**Tutorial on neuromorphic engineering**
Part 1: Motivation, history, community
Part 2: Vision circuits and chips
Part 3: Hands-on work

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## Hands-on work

Components available
- 3x Tmpdiff128 silicon retinas with USB2 interface
- 1x Tmpdiff128 Stereo board with USB2 interface
- 1x Physiologist's Friend chip
- 2x Servo controller with USB1 interface
- 1x Stocker Optical Flow Sensor with USB1 interface

Hands-on project/discussion ideas
- Plotting receptive fields of retinal and cortical cells using PhysioFriend chip
- Measuring photoreceptor responses and observing membrane voltage of spiking neuron using PhysioFriend
- Building a "Bill Catcher" robot using silicon retina, jAER, and a servo
- Discussing bias generator design

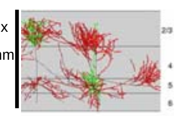
## Part 1: Motivation, history, community

## 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 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!<br>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 |

## The World of Neuromorphic Engineering 2007

Shih-Chii Liu

## Types of Neuromorphic chips

- Silicon retinas—electronic models of retinas
- Silicon cochleas—electronic models of cochleas
- Smart vision chips (e.g. tracking chips, motion sensors, presence sensors)
- Neural networks of spiking neurons
- Central pattern generators
- Models of specific systems:
  e.g. bat sonar echolocation, lamprey spinal cord for swimming, lobster stomatogastric ganglion, electric fishes
- Multichip systems that use spikes for interchip communication

## Brief history of neuromorphic engineering

## 1967-1972 – "The subterranean group" Biophysics of membrane channels

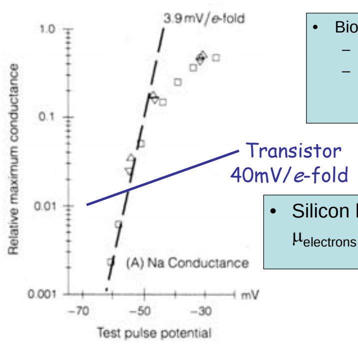
Carver Mead (Caltech)

Max Delbruck (Caltech)

Paul Mueller (UPenn)

Moshe Eisenberg (from UPenn)
Jim Hall (recalled early from Vietnam)
Peter Leuger (Konstanz)
Fred Sigworth

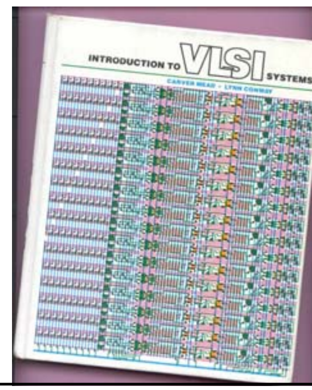
## Device physics of membrane channels




- Biology has
  - Fancy molecules
  - Development and constant adaptation

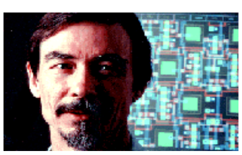
- Silicon has speed
  $\mu_{electrons}$ is $10^7$ times $\mu_{ions}$

## Fast forward to 1980




## Physics of Computation Course

1982
1985



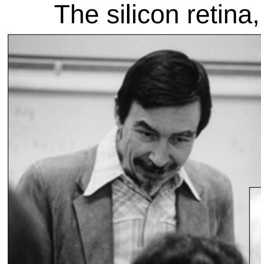
Carver Mead

Dick Feynman

John Hopfield

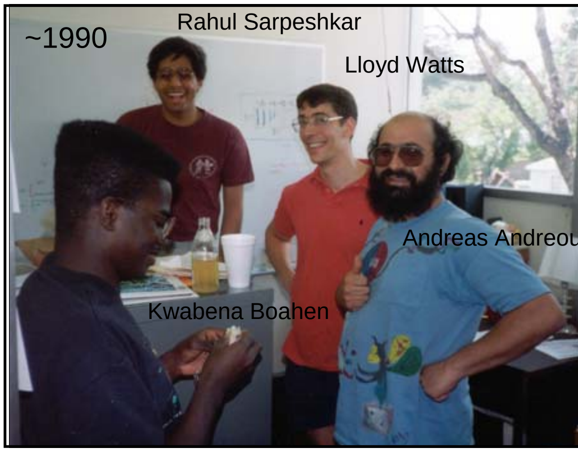
## History of Neuromorphic Engineering The silicon retina, and all that

