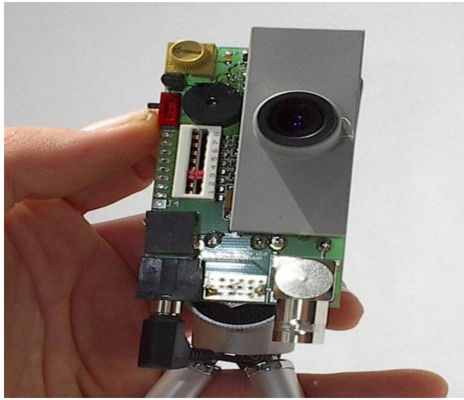
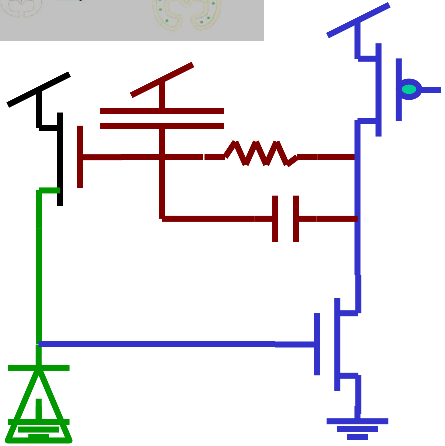
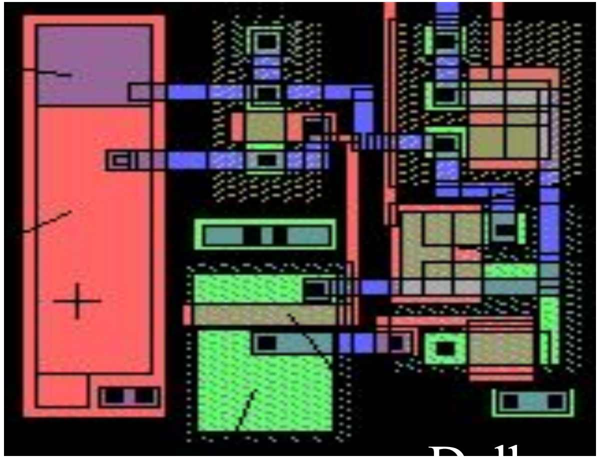
Photoreceptors II











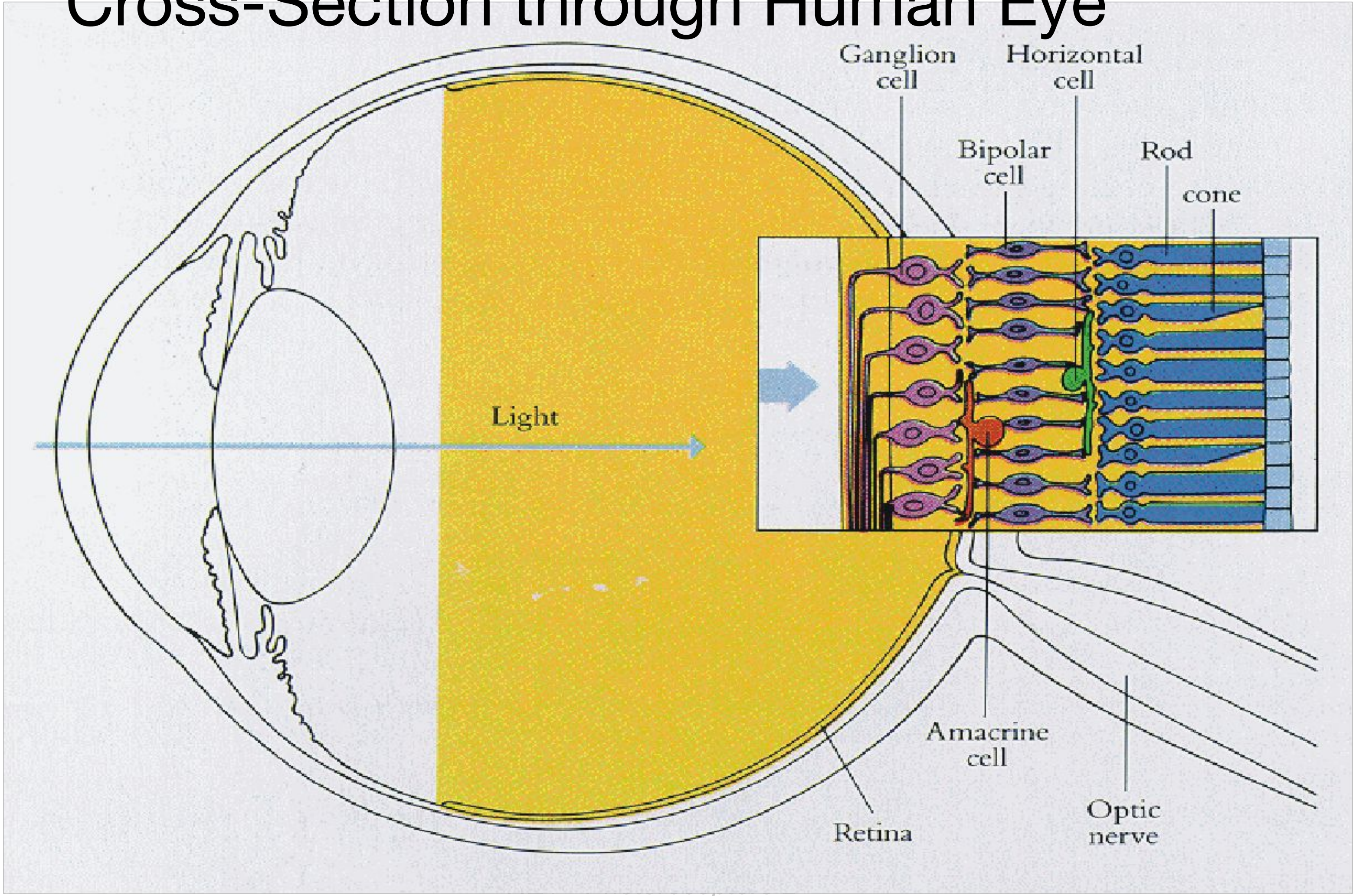
Photoreceptors II

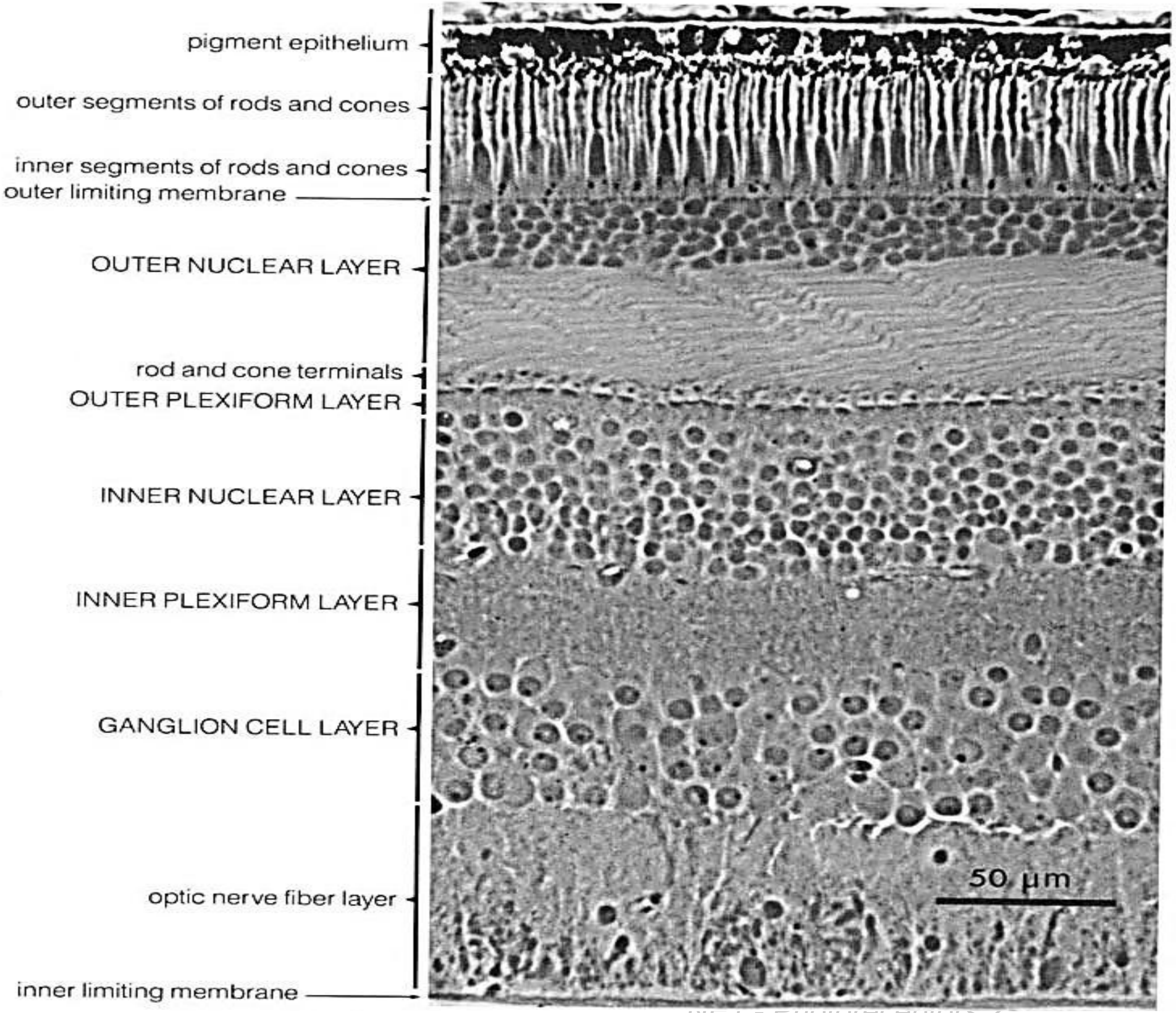
- Basic three-layer retina circuit (photoreceptors+bipolar cells+horizontal cells -> ganglion cells)
- Physiologist's Friend Chip
- Logarithmic photoreceptor review
- Adaptive photoreceptor, cap feedback, adaptive element pseudo resistor
- Circuit techniques – cascode, Miller effect, Speedup in transimpedance amplifiers, second-order system analysis via canonical 2nd-order system, Q quality factor and root locus plot

T. Delbruck, S.C. Liu

THREE LAYER RETINA CIRCUIT

Cross-Section through Human Eye





Cross section of human retina

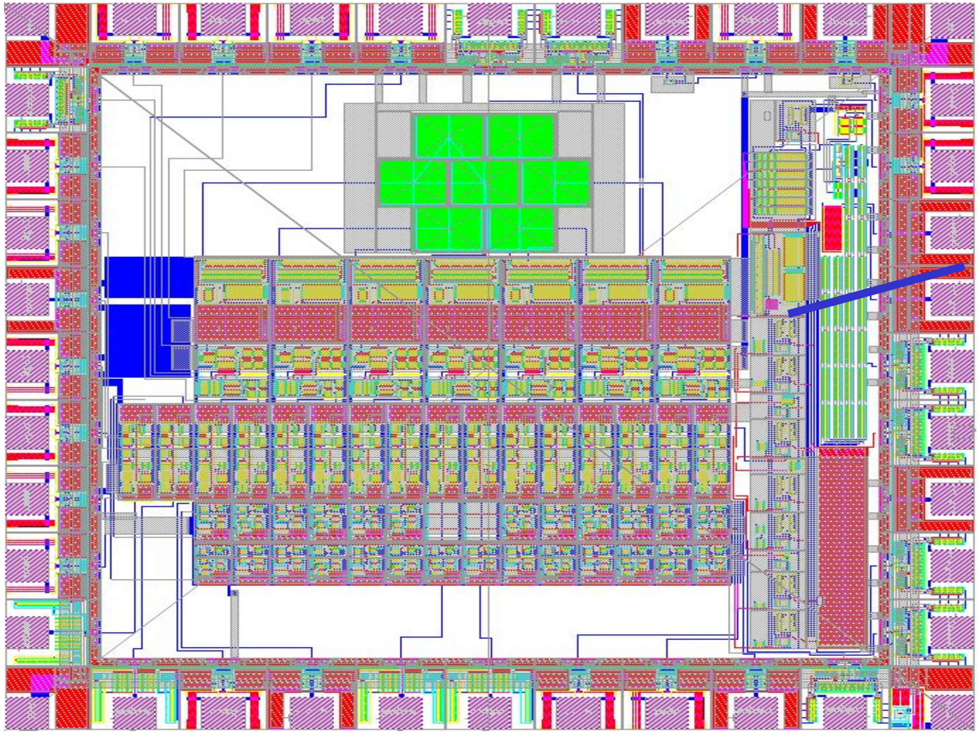
Physio Friend Layout

Photodiodes

Photoreceptors

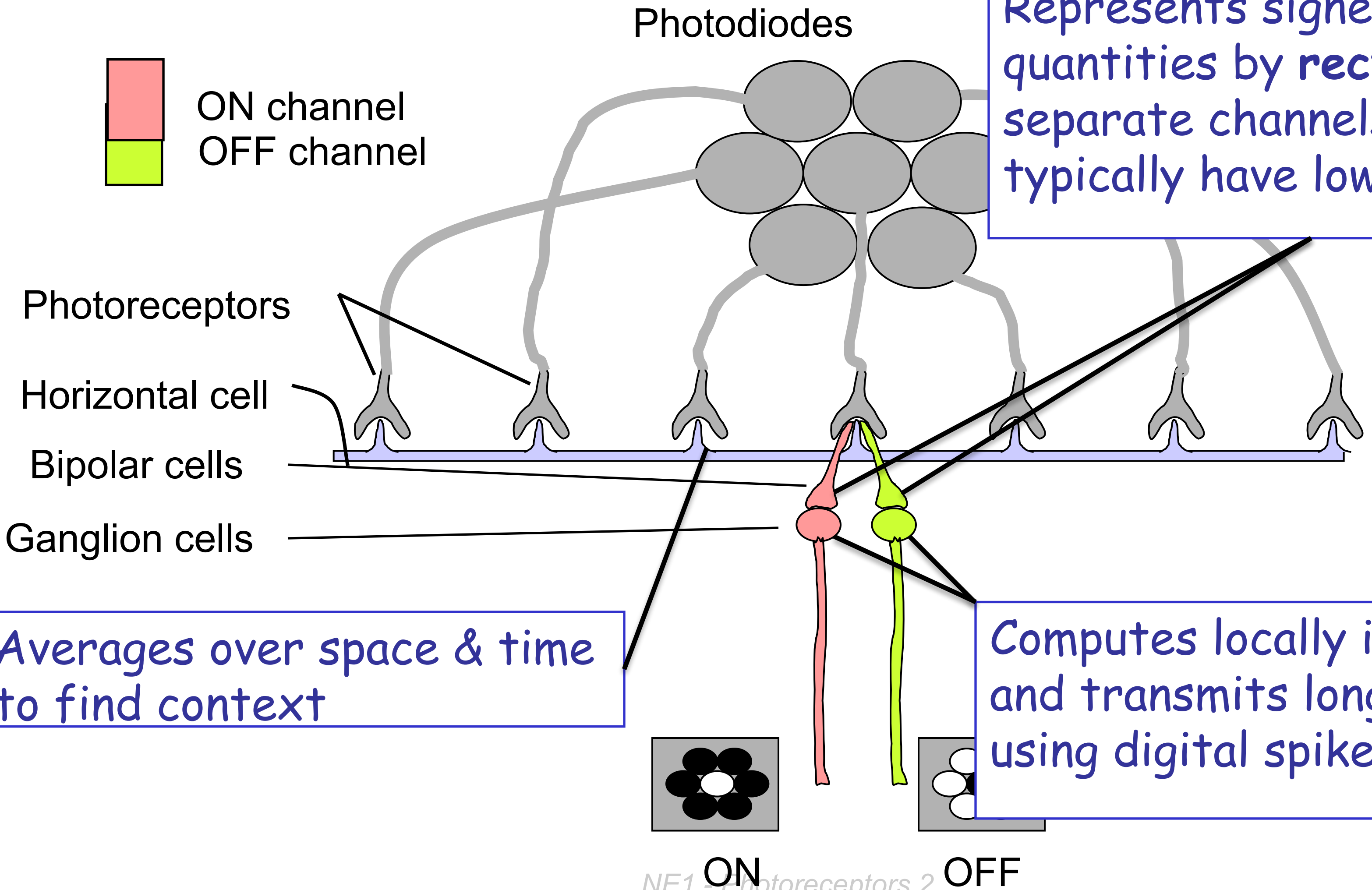
Bipolar/Horizontal cells
Ganglion & Simple cells

