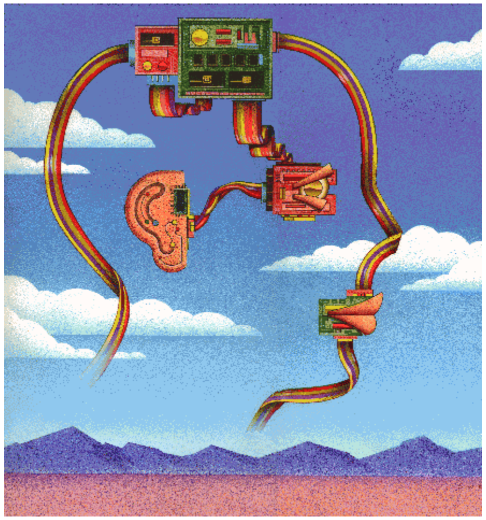

Towards “Eyes” for Sensor Network Systems

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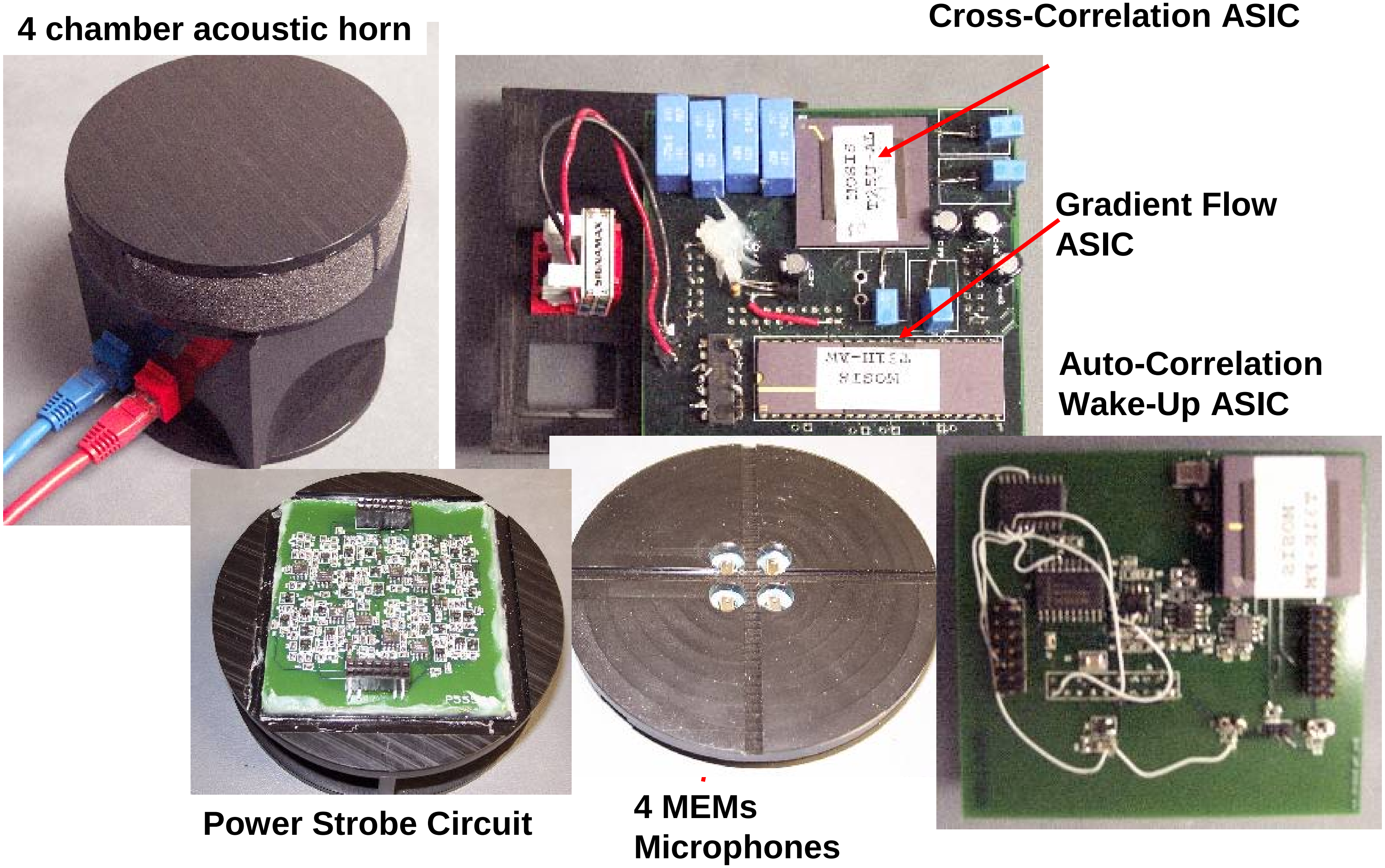
Electrical and Computer Engineering and
Whitaker Biomedical Engineering Institute
Johns Hopkins University
http://www.ece.jhu.edu/faculty/andreou/AGA/index.htm