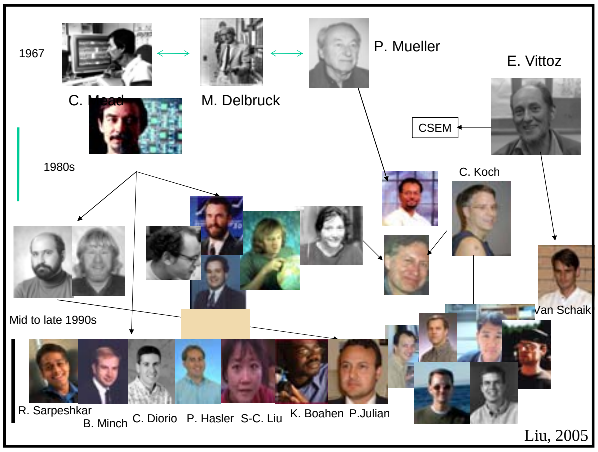
1980s



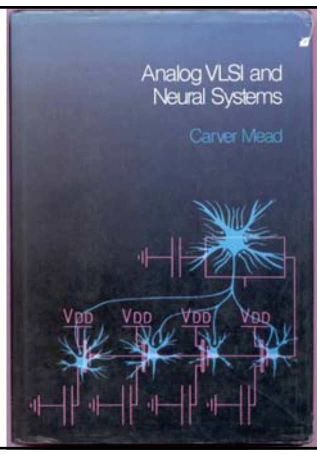
Carver Mead

Misha Mahowald



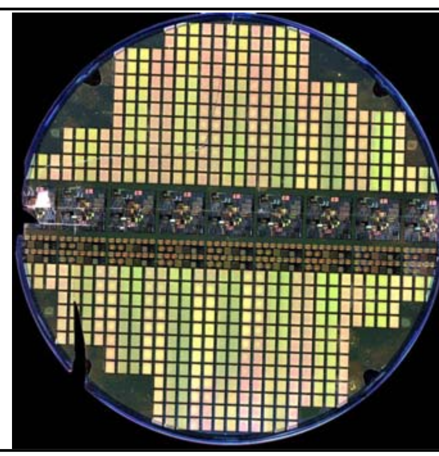

1989

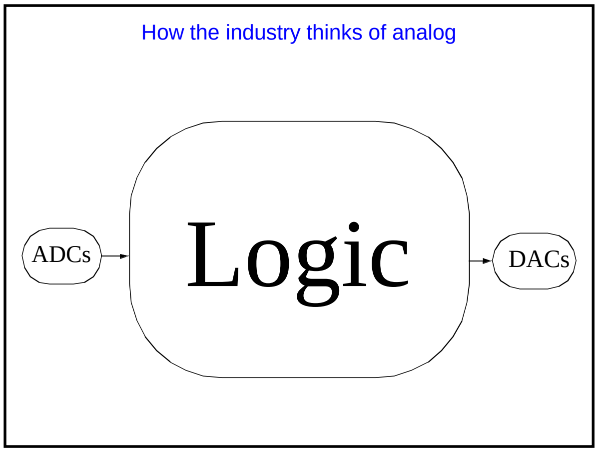


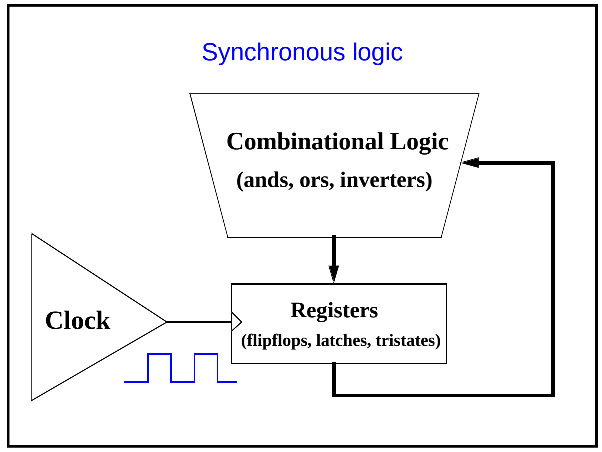

The motivation for neuromorphic engineering

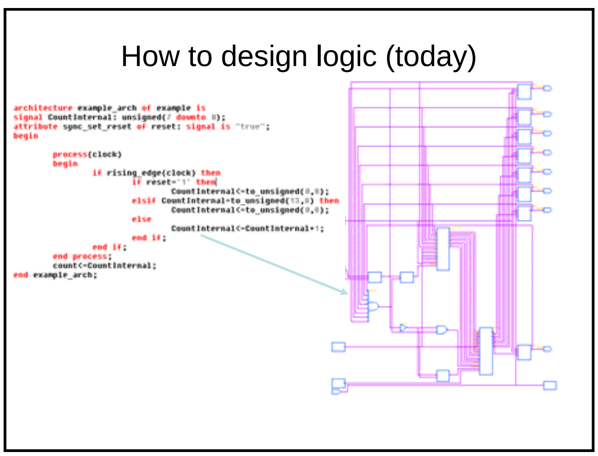
1947

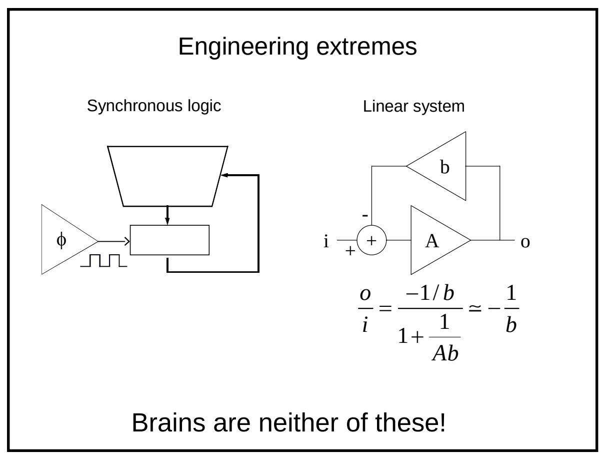
2000

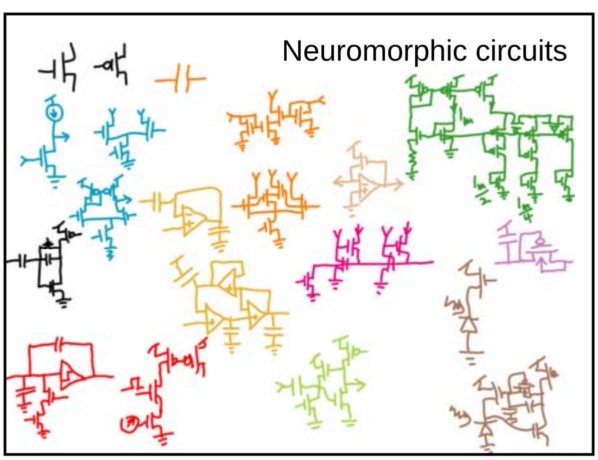


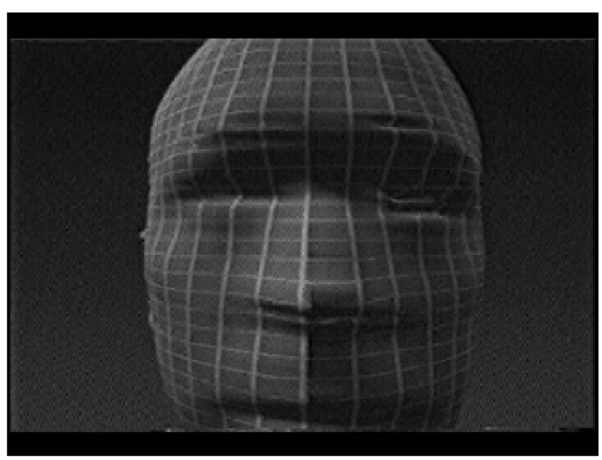

How the industry thinks of analog
ADCs
Logic
DACs


Synchronous logic
Combinational Logic
(ands, ors, inverters)
Clock
Registers
(flipflops, latches, tristates)


How to design logic (today)


Engineering extremes
Synchronous logic