Synapses



Biases

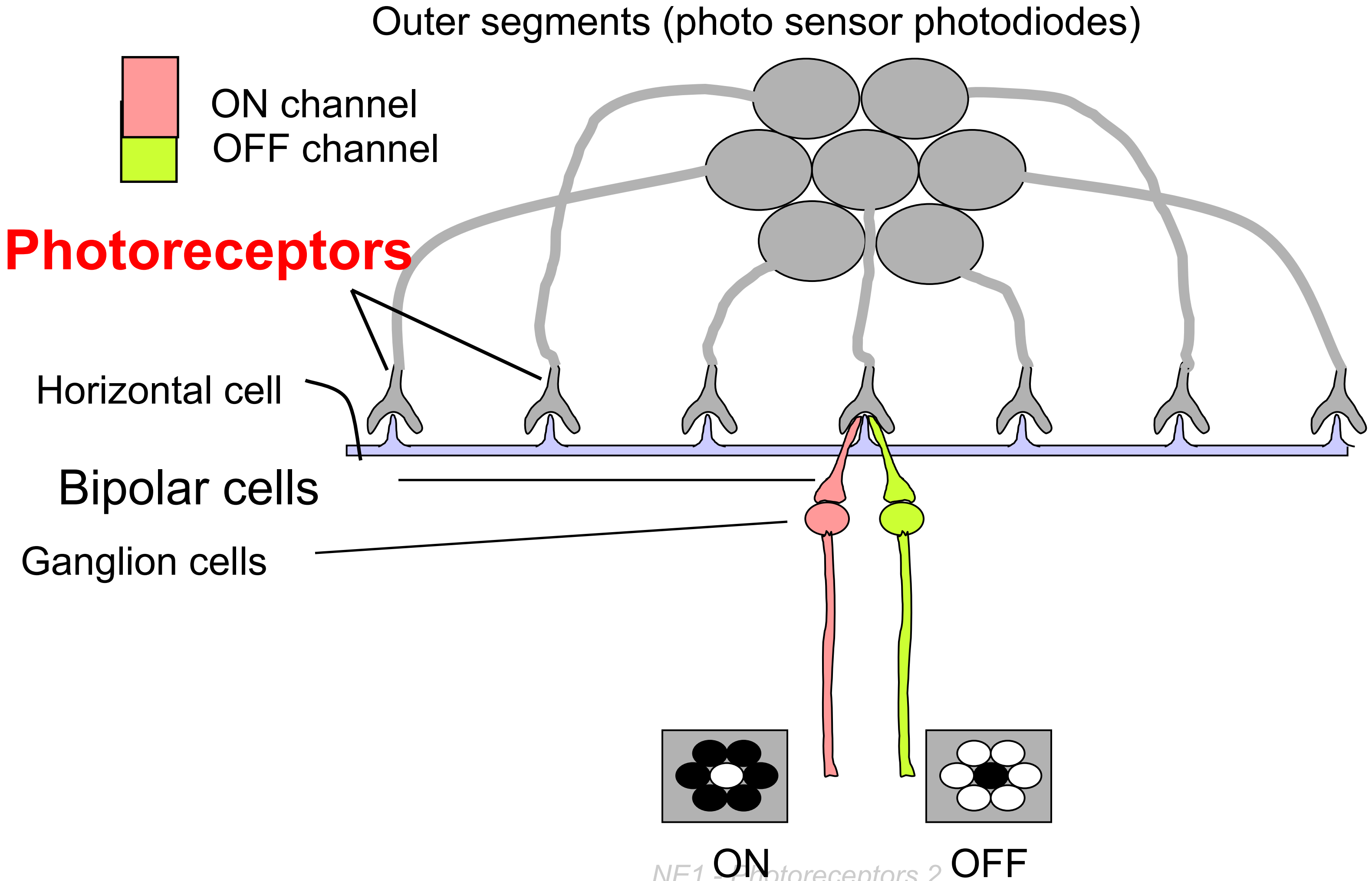
2.2mm

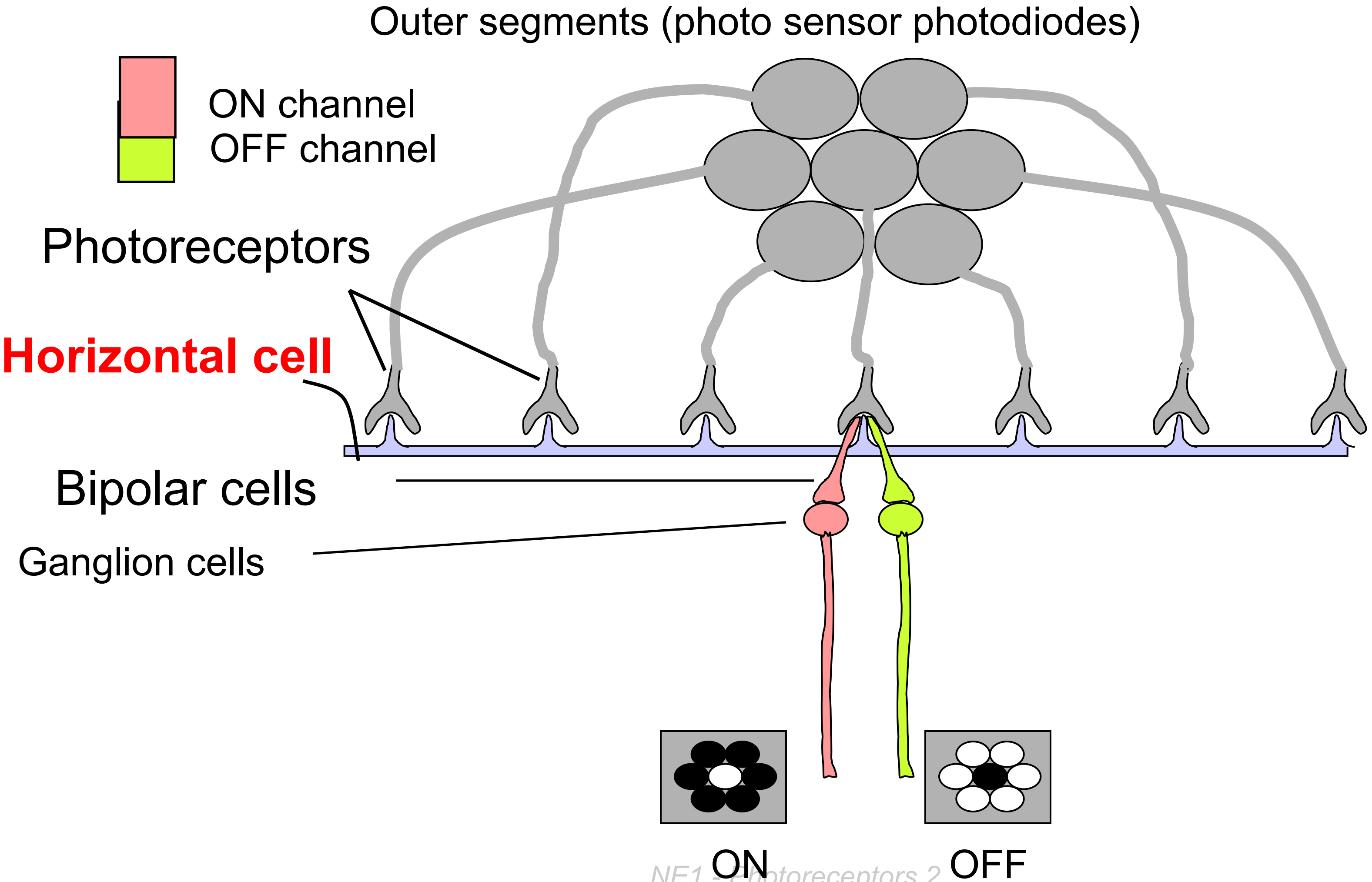


Represents signed quantities by **rectifying** into separate channels that typically have low activity

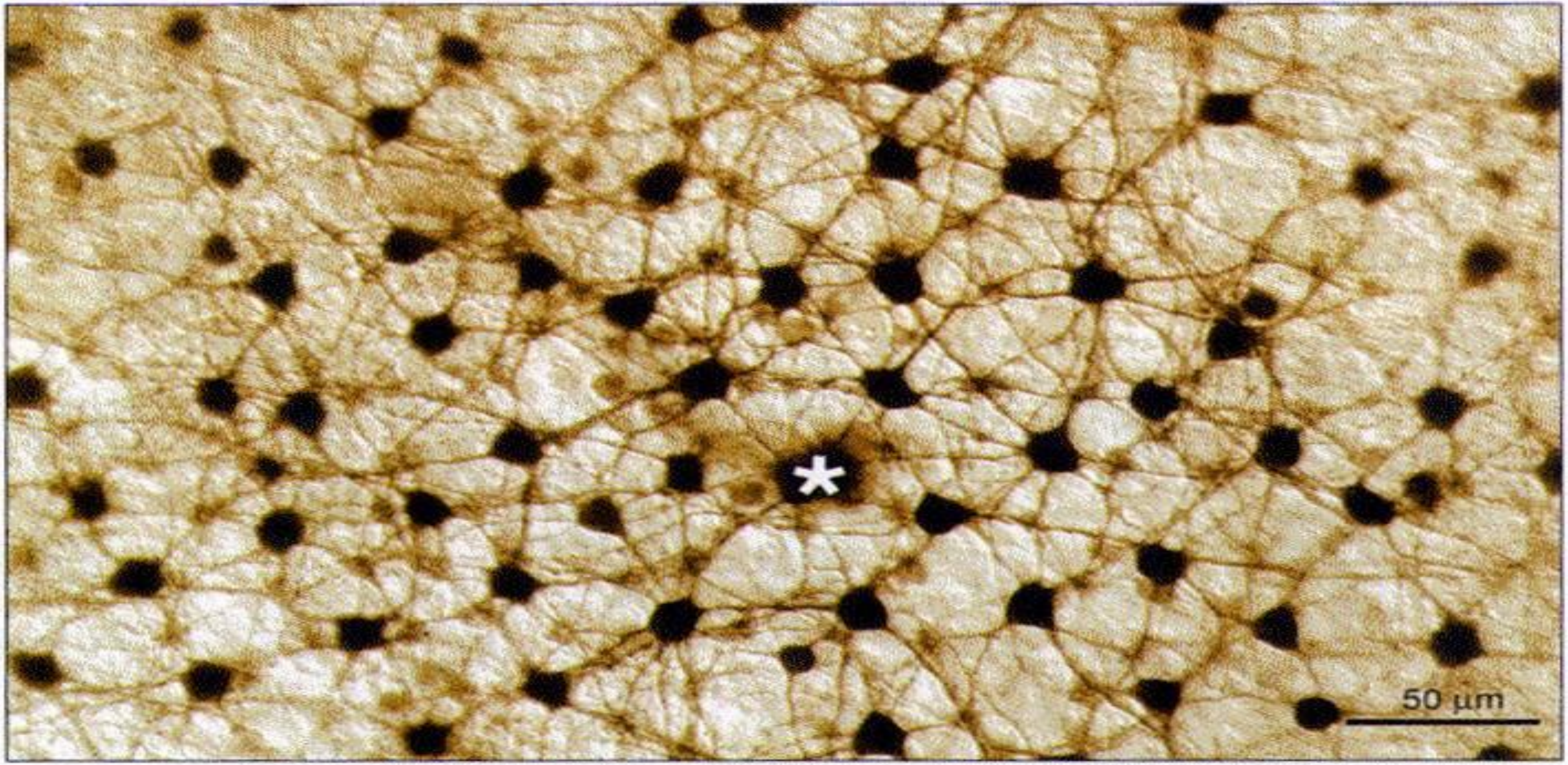
Averages over space & time to find context

Computes locally in analog and transmits long distances using digital spikes


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



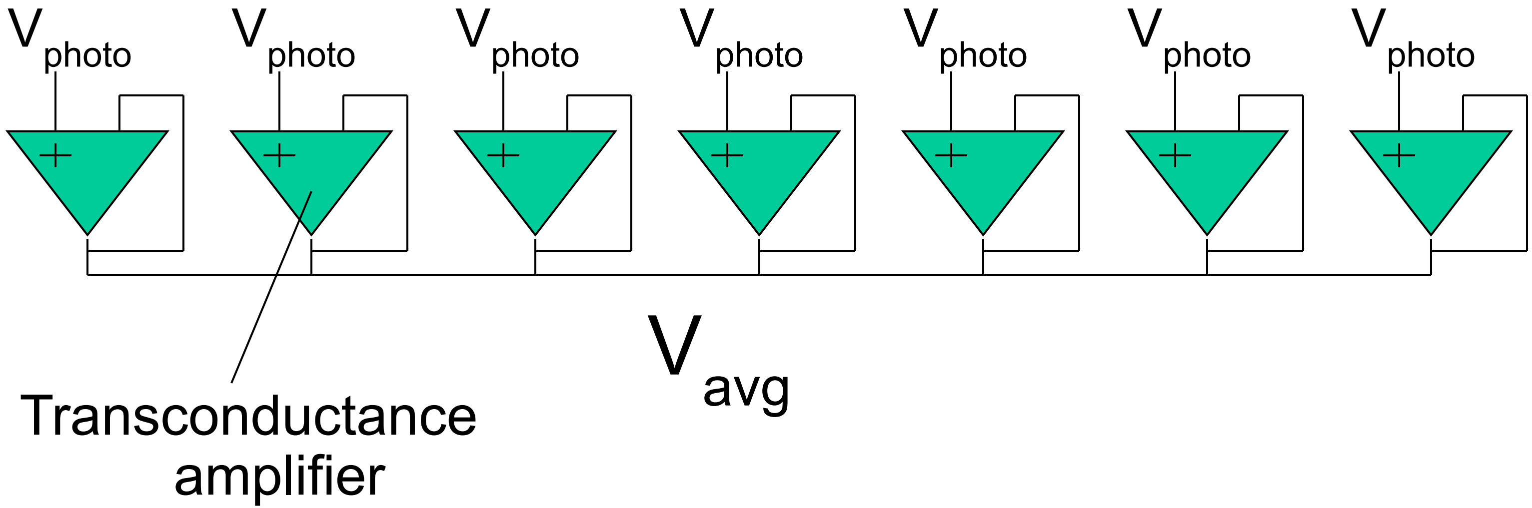
Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF



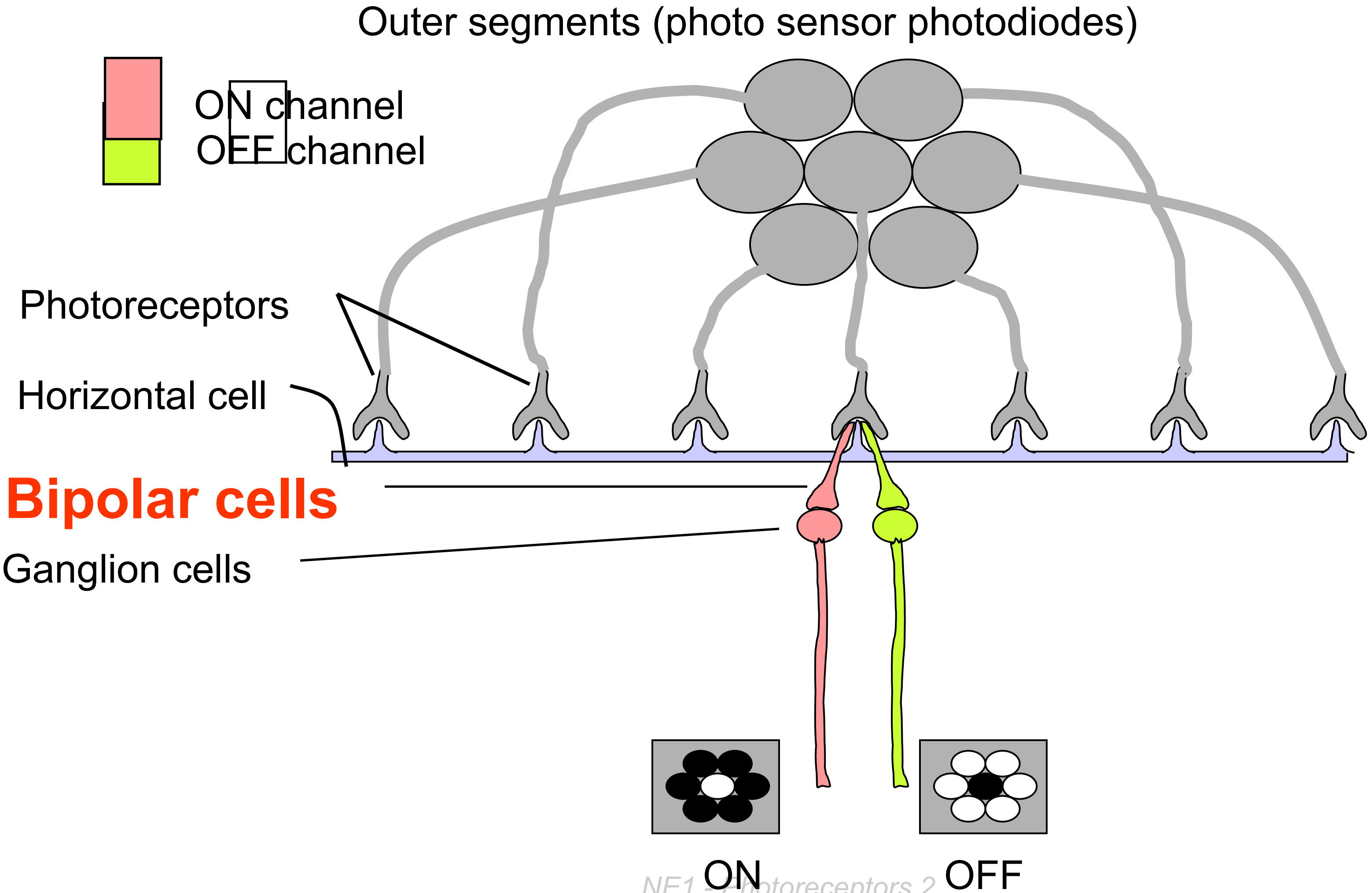
×300
HI horizontal cells labeled following injection of one HI cell (⋆)
after Dacey, Lee, and Stafford, 1996

Horizontal cell

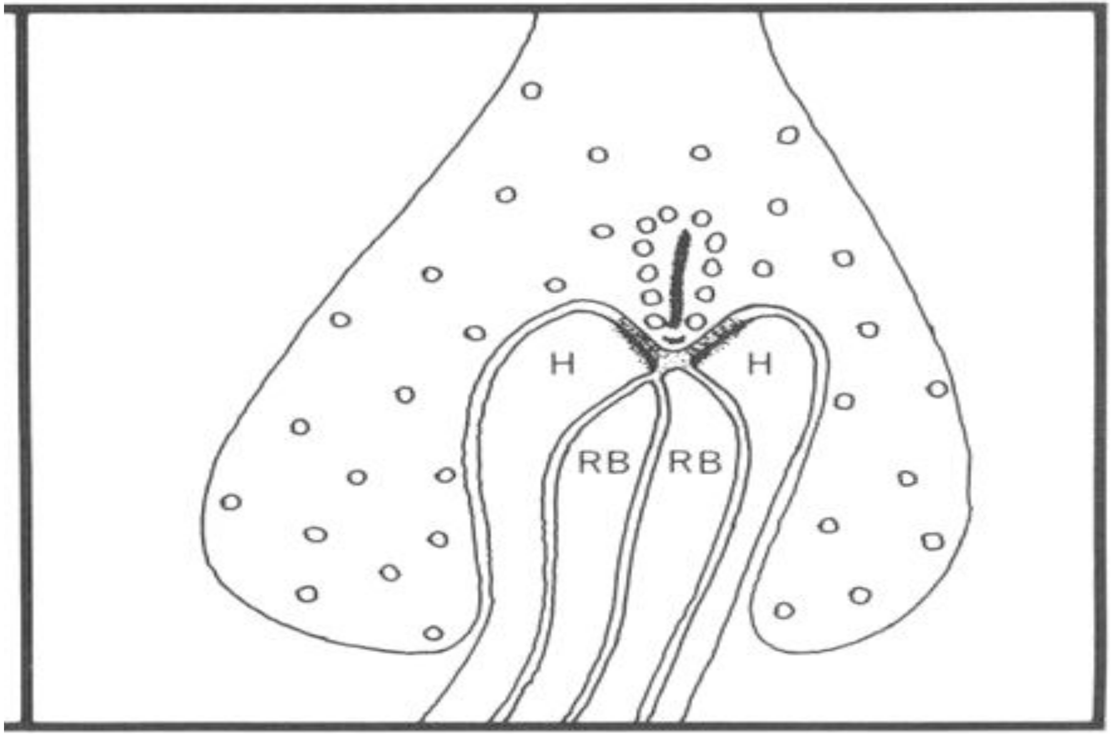
A *Follower-Aggregator* averages the photoreceptor outputs to compute the average of the inputs. This average is the *context* which is compared to the photoreceptor.



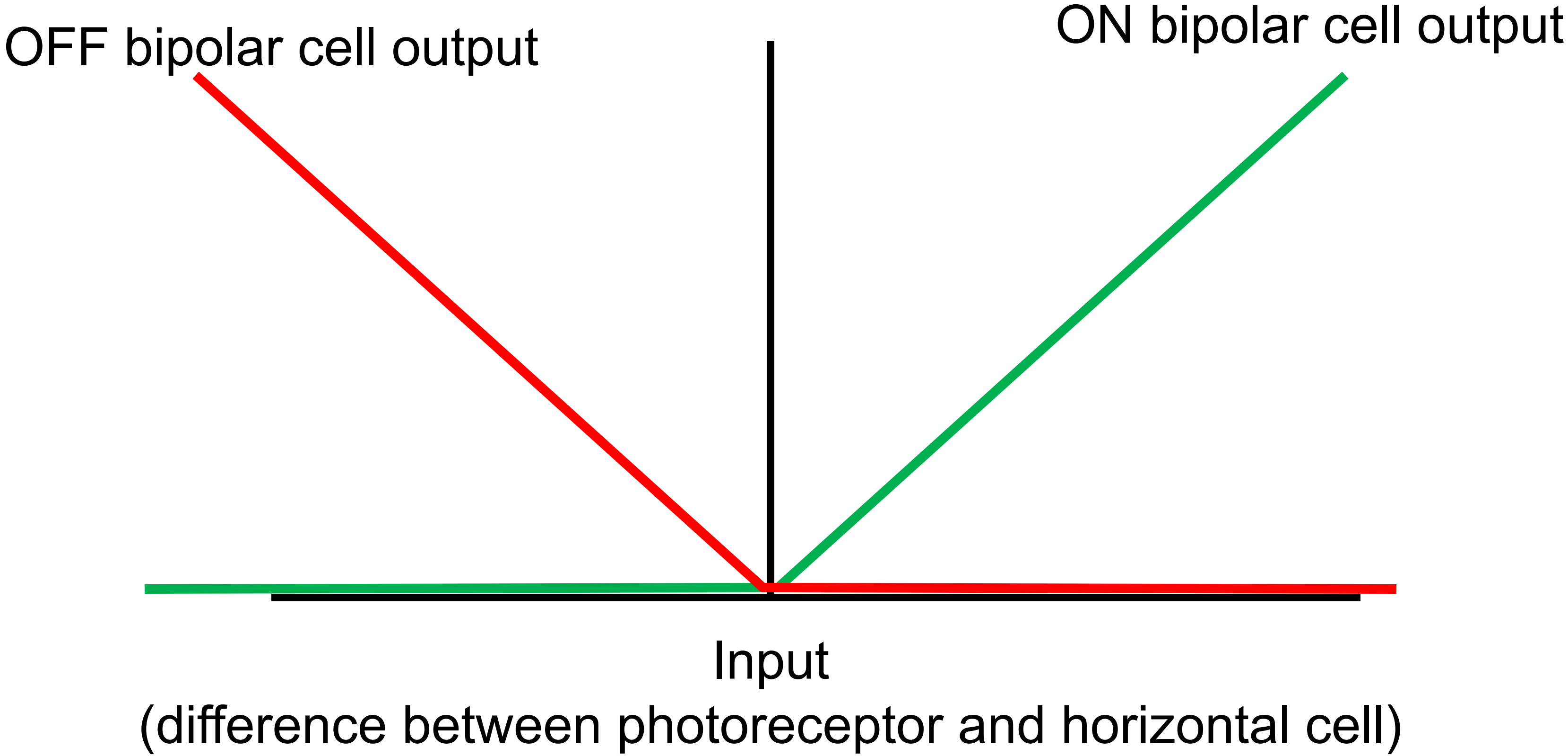
Because the follower output current saturates, the follower-aggregator computes **mean** for small signals and **median** for large signals


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

Rod-Horizontal Cell-Bipolar cell junctions

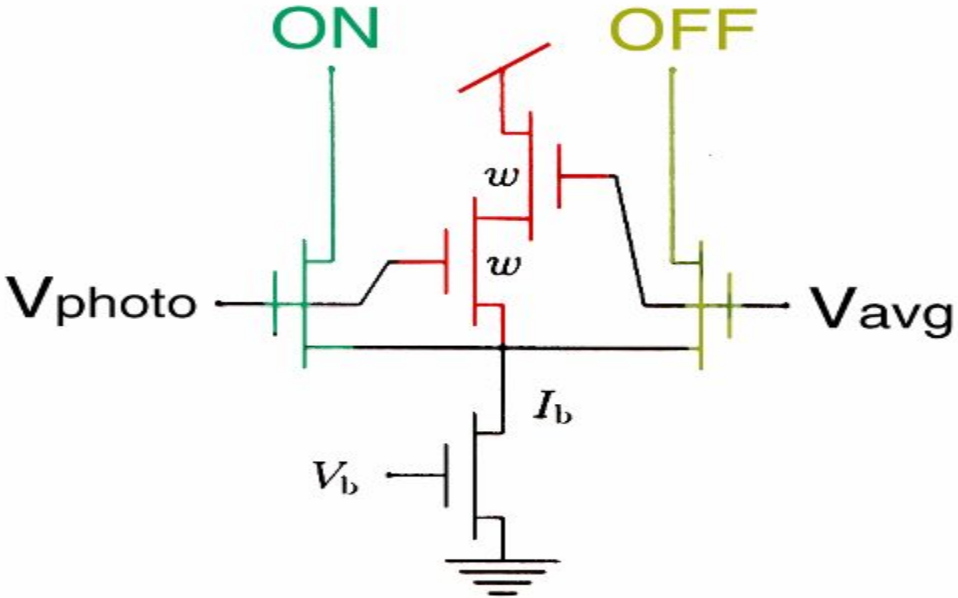


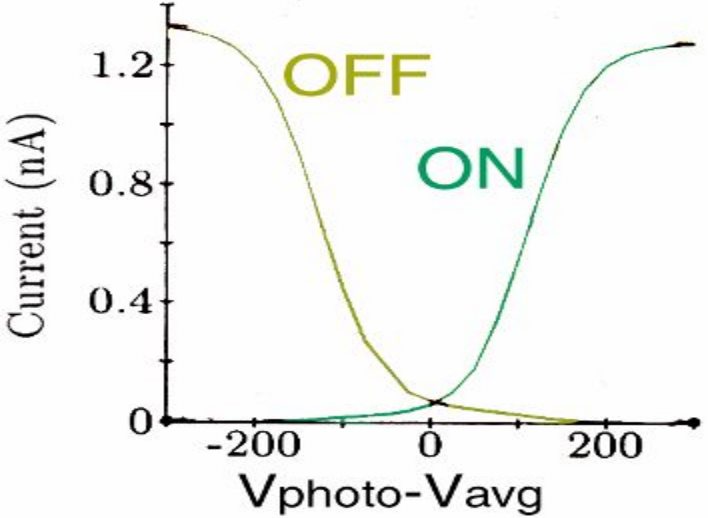
Rectification at the photoreceptor-horizontal cell-bipolar cell synapse