outline

- "Ears" for sensor network systems: a brief detour
- Introduction
  - Light, photons, noise, bandwidth
  - Current signal processing and translinear networks
- Systems
  - Polarization contrast chip
  - Spatial-temporal processing
  - Ego-motion compensation chip in a balloon observatory
  - Network architecture for distributed feature extraction.
- Conclusions

smart microphone project



http://www.signalsystemscorp.com/acoustic_surv.htm

and some related papers

P. Julian, A.G. Andreou, P. Mandolesi, D. Goldberg, “A low-power CMOS integrated circuit for bearing estimation,” *Proceedings of the 2003 IEEE International Symposium on Circuits and Systems, (ISCAS 2003)*, Bangkok, Thailand, Vol. 5, pp. 305 -308, May 2003.

P. Julian, A.G. Andreou, L. Riddle, S. Shamma, G. Cauwenberghs, “A comparative study of sound localization algorithms for energy aware sensor network nodes, *IEEE Transactions on Circuits and Systems: Part II: Analog and Digital Signal Processing*, to appear, 2004.

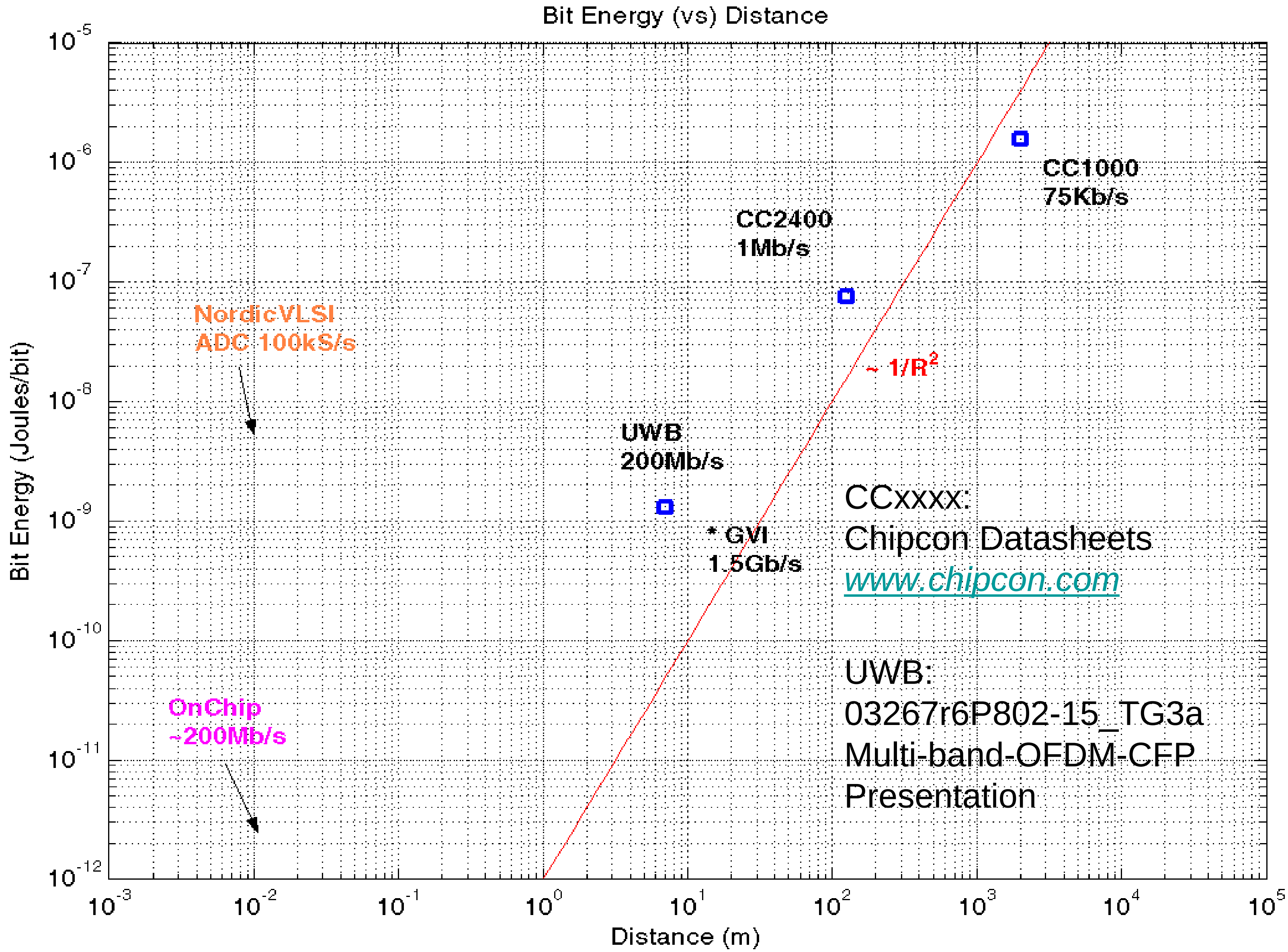
D. Goldberg, A.G. Andreou, et.al., “A wake-up detector for an acoustic surveillance sensor network: algorithm and VLSI implementation”, submitted to IPSN-04.

M. Stanacevic and G. Cauwenberghs, ``Micro-power mixed-signal acoustic localizer,'' in Proc. European Solid State Circuits Conf. (ESSCIRC 2003), Estoril, Portugal, September 2003.