Linear system
ϕ
b
A
i
o
$\frac{o}{i} = \frac{-1/b}{1+\frac{1}{Ab}} \simeq -\frac{1}{b}$
Brains are neither of these!


Neuromorphic circuits



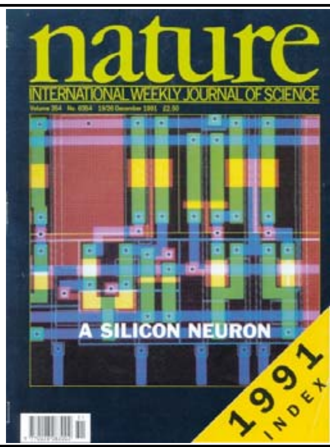
If we are to avoid the AI Trap
we had better evolve our systems
with real input data
(Bottom up)

The AI Trap:

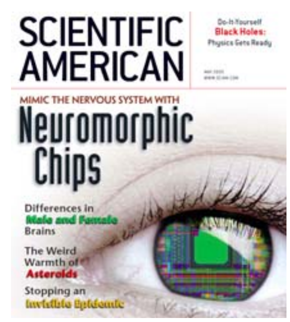
1. Announce intention to solve an obviously difficult problem
2. Work long enough to learn that it is much more difficult than was initially supposed
3. Find a toy example that contains only the easy parts of the problem
4. Make demo of toy example
5. Declare the problem solved without revealing what has been learned about the hard parts
6. Go to step 1. of a more difficult problem