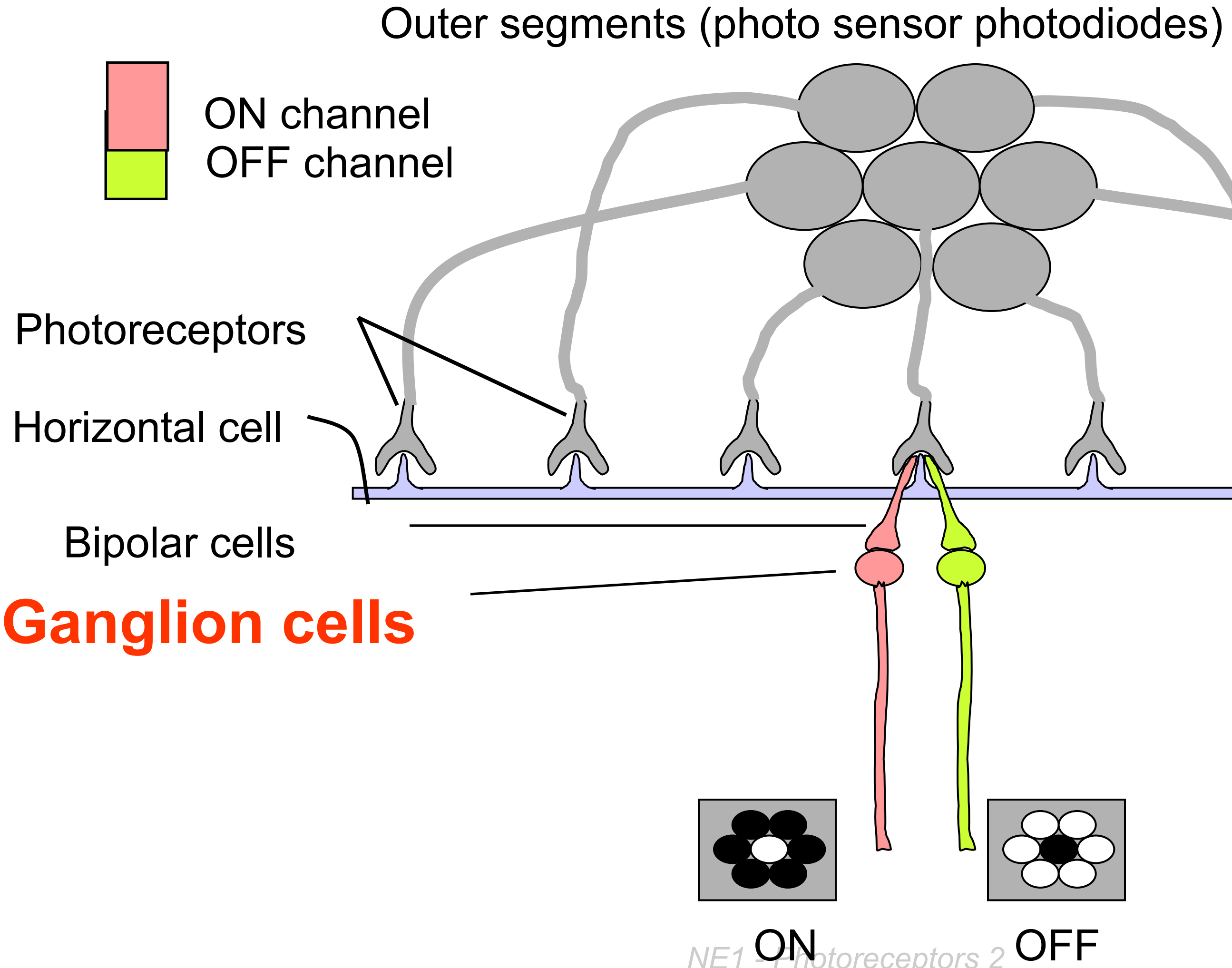


Bipolar Cell (Anti-bump circuit)

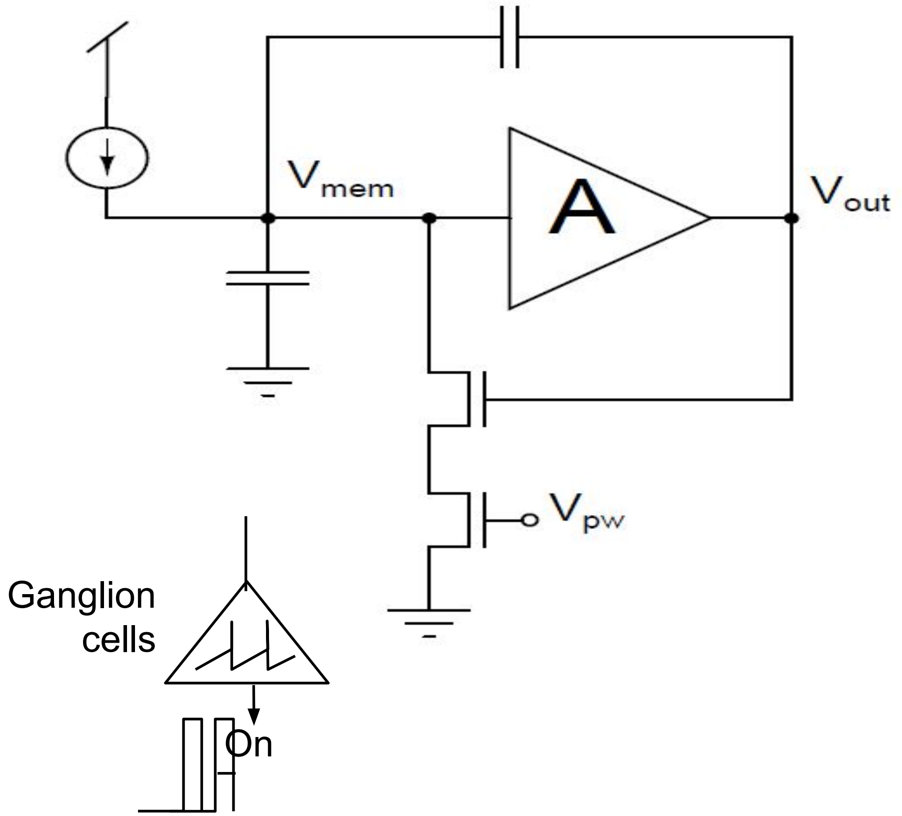
Rectifies into ON and OFF currents

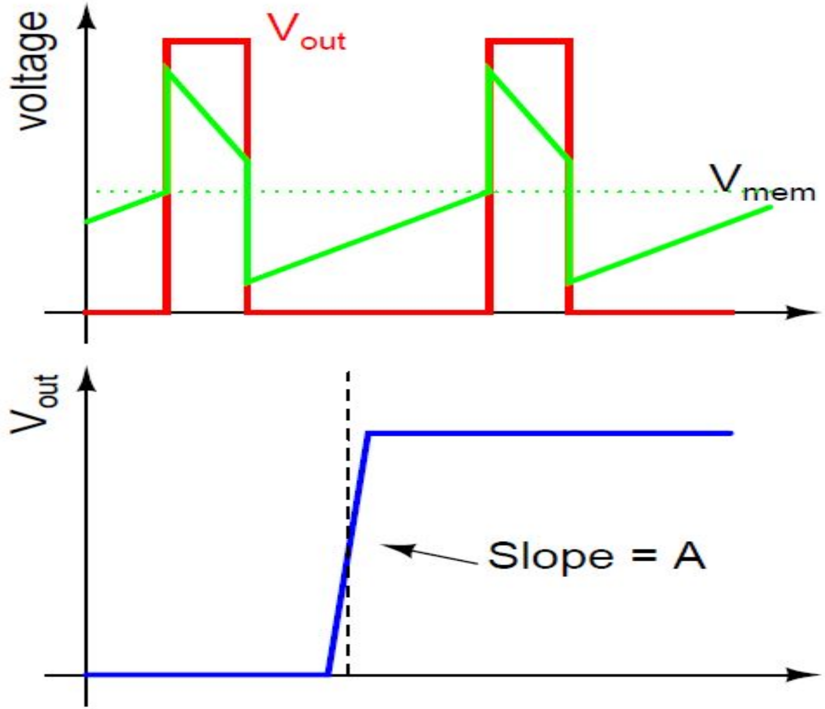




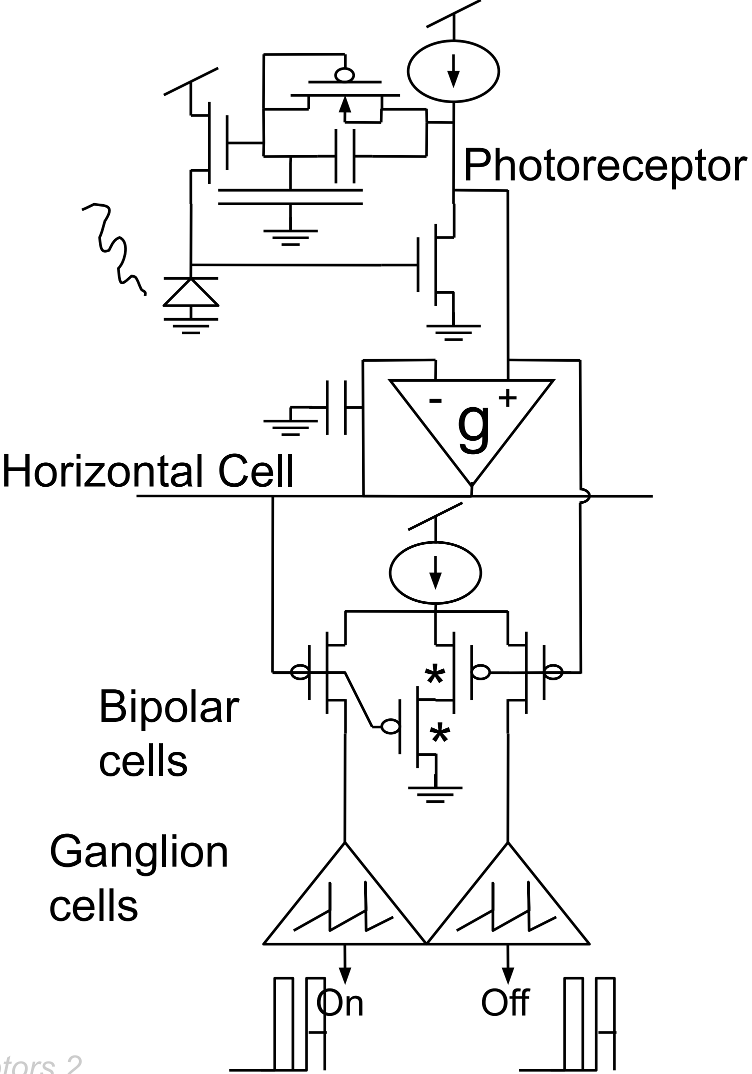

Outer segments (photo sensor photodiodes)
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF

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

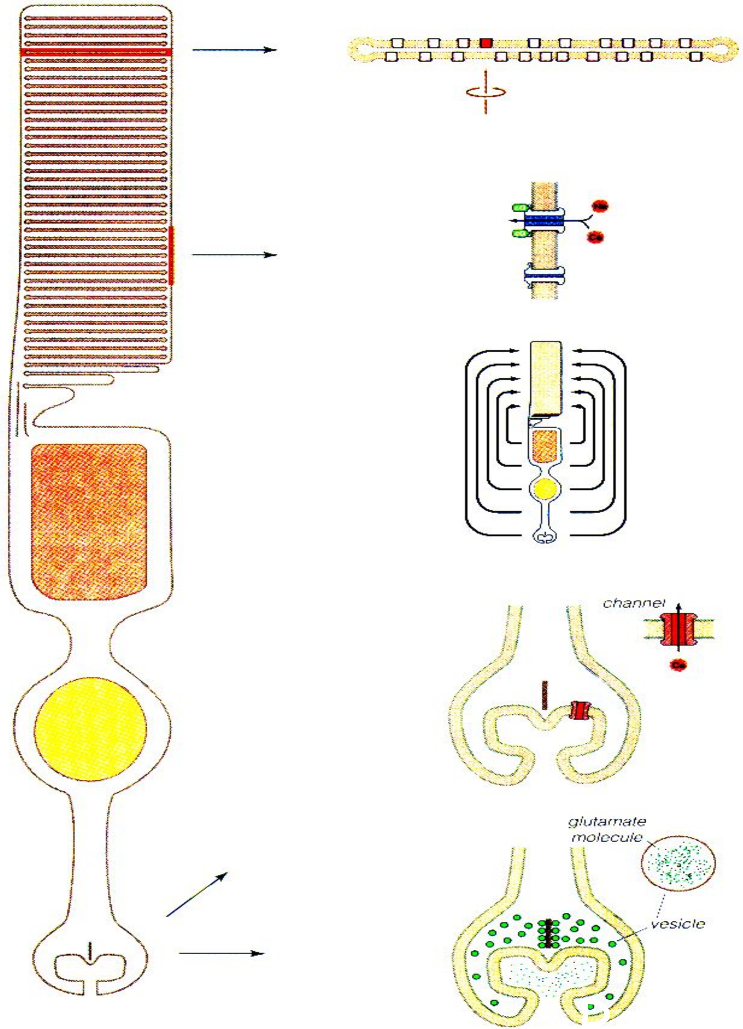




Complete circuit for retina part of Physiologist's Friend circuit



LOGARITHMIC AND ADAPATIVE PHOTORECEPTOR



Photoactivation:

A photon is absorbed by a visual pigment molecule lying in one of the membranous discs contained in the outer segment.

↓

Biochemical cascade:

In the dark there is a steady movement of positively charged ions (cations) into the outer segment, via ionic channels. The visual pigment molecule, activated by the photon, initiates a cascade of events that ultimately closes these channels.

↓

Electrotonic spread:

Normally, the movement of cations into the outer segment is balanced by the outward movement of cations, mainly through the inner segment. The decrease in inward current creates a net outward current, which makes the interior of the cell even more negative. This hyperpolarization of the cell membrane spreads throughout the cell. This is how the information about light absorption spreads to the synaptic terminal.

↓

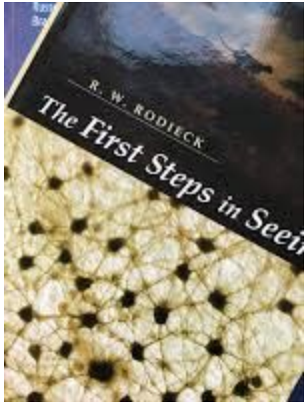
Synaptic deactivation:

At the synaptic terminal there are calcium channels that open when the voltage across the cell membrane depolarizes and close when it hyperpolarizes. Thus the hyperpolarization of the cell membrane leads to a decrease in the rate of entry of calcium ions. Free calcium ions are continuously being removed from the cell interior, so a decrease in the rate of entry of calcium leads to a decrease in the internal concentration of free calcium ion.

↓

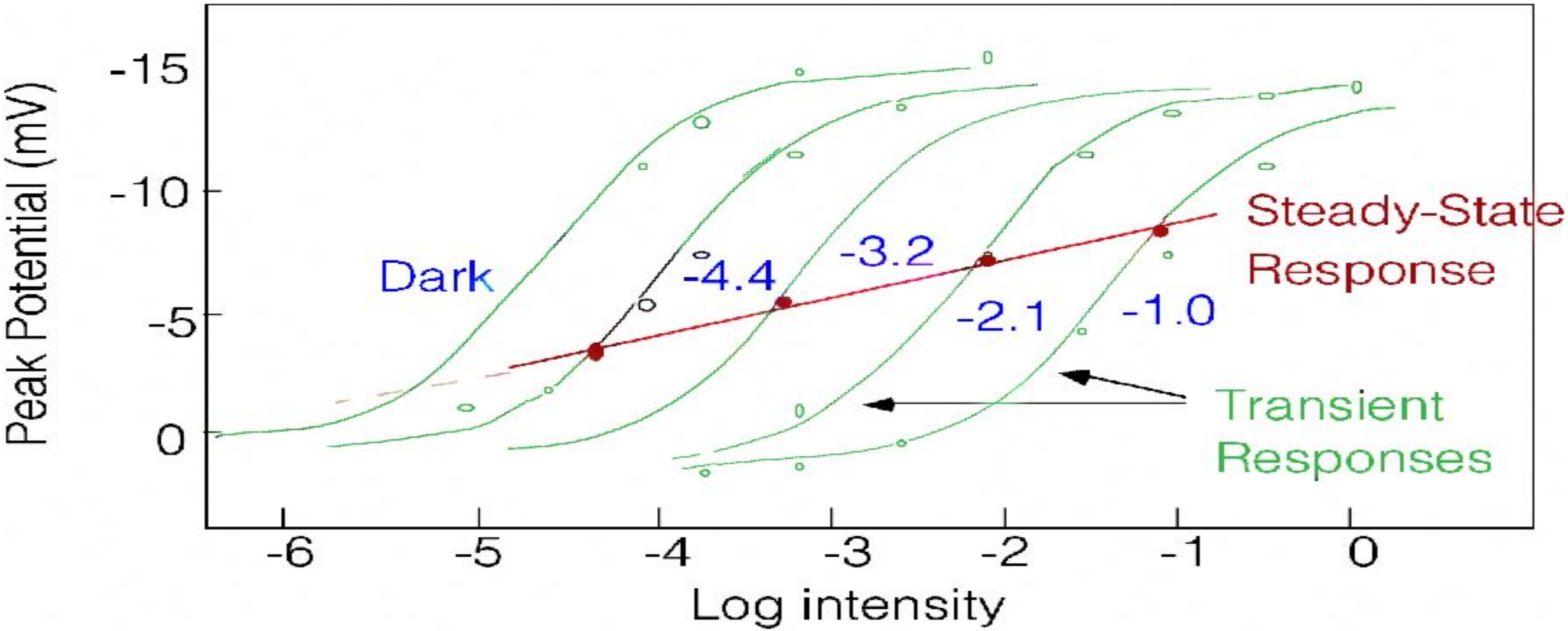
Decrease in glutamate release:

The synaptic terminal contains vesicles that in turn contain glutamate molecules. In the presence of calcium ions, they are continuously released into the synaptic cleft. Thus a decrease in the internal concentration of calcium ions leads to a decrease in the rate of release of glutamate molecules.