what did we learn?

- COTS can take you up to a point.
- DSP and FPGA also take you up to a point, custom analog or digital design is necessary.
- Event based, one bit digital processing.
- Interfaces are critical! –necessity for system level design-
- Algorithm exploration is necessary with real data and the actual application environment.
- Wireless data communication is expensive; do the computation locally if you can!
- Analog subthreshold CMOS works well if designed properly!

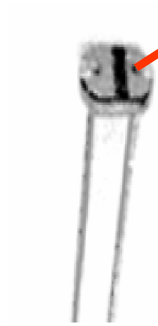
the energy cost of bits –in wires and wireless-



the not-so-state-of-the-art not-eye

CrossBow MTS310CASensorBoard

Clairex CdSe photoconductor
~ 2 mW power (light ON)
~ 47 uW power (light OFF)
~ 10 kHz bandwidth
5 Volts power supply (signal)
10 bits ADC, 15 KS/s



http://www.xbow.com

13 nJ per bit of light data –NOT information-

electrical characteristics (T_A = 25°C unless otherwise noted)

Part Number	Material Type	λ_p nm	R_{ON} (1)(2) Ω(typ)	R_{OFF} (3) Ω (min.)	V_{meas} (4) Volts	$V_{(max)}$ Volts
CL9P4L	4, CdSe	690	2.0K	520K	8.0	170

http://www.clairex.com/

“eyes” for sensor network systems

Eyes: sensory structures capable of spatial vision, i.e. imaging the environment, no matter how crude the image is