Mead ca. 1990

Accomplishments of neuromorphic engineering

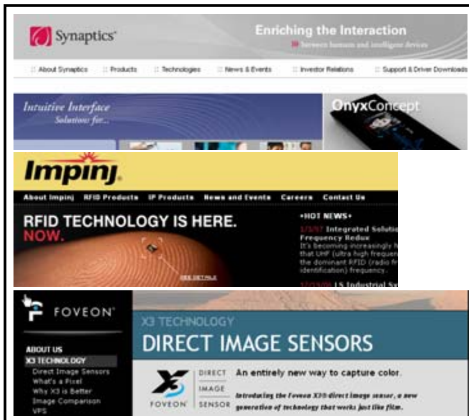



Mahowald, Douglas, 1991

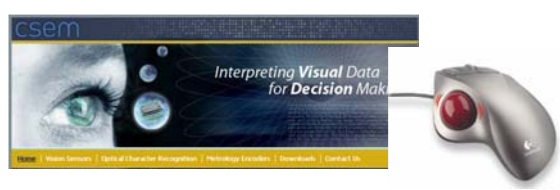




Mahowald, Mead, 1991

Boahen, 2005

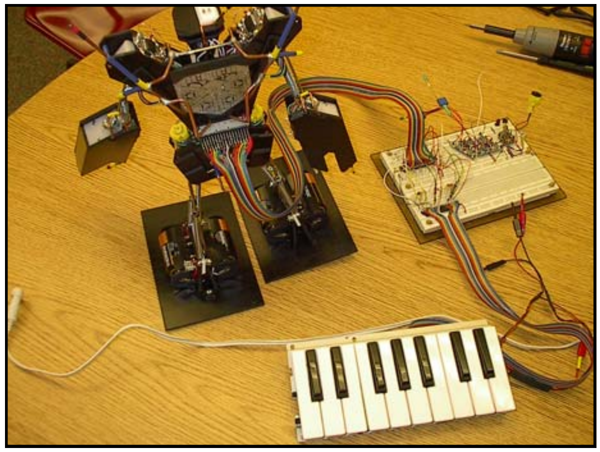



Eric Vittoz




## What is the Telluride Workshop on Neuromorphic Engineering?

- Focus is on
  - fostering the neuromorphic community,
  - tutorials, hands-on workgroups,
  - establishing long-lasting collaborations
- Running 12 years now, started by Rodney Douglas and Misha Mahowald
- Funded by NSF & others, steadily at about $110k/yr
- 60 people each year, about half invited and half applicants – **you can apply.** Housing and part of travel is covered.
- 3 weeks long each July, in the mountains in Colorado, USA.
- Google “Telluride Neuromorphic” for more info




Mark Tilden
WowWee Toys
Hong Kong

## Listen to lectures


March in the parade


Work on projects


Backpack in the mountains


And of course play poker

## 2007 Workgroups

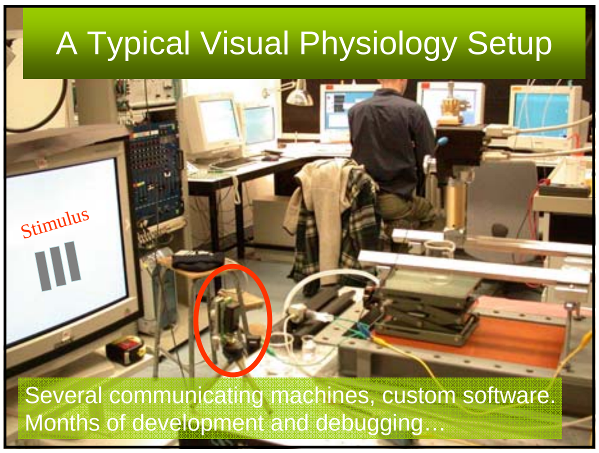
- Workgroups
  - Vision Systems
  - Audition
  - jAER Project: Algorithmic Event-based Computation
  - Spike-based computation and learning with neuromorphic VLSI chips
  - Relational networks of neuromorphic VLSI chips
  - NeuroClone
  - USB Bootcamp
  - Locomotion and Robotics
  - Bias Generators
  - Toy Hacking
  - Analog VLSI Tutorial
  - Design and Test Asynchronous Circuits
  - SMD Soldering Tutorial
  - Using SubVersion for projects
  - Floating Gate Tutorial
  - 3D Animation (Blender)
  - Moth-Machine Interfacing
- Discussion Groups
  - AER Standards Specifications
- Non-Technical Stuff
  - T-Shirt Contest
  - Skits
  - Poker
  - Volleyball
  - Tennis
  - Soccer
  - Flyfishing
  - Paragliding
  - Mountain Biking
  - Workshop Photographers