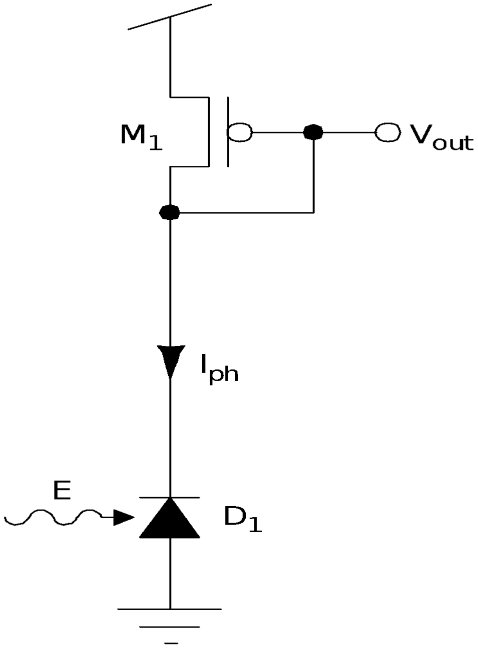
Bob Rodieck, ca 1975

Biological photoreceptors amplify changes more than DC

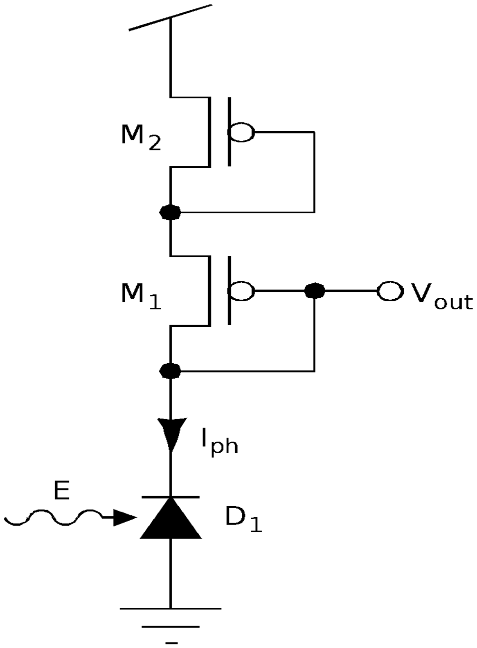


Normann & Perlman, 1979

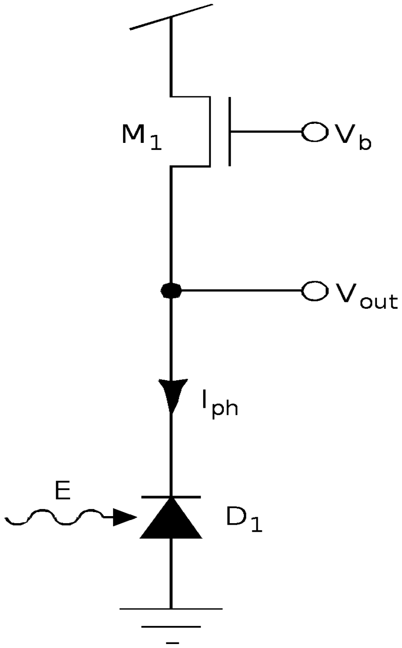
Logarithmic Photosensors



Diode-connected
MOSFET

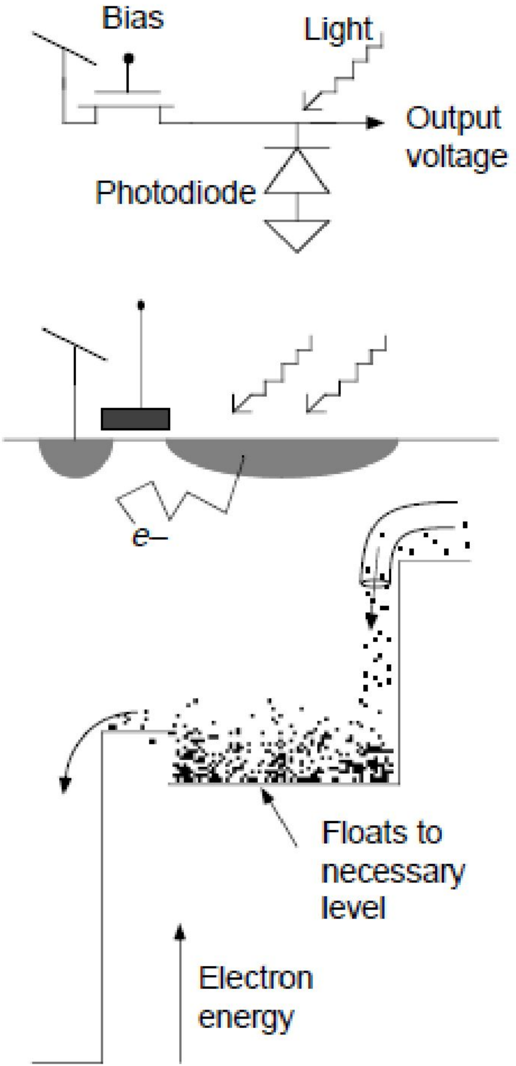


Double diode-connected
MOSFET



Source-follower
MOSFET

How the source follower receptor works



Characteristics of Logarithmic Photosensors

Diode-connected MOSFET:

$$V_{out} = V_{dd} - \frac{U_T}{\kappa}\log\left(\frac{I_{ph}}{I_0}\right)$$

Double diode-connected MOSFET:

$$V_{out} = V_{dd} - U_T\frac{\kappa+1}{\kappa^2}\log\left(\frac{I_{ph}}{I_0}\right)$$

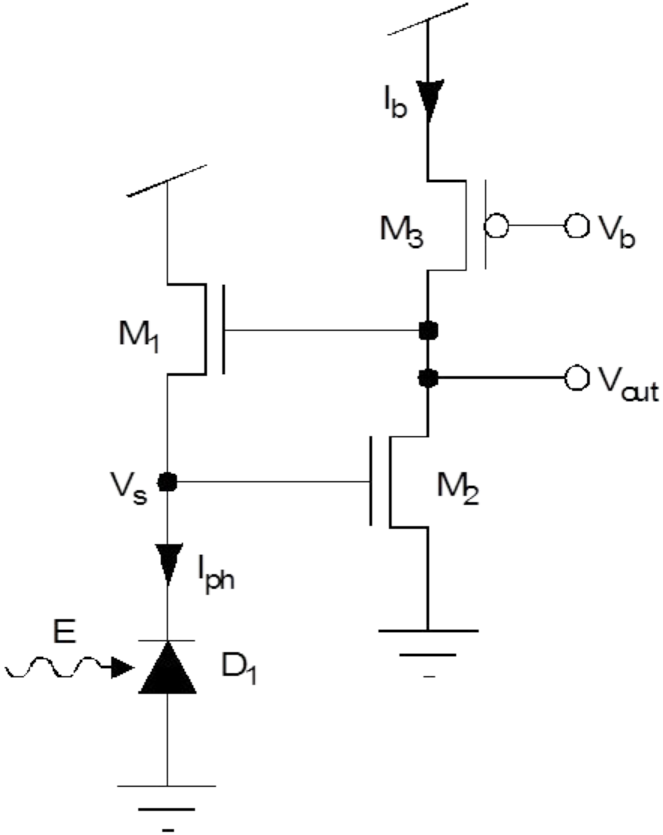
Source-follower MOSFET:

$$V_{out} = \kappa V_g - U_T\log\left(\frac{I_{ph}}{I_0}\right)$$

Contrast encoding:

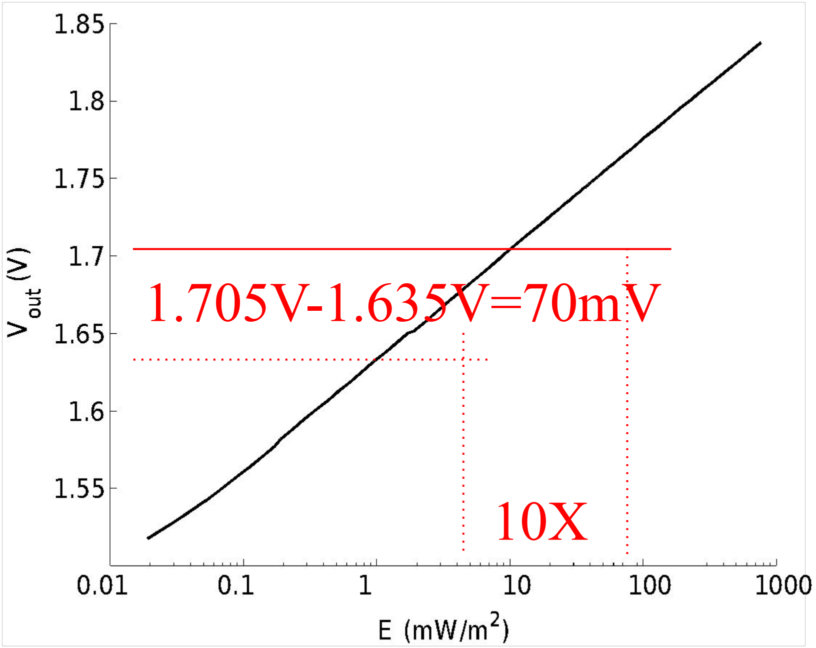
$$dV_{out} = -U_T\frac{dI_{ph}}{I_{ph}}$$

Transimpedance Logarithmic Photosensor with Feedback Loop



- Photodiode has large capacitance
  - Small photocurrent takes a long time to change V_S
- High-gain feedback loop clamps V_S and speeds up response
- Output voltage V_{out} is also the the gate of feedback M_1

Current-Voltage Characteristics of Logarithmic Photosensor with Feedback Loop



$$V_{out} = \kappa^{-1}\left(V_S + U_T \log\left(\frac{I_{ph}}{I_0}\right)\right)$$

$$dV_{out} = U_T \frac{A}{\kappa A - 1} \frac{dI_{ph}}{I_{ph}} \approx \frac{U_T}{\kappa} \frac{dI_{ph}}{I_{ph}}$$

$$dV_S = \frac{U_T}{\kappa A - 1} \frac{dI_{ph}}{I_{ph}} \approx \frac{U_T}{\kappa A} \frac{dI_{ph}}{I_{ph}}$$

Per decade:
$\ln(10)U_T/k = 25mV/0.8 = 72mV$

Amplification of Response by κ^{-1}
Speedup of response by κA

Adaptation

- DC operating point set at a mean value
- Transient variations around operating point amplified
  – Efficient use of dynamic range

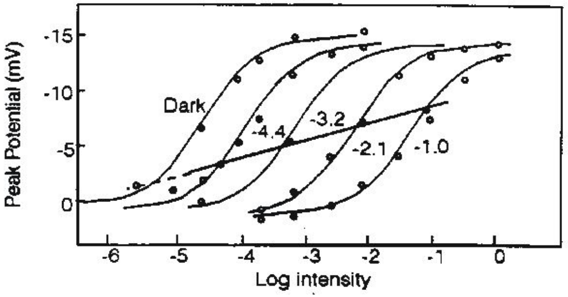


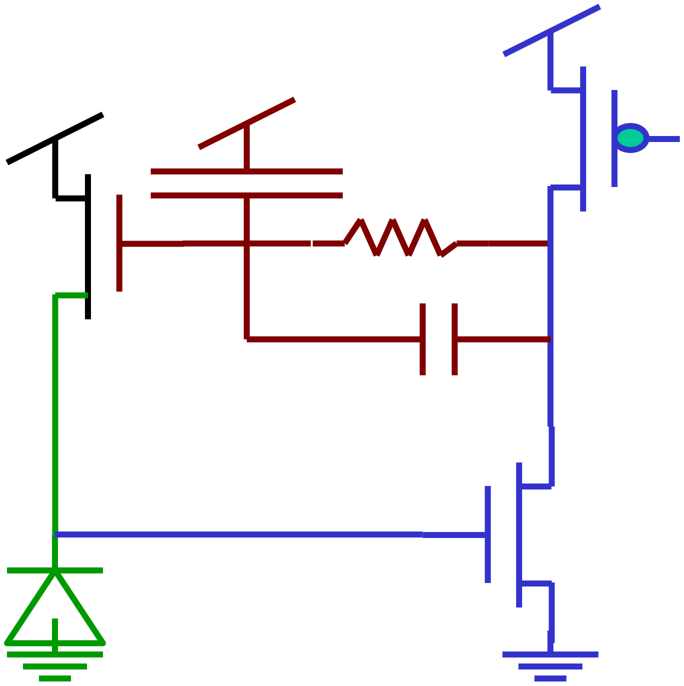
FIGURE 2.31 Gain adjustment in turtle cones (recorded intracellularly) caused by background illumination. The stimuli are 0.5 s increments or decrements on a steady background (except for the curve for the dark adapted cone which only is for increments). The stimulus spot is 3.2 mm in diameter on the retina. Peak responses measured from the dark-adapted resting potential (dotted line) are plotted as a function of test illumination. The thin curves connect the measured points. The thick curve is the steady membrane potential measured at least two minutes after background onset. The average slope of the transient responses is 9.5 mV/decade, and the slope of the steady-state, adapted response is about 1.8 mV/decade. The ratio of transient gain to the steady-state gain is about 5. The total dynamic range is about 15 mV. The illuminations are given as log attenuation from a baseline value. The unattenuated test stimulus (0 log) is 6.4 10^{15} quanta(640 nm)$(cm^2s)^{-1}$ on the retina, equivalent to an irradiance of about 20 W/m^2. (Direct office fluorescent lighting is about 1 W/m^2.) The unattenuated background illumination is 9.1 10^{15} quanta(640 nm) $(cm^2s)^{-1}$. Source: Adapted from [14].