Land and Nilsson, Animal Eyes

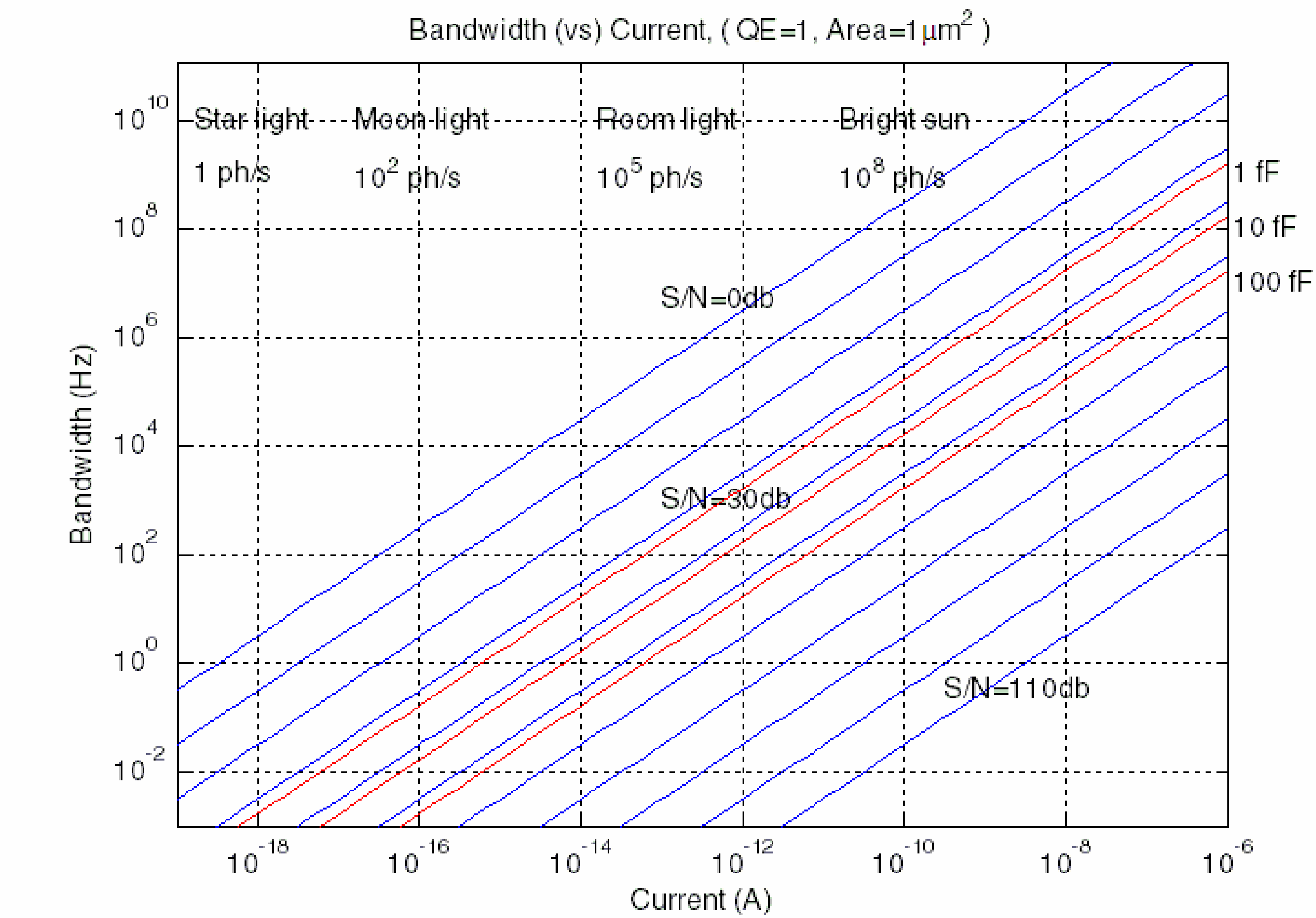
- Is there something interesting in the environment ?
  - in a specific class of objects
- Where is it ?
- What is it ?