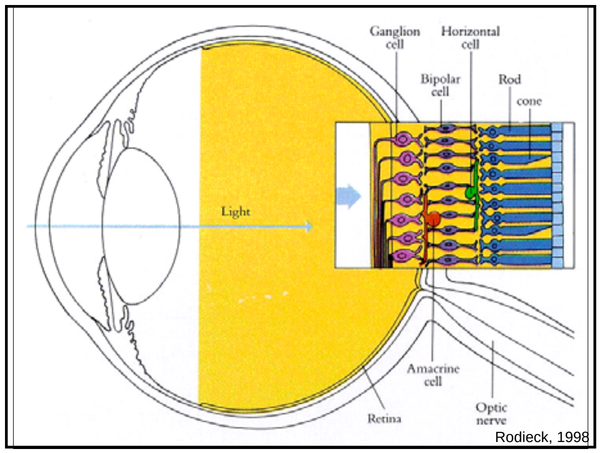
## Part 2: Vision circuits and chips

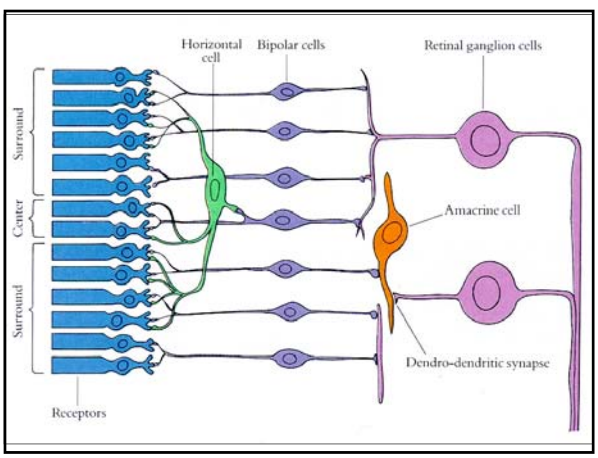
## Types of neuromorphic vision sensors

- Silicon retinas as models of biology
- Spike-based sensors for applications
- Motion sensors (many varieties)
- Specialized sensors (activity, tracking)
- Computation-On-Readout (COR) architectures
- Pattern extraction sensors
- Cellular Neural Network (CNN) focal plane processors
- Others: e.g. SeeHear, optical mice, torque sensor, character recognition, check reader