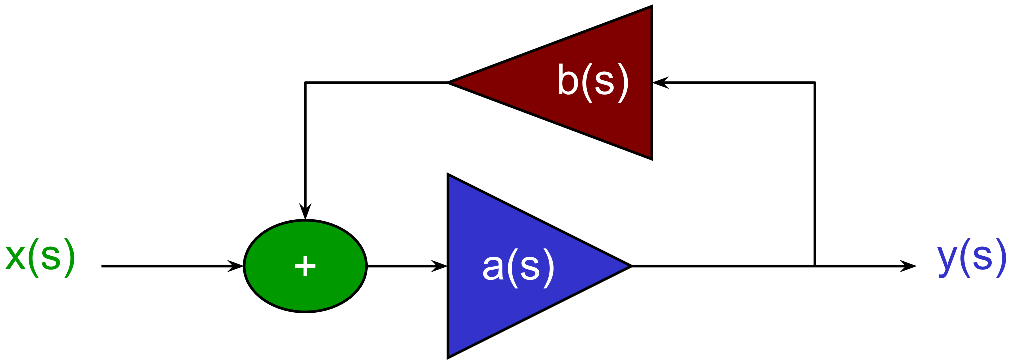
14. R.A. Norman and I. Perlman, "The effects of background illumination on the photoresponses of red and green cones," *J. Physiol.*, vol. 286, pp. 509–524, 1979.

Adaptive Photoreceptor

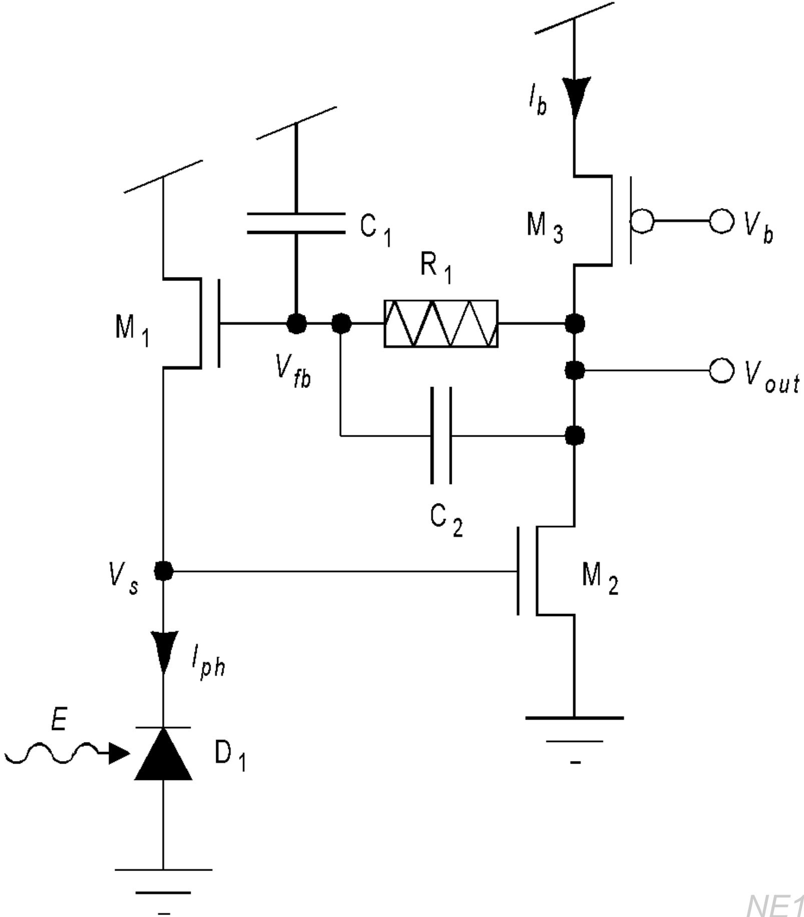
- Logarithmic photosensor covers large range of illumination, but contrast-response is small (~100mV for a b/w transition (one decade of illumination))
- Imaging arrays suffer from fixed-pattern noise (FPN), i.e. different photosensors have different output signals for same illumination, due to spatial variation of fabrication parameters (different I_0, κ)
  - Low-FPN amplification of transient signals required to detect low-contrast features
  - Use capacitive divider for amplification and resistive element for adaptation

Adaptive photoreceptor as feedback system



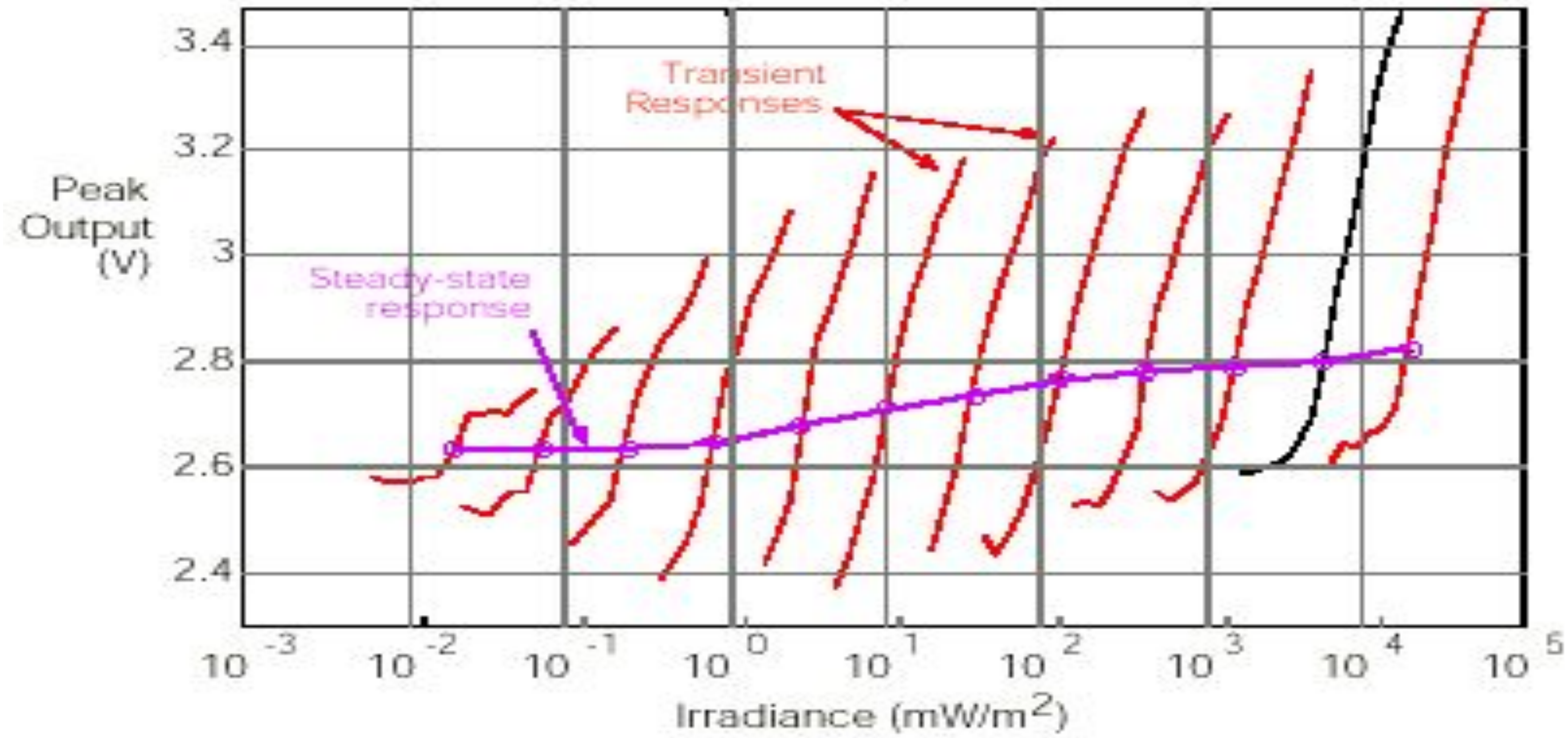


Adaptive Photoreceptor



- Transient amplification of logarithmic signal V_{fb} onto V_{out} by capacitive gain stage (C_1, C_2)
- Slow adaptation of V_{fb} to V_{out} via current through pseudo-resistor R_1
- State of adaptation stored as charge Q_{fb} on V_{fb} node

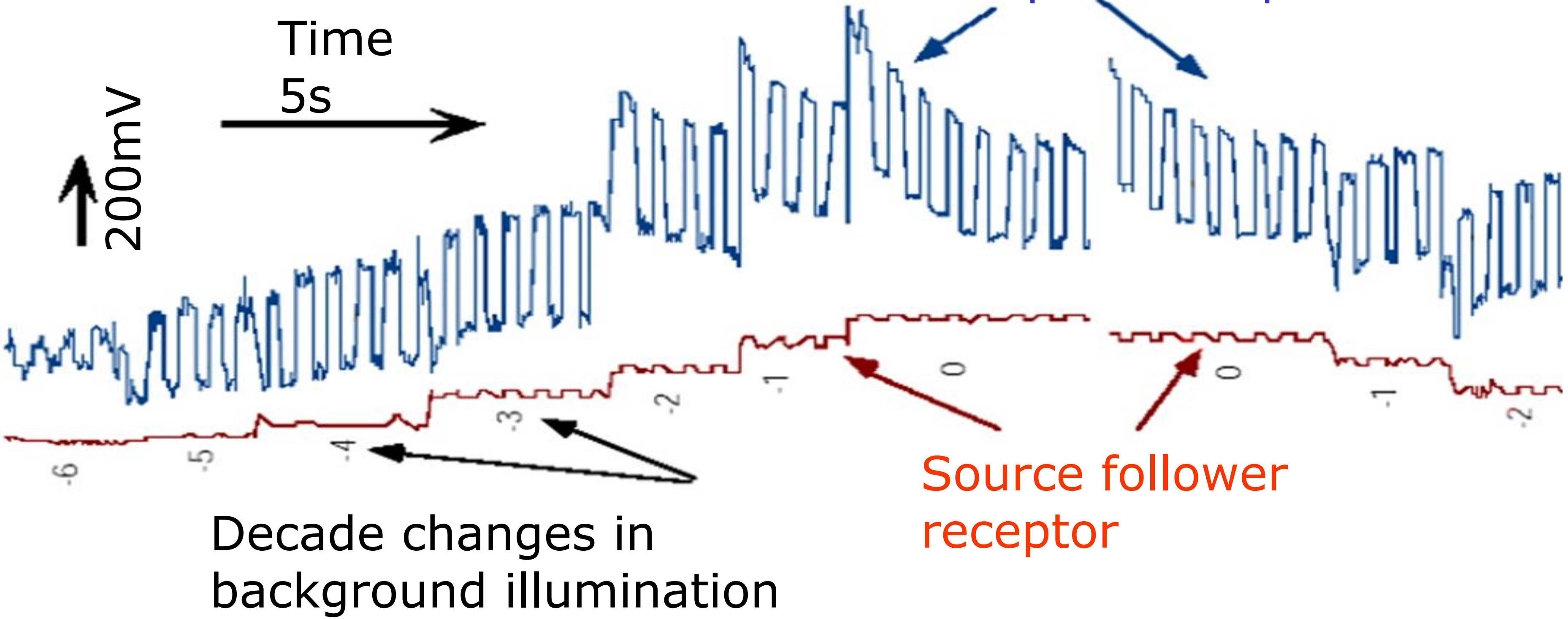
Adaptive Photoreceptor Response Curves



Delbruck and Mead 1993

Comparing source-follower and adaptive photoreceptor

Square wave input over 7 decades illumination



Constrast ratio 2:1
Brightest 3W/m^2

Characteristics of Adaptive Photoreceptor

Adapted signal: $$V_{fb} = \kappa^{-1}\left(V_S + U_T \log\left(\frac{I_{ph}}{I_0}\right)\right)$$

Transient amplification: $$A_C \equiv \frac{C_1 + C_2}{C_2}$$

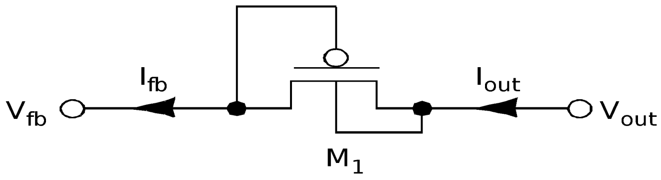
Transient signal: $$V_{out} = A_C V_{fb} - \frac{Q_{fb} + C_1 V_{dd}}{C_2}$$

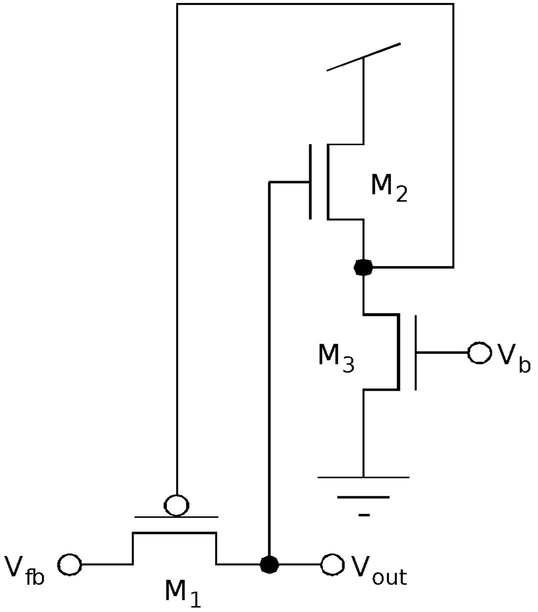
Small-signal response: $$dV_{out} = A_C U_T \frac{A}{\kappa A - 1} \frac{dI_{ph}}{I_{ph}} \approx A_C \frac{U_T}{\kappa} \frac{dI_{ph}}{I_{ph}}$$

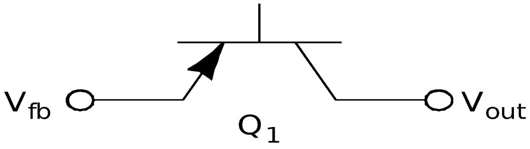
Delbruck 1993

PSEUDO RESISTORS (ADAPTIVE ELEMENTS)

Pseudo Resistors





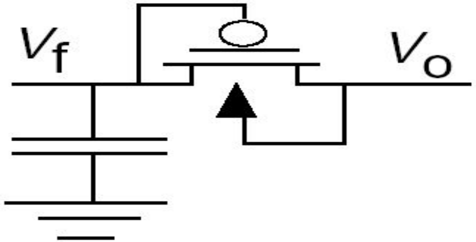


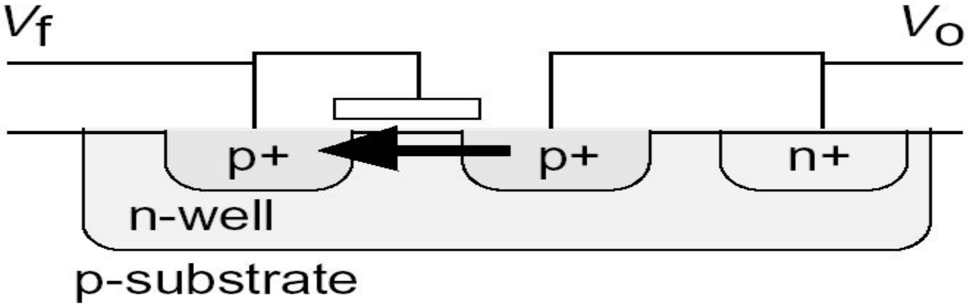
Expansive element with low common-mode sensitivity