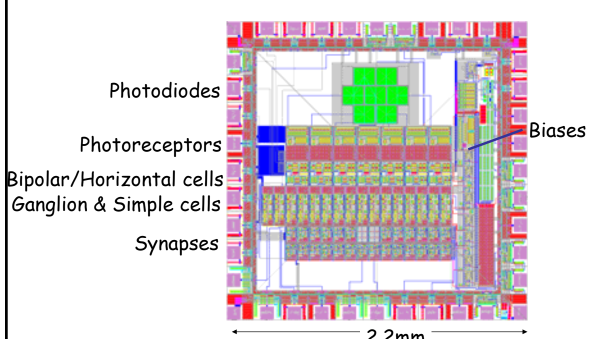
## The “Physiologist’s Friend” chip

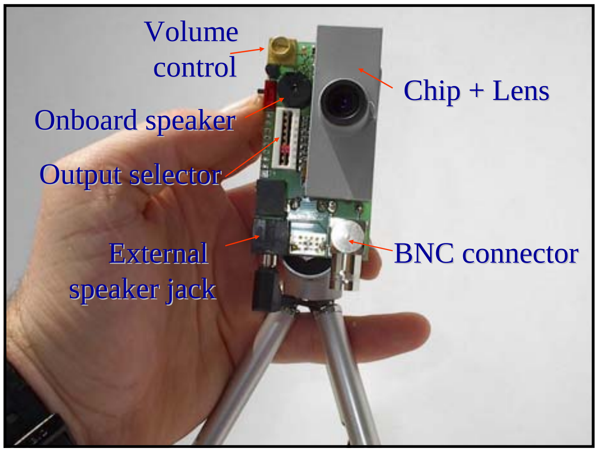


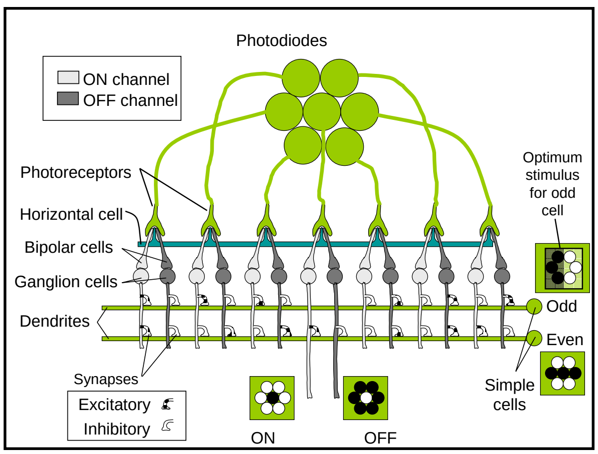



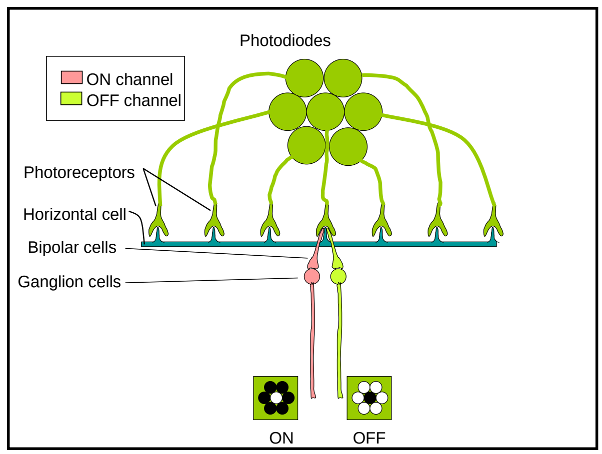



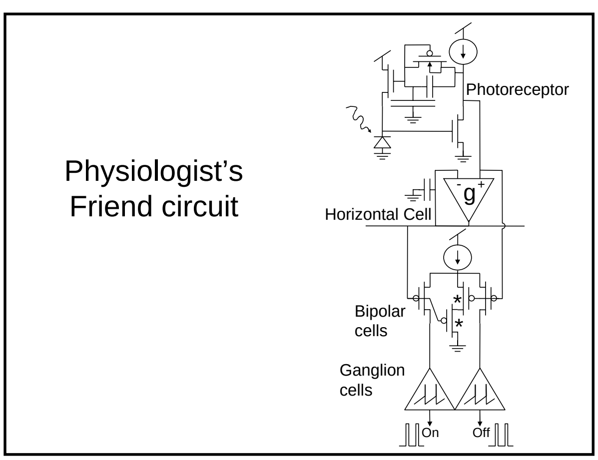

## Physio Friend Layout

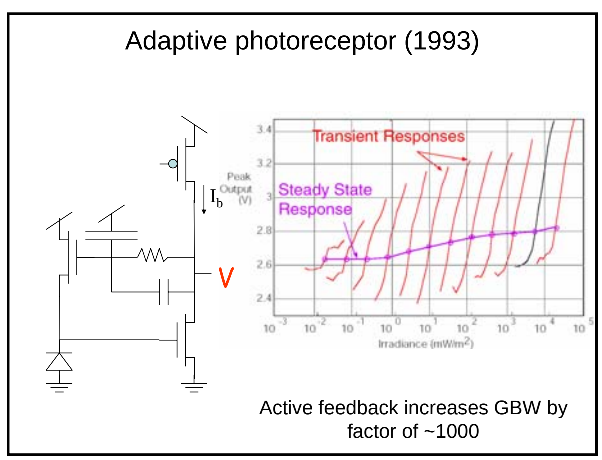



Volume control
Onboard speaker
Output selector
External speaker jack
Chip + Lens
BNC connector


Photodiodes
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
Dendrites
Synapses
Excitatory
Inhibitory
Optimum stimulus for odd cell
Odd
Even
Simple cells
ON
OFF

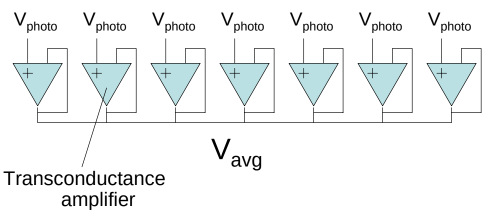

Photodiodes
ON channel
OFF channel
Photoreceptors
Horizontal cell
Bipolar cells
Ganglion cells
ON
OFF


Physiologist's Friend circuit
Photoreceptor
Horizontal Cell
g
Bipolar cells
Ganglion cells
On
Off


Adaptive photoreceptor (1993)
I_b
V
Transient Responses
Steady State Response
Peak Output (V)
Irradiance (mW/m²)
Active feedback increases GBW by factor of ~1000

## Horizontal cell

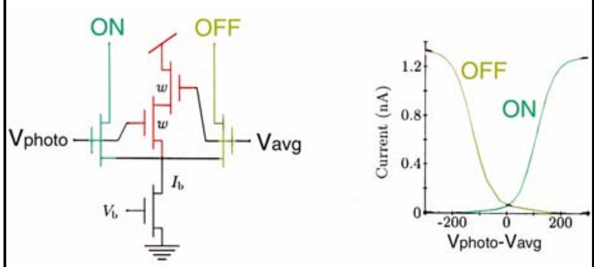
Follower-aggregator averages the photoreceptor outputs to compute the *context.*



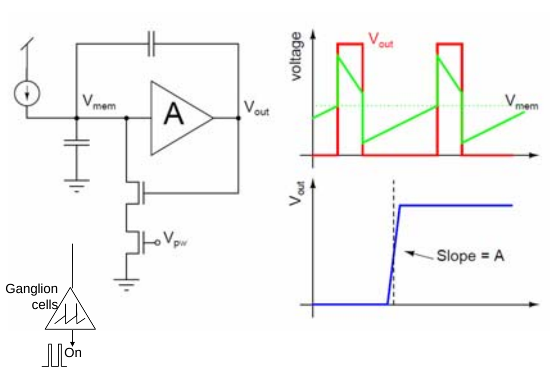

The follower-aggregator computes **mean** for small signals and **median** for large signals

## Bipolar Cell (Anti-bump circuit)

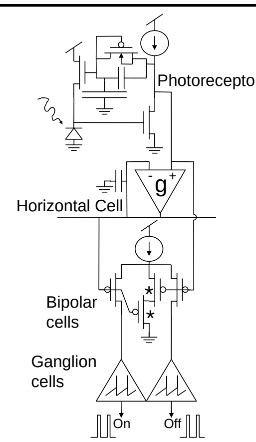
Rectifies into ON and OFF currents



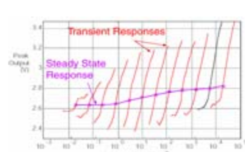

## "Axon-hillock" spiking soma circuit turns the bipolar outputs into ganglion cell spikes

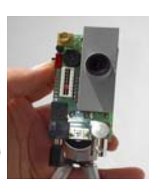


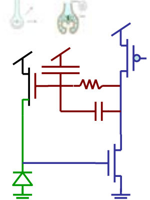

## Physiologist's Friend circuit

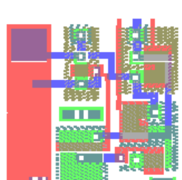


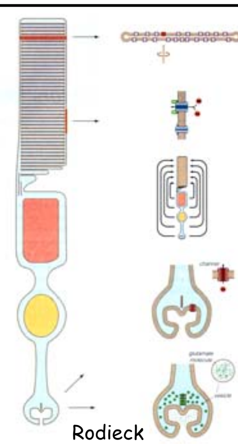

## Understanding silicon photoreceptors





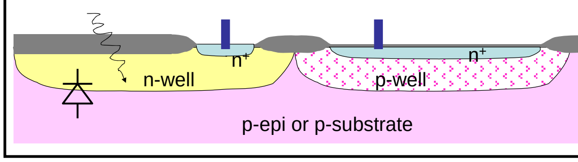




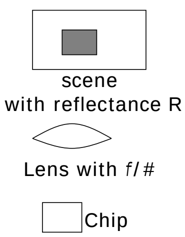
## Practical aspects of photodiode design

## Drawing a photodiode

- You can use either *nwell* or *ndiff* as a photodiode in any CMOS process. It may be leaky and have low quantum efficiency but it will make photocurrent.
- Make sure you **block the salicide!**
- **Parasitic photodiodes can kill you!** Any other junction will act as a photodiode unless you protect it from light and minority carriers.



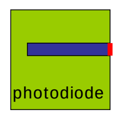

## Estimating photocurrent




- Good rule of thumb:
  1 lux = $10^4$ photons/um²/s (Rose, 1973)
  - Moonlight 0.1 lux
  - Office light 500 lux
  - Sunlight $10^5$ lux
- Average scene reflectance *R* is 18% (Kodak gray)
- Lux falling on chip is $1/8f^2$ imaged from white surface. *f* is aperture/focal-length
- Quantum efficiency is about 0.5

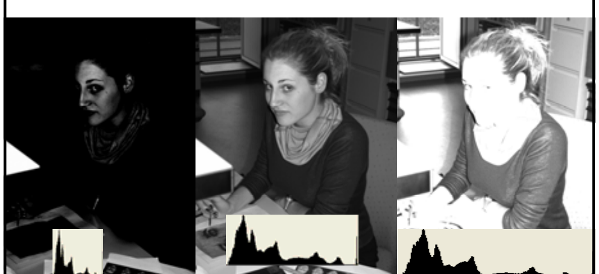
$$I_{\text{chip}} = \frac{I_{\text{scene}} R}{8 f^2}$$

## Dark current limits low-light performance




- Typical process leak 1nA/cm² for large area junctions at 25°C
- Corresponds to about moonlight **scene** illumination
- Dominated by edges of junctions, where leakage is 10-100x higher: red edge leaks as much as blue area.
- Doubles every ~6-8°C; from 25°C to 60°C increases 30X
- Is *expansive* nonlinear function of reverse bias (esp. for deep submicron processes)
- image sensor processes advertise 20-50x lower dark current, but these processes not available to usual multiproject services like MOSIS and Europractice
- Pinned photodiodes reduce even more, but have many restrictions, e.g. no nwell in pixel!