Expansive element with more symmetric characteristics

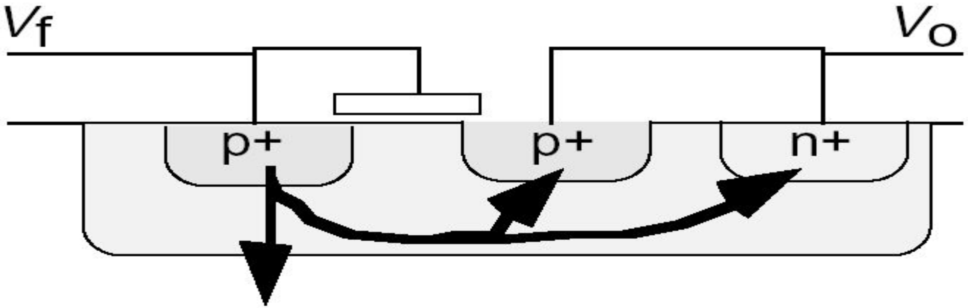
Compressive element

Delbruck and Mead 1993
Liu 1998





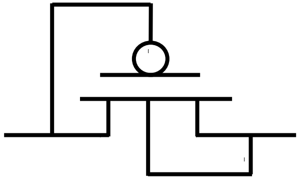
$V_o > V_f$

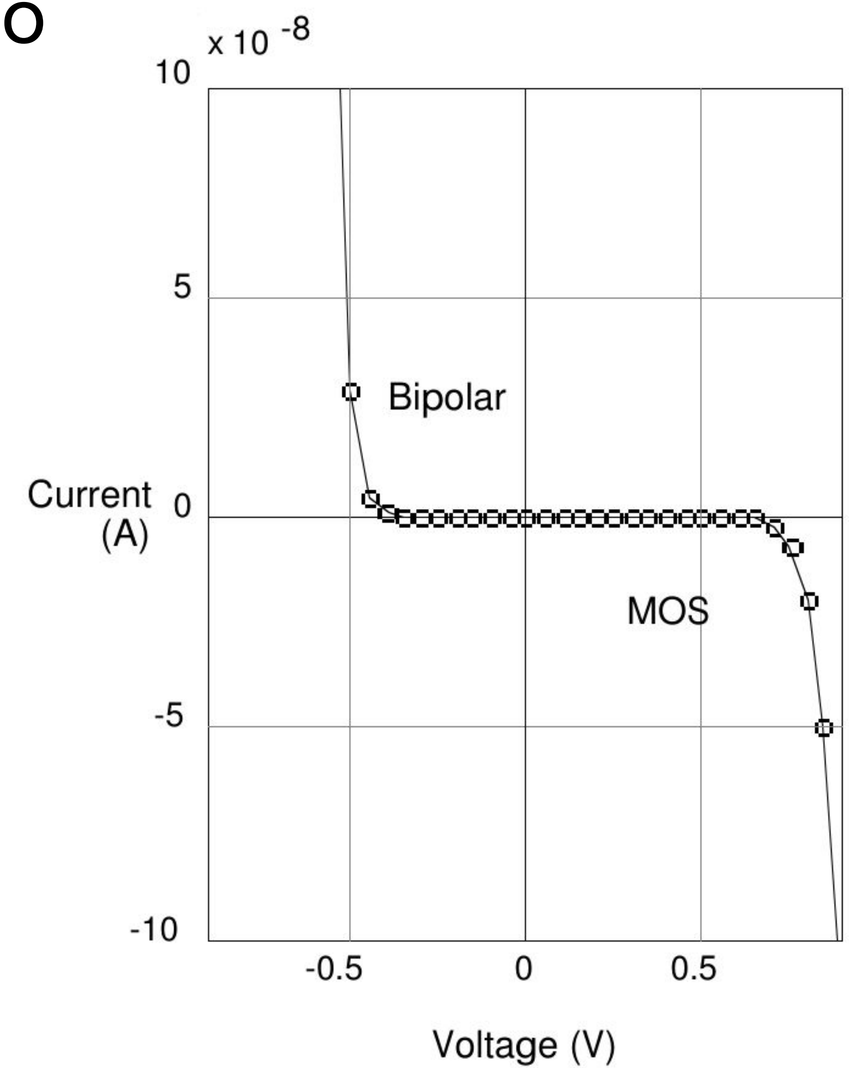


$V_o < V_f$

Expansive Pseudo Resistor

Current-Voltage Characteristics of Expansive Resistive Element

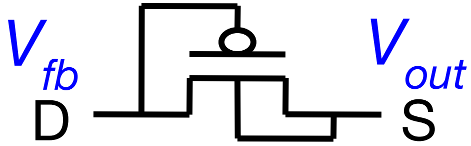


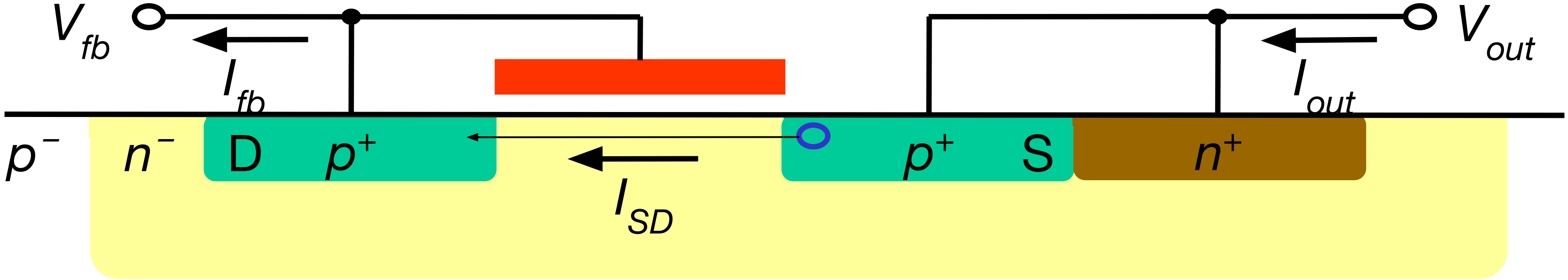


Delbruck and Mead 1993

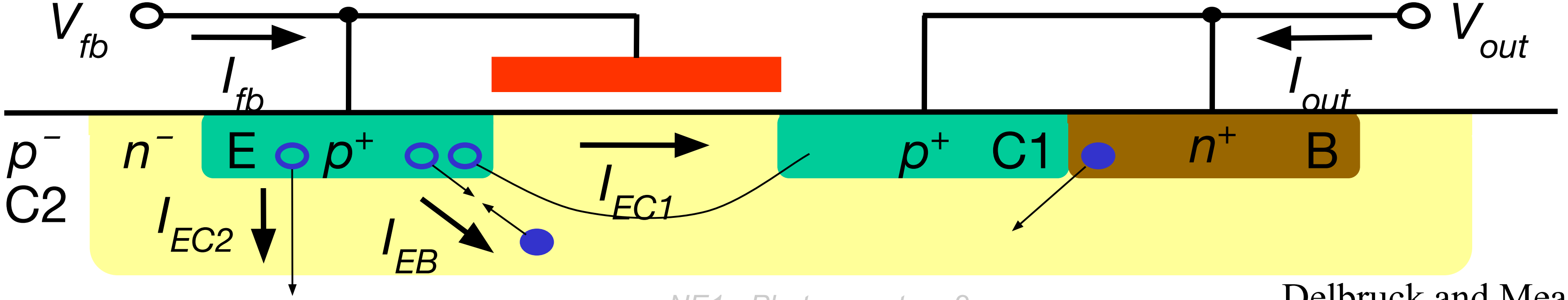
Expansive Pseudo Resistor

$V_{out} > V_{fb}$: diode-connected MOSFET



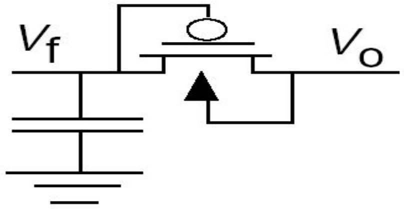


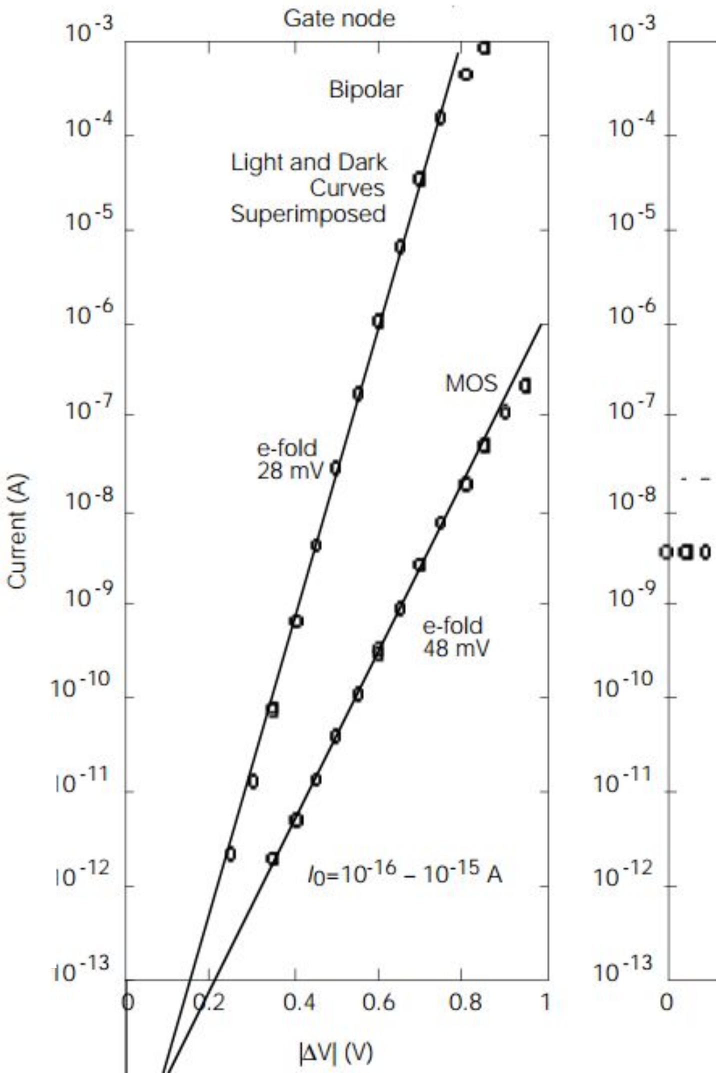
$V_{fb} > V_{out}$: 2-collector bipolar transistor