## The *contrast* of reflective scenes is invariant to illumination

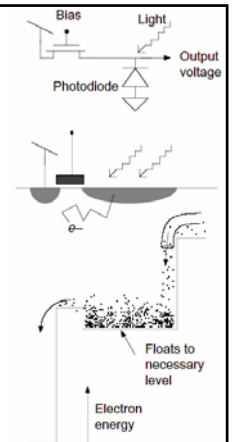


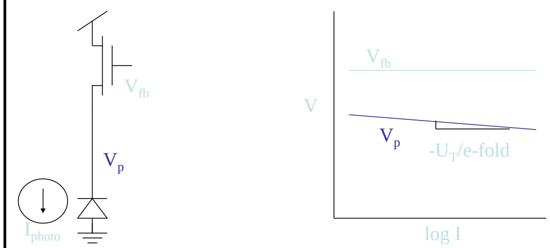
A logarithmic representation of luminance preserves reflectance

## log is self-normalizing and automatically preserves reflectance differences

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

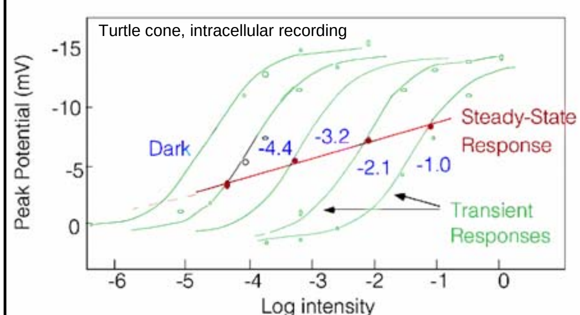
A simple logarithmic photoreceptor circuit



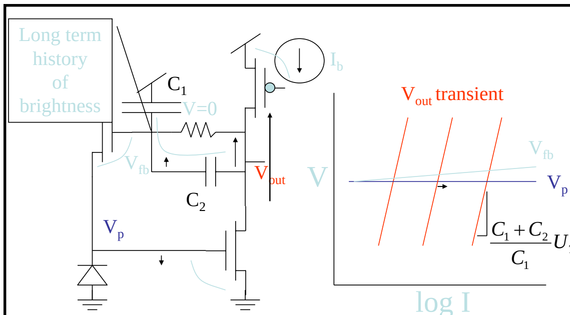




Problem is that mismatch of DC levels is larger than signal

Biological photoreceptors amplify changes more than DC

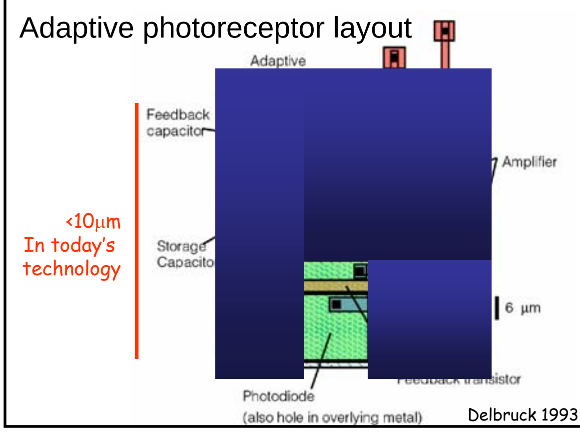



Normann & Perlman, 1979



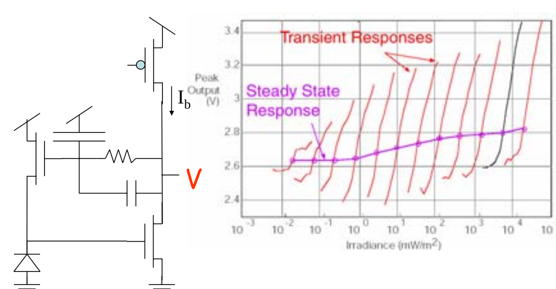

In steady state (DC)

Adaptive photoreceptor layout



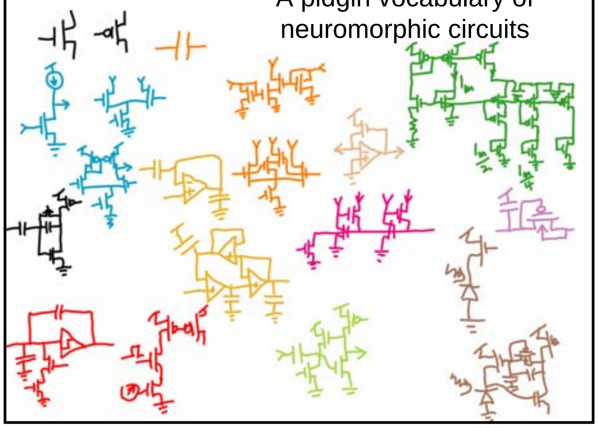

Delbruck 1993

Adaptive photoreceptor (1993)




Active feedback increases GBW by factor of ~1000

A pidgin vocabulary of neuromorphic circuits



For more information, google "Tobi Delbruck" and look for wiki – follow links there


Apply to Telluride workshop!