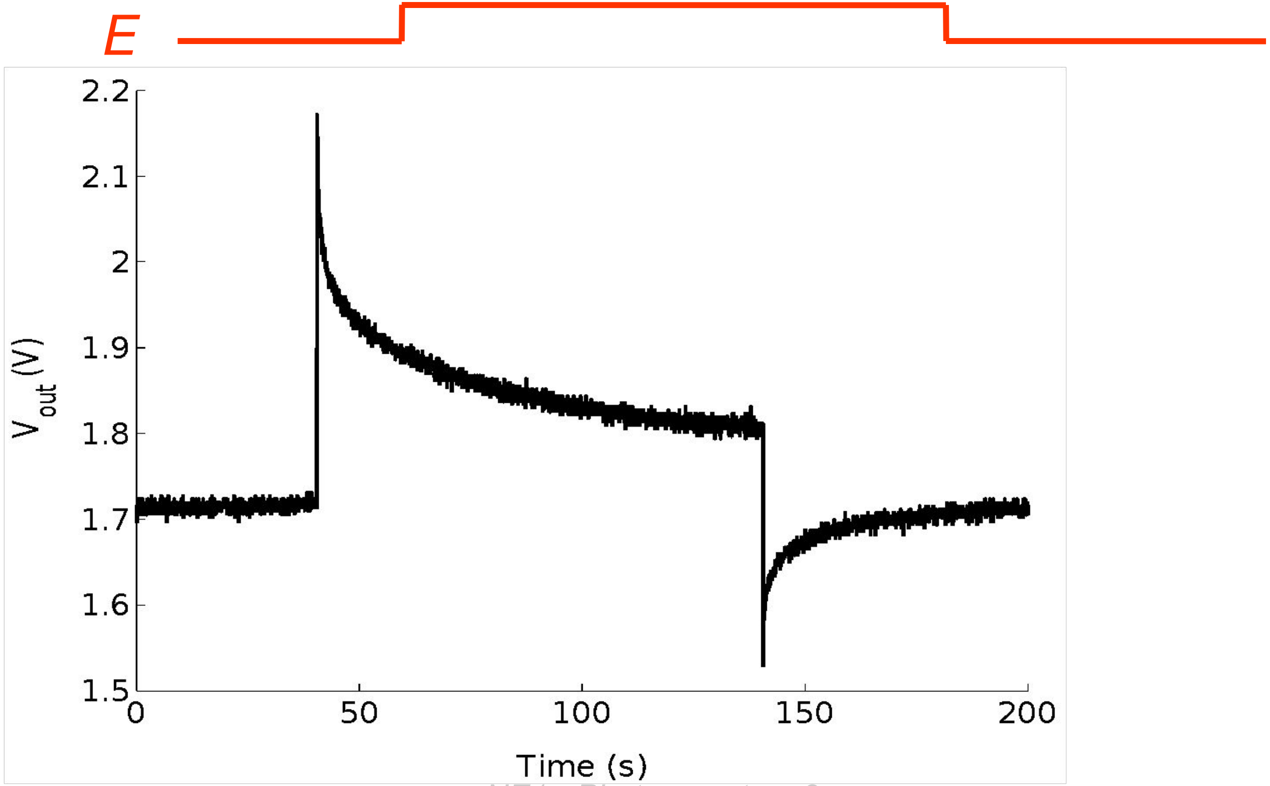
Delbruck and Mead 1993

Current-Voltage Characteristics of Expansive Pseudo Resistive Element

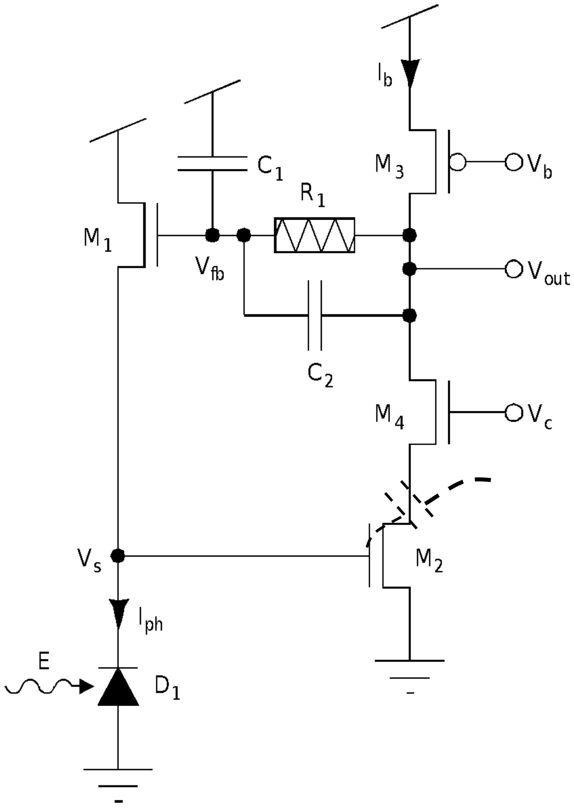




Step-Response of Adaptive Photosensor



Adaptive Photoreceptor with Cascode

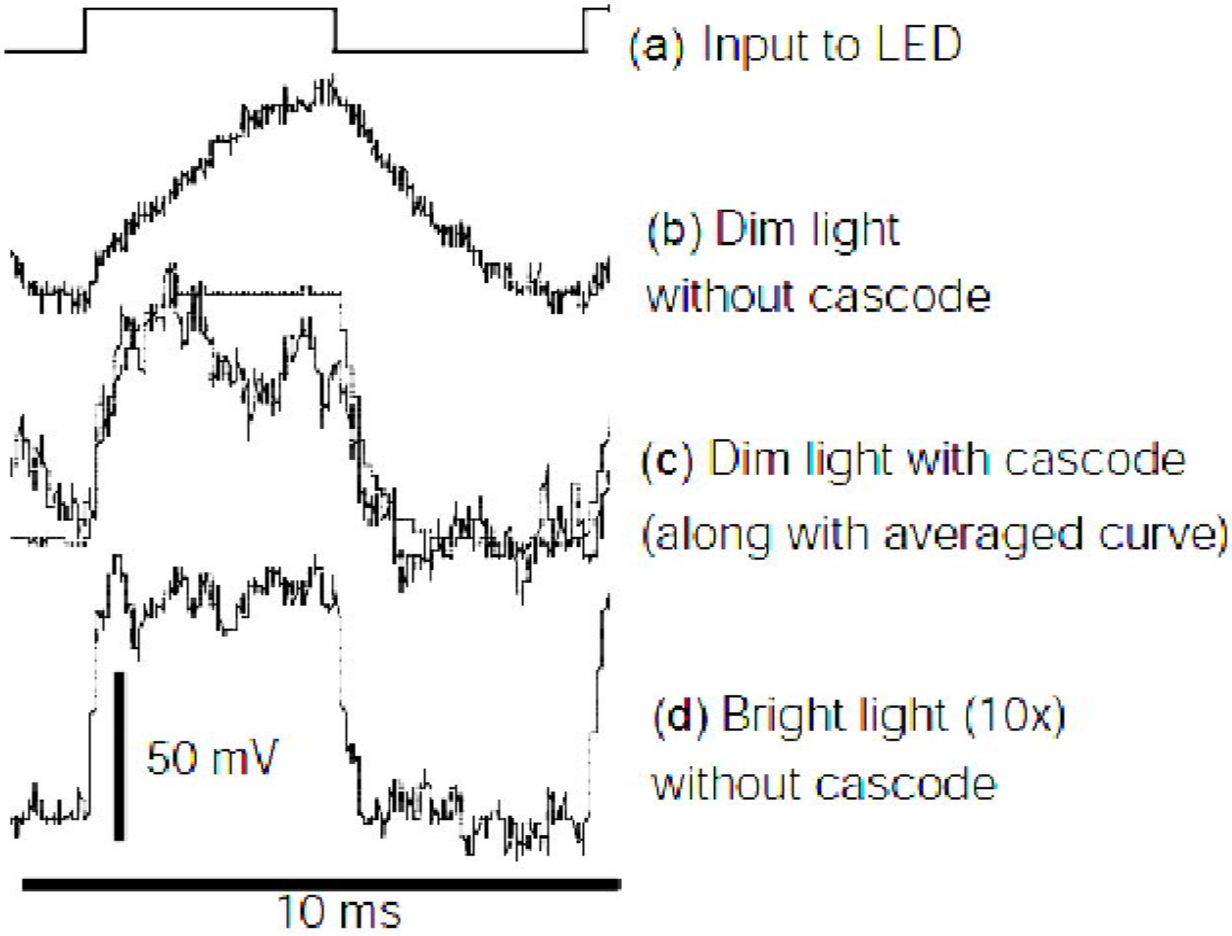


Miller effect: Parasitic gate-to-drain capacitance of M_2 is driven by V_{out} node and thus effectively amplified by large gain of inverting amplifier

Cascode M_4 shields drain of M_2 from large output voltage swing at V_{out} to speed up response

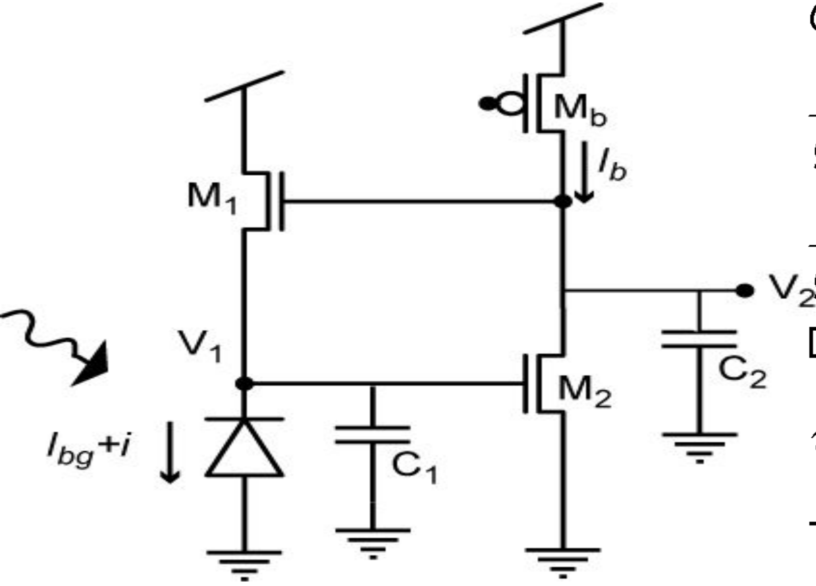
Delbruck 1993

Measured effect of cascode on adaptive photoreceptor



SMALL SIGNAL ANALYSIS OF ADAPTIVE PHOTORECEPTOR

Small signal analysis of active log photoreceptor



Small signal equations

$$C_2\dot{v}_2 = -g_{o2}v_2 - g_{m2}v_1$$

$$C_1\dot{v}_1 = g_{m1}v_2 - g_{s1}v_1 - i$$

$$\frac{C_2}{g_{o2}}\dot{v}_2 + v_2 = -\frac{g_{m2}}{g_{o2}}v_1$$

$$\frac{C_1}{g_{s1}}\dot{v}_1 + v_1 = \frac{g_{m1}}{g_{s1}}v_2 - \frac{i}{g_{s1}}$$

Define time constants and forward amplifier gain

$$\tau_1 \equiv \frac{C_1}{g_{s1}} \quad \tau_2 \equiv \frac{C_2}{g_{o2}} \quad A_2 = \frac{g_{m2}}{g_{o2}}, \kappa = \frac{g_{m1}}{g_{s1}}$$

The source conductance of M_1 is set by the background photocurrent

$$g_{s1} = \frac{I_{bg}}{U_T}$$

Small signal equations

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The source conductance of M_1 is set by the background photocurrent

$$g_{s1} = \frac{I_{bg}}{U_T}$$

Go to the s-plane

$$(\tau_2 s + 1) v_2 = -A_2 v_1$$

$$(\tau_1 s + 1) v_1 = \kappa v_2 - U_T \frac{i}{I_{bg}}$$

Solve for the transfer function $H(s)=\frac{v_2}{i}$

$$v_1 = \frac{\kappa v_2 - U_T \frac{i}{I_{bg}}}{(\tau_1 s + 1)}$$

$$(\tau_2 s + 1) v_2 = -A_2 \frac{\kappa v_2 - U_T \frac{i}{I_{bg}}}{(\tau_1 s + 1)}$$

$$\left[(\tau_2 s + 1)(\tau_1 s + 1) + \kappa A_2\right] v_2 = A_2 U_T \frac{i}{I_{bg}}$$

$$\left[\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2) s + 1 + \kappa A_2\right] v_2 = A_2 U_T \frac{i}{I_{bg}}$$

If $\kappa A_2 >> 1$

$$\frac{\tau_1 \tau_2}{\kappa A_2} s^2 + \frac{\tau_1 + \tau_2}{\kappa A_2} s + 1 \approx \frac{U_T}{\kappa} \frac{i}{I_{bg}}$$

The DC gain is

$$v_2 = \frac{U_T}{\kappa} \frac{i}{I_{bg}}$$

The denominator of H(s) is transformed to the canonical form

$$D(s) = \tau^2 s^2 + \frac{\tau}{Q} s + 1 = 0$$

where

$$\tau^2 = \frac{\tau_1 \tau_2}{\kappa A_2} \quad \frac{\tau}{Q} = \frac{\tau_1 + \tau_2}{\kappa A_2}$$

$$\tau = \sqrt{\frac{\tau_1 \tau_2}{\kappa A_2}} \quad Q = \frac{\tau}{\frac{\tau_1 + \tau_2}{\kappa A_2}} = \frac{\sqrt{\frac{\tau_1 \tau_2}{\kappa A_2}}}{\frac{\tau_1 + \tau_2}{\kappa A_2}} = \sqrt{\frac{\tau_1 \tau_2 \kappa A_2}{(\tau_1 + \tau_2)^2}}$$

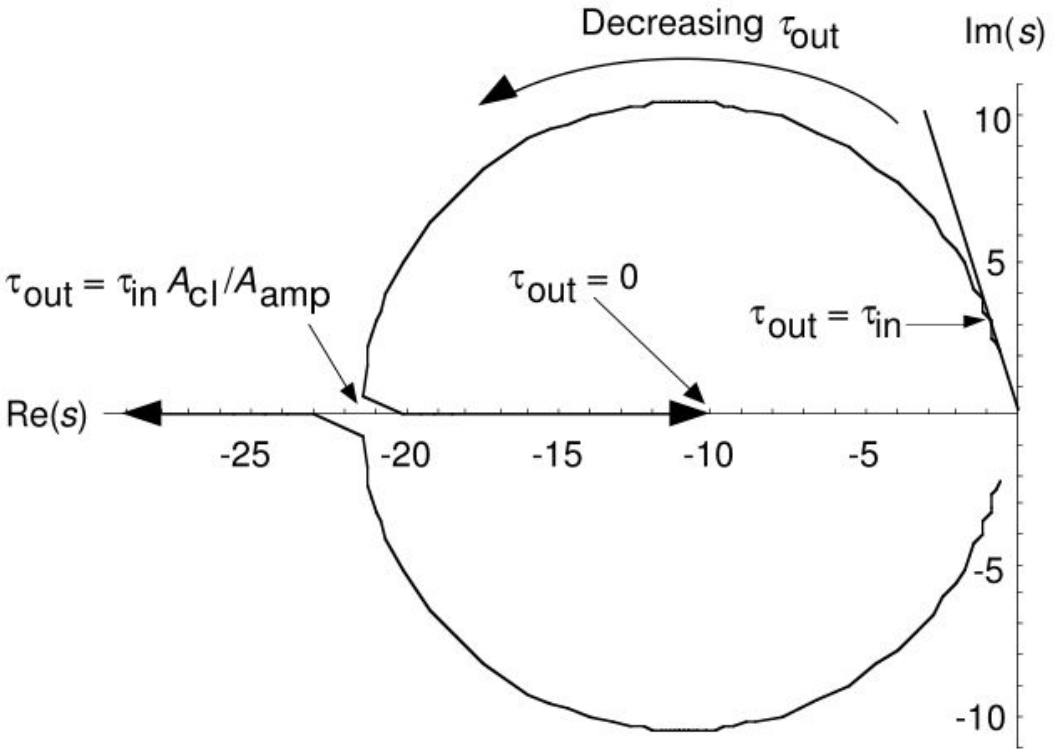
If $\tau_1 >> \tau_2$, then $Q \approx \sqrt{\kappa A_2 \frac{\tau_2}{\tau_1}}$

Then Q=$\frac{1}{2}$ when $\tau_2 = \frac{\tau_1}{4\kappa A_2}$

When Q=$\frac{1}{2}$, $\tau = \sqrt{\frac{\frac{\tau_1^2}{4\kappa A_2}}{\kappa A_2}} = \frac{\tau_1}{2\kappa A_2}$, this is the speedup

Root locus plot of poles of H(s) of adaptive photoreceptor

FIGURE 13 Root-locus plot for adaptive receptor, showing the poles of the transfer function in Equation 12, parameterized by the output time constant τ_{out} of the feedback amplifier. Parameters: $A_{amp} = 100$, $A_{cl} = 10$, $\tau_{in} = 1$.



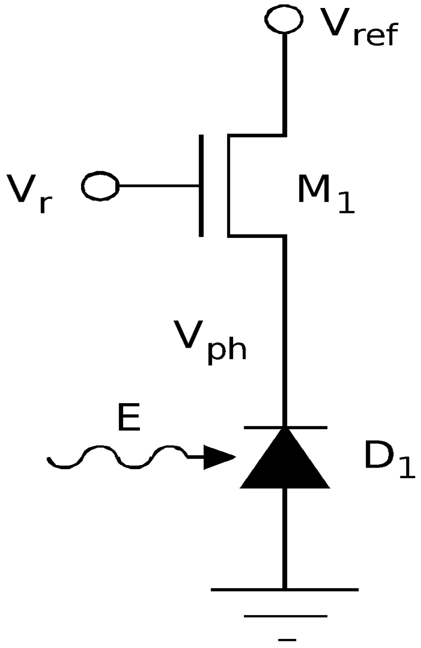
CNS Memo #30 T. Delbrück & C.A. Mead

IMAGE SENSORS

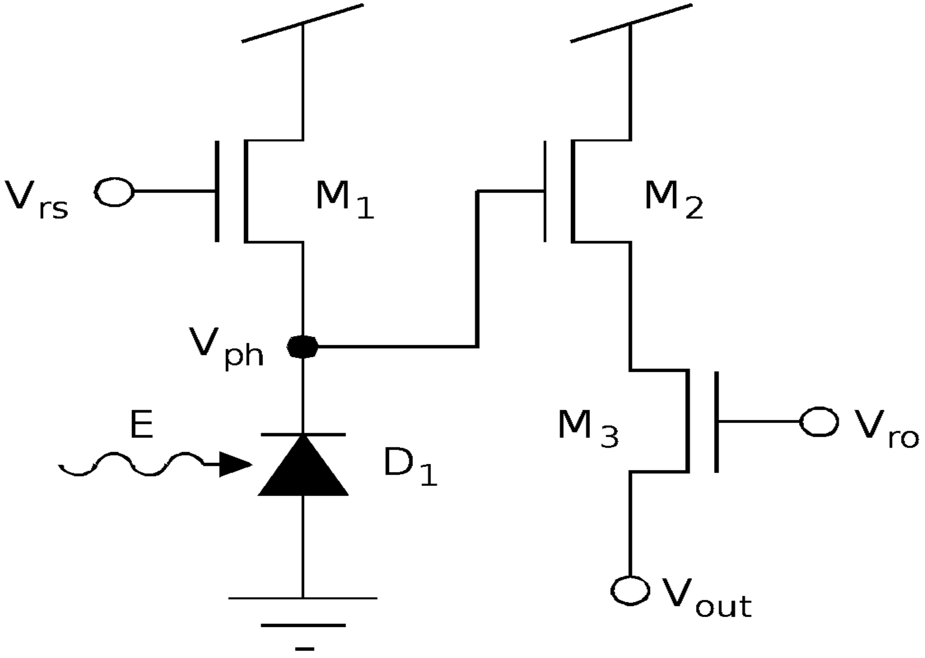
Imaging arrays

- 1D or 2D array of photosensors can record optical images projected onto it by lens system
- Individual photosensor in an imaging array is called pixel (picture element)
- High image resolution requires small pixels
- Outputs of a set of pixels have to be multiplexed onto a single signal line small read-out duty cycle
- Two strategies for pixel operation:
  - Continuous-time mode: Conversion of photogenerated charge into steady-state photocurrent
  - Integration mode: Collection of photogenerated charge on capacitor until readout, followed by reset

Integrating Photodiode Pixels



Passive pixel



Active pixel