often it is about a few bits
in the right place at the right time

the way natural eyes see

- Continuous sensing
- Polarization sensitivity
- Contrast sensitivity
- Local gain control
- Spatial filtering
- Temporal filtering
- Sampling on demand

light, photons, photon shot-noise, bandwidth …



analog, digital and all that …

CVDT

Continuous-Value
Discrete-Time

CCD
Switched Capacitor

CVCT

Continuous-Value
Continuous-Time

Linear and non-linear analog

Binary digital
Multivalue digital

Discrete-Value
Discrete-Time

DVDT

Asynchronous digital
Neuron spikes
Anisochronous Pulse Time Modulation

Discrete-Value
Continuous-Time

DVCT

subthreshold CMOS

- Current is exponential function of the terminal voltages Vs, Vb, Vg, Vd
- Large dynamic range
- High gain (transconductance)
- Low saturation voltage Vdsat ~100mV
- Lossless channel and source/drain symmetry (diffusive networks)
- Zero conductance control node (gate); possibility of floating gate for long term charge storage
- Mobility considerations
- Frequency limitations

$$f_{T\,\max} = \frac{g_m}{2\pi C} \quad \frac{\mu V_t}{\pi L^2}$$

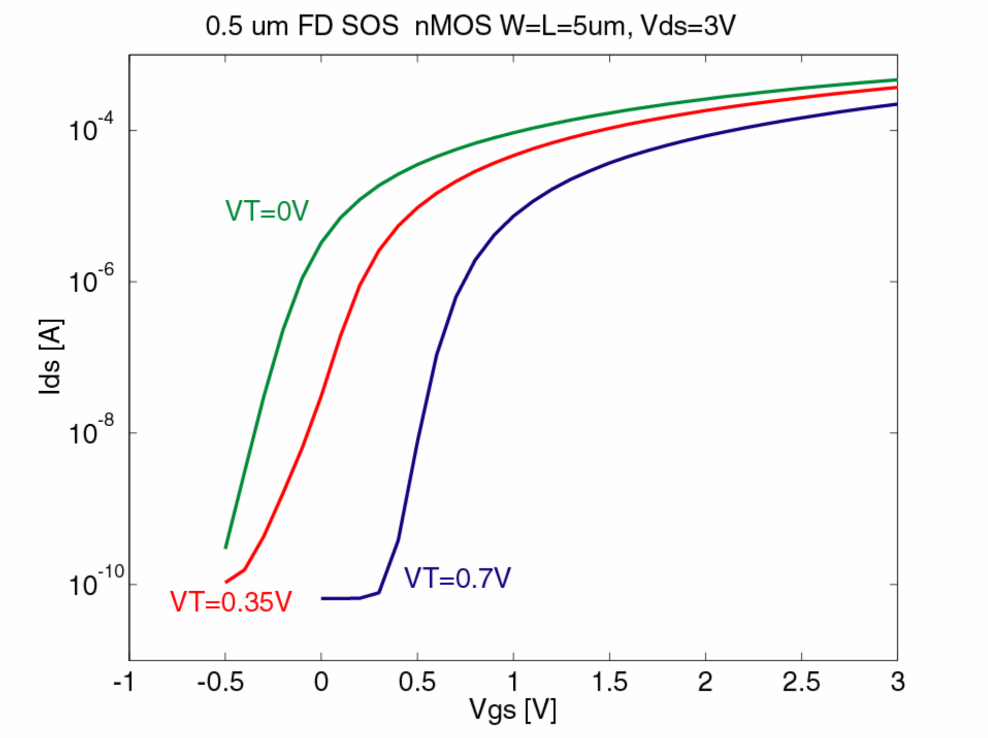
$$1\mu m \rightarrow 100MHz$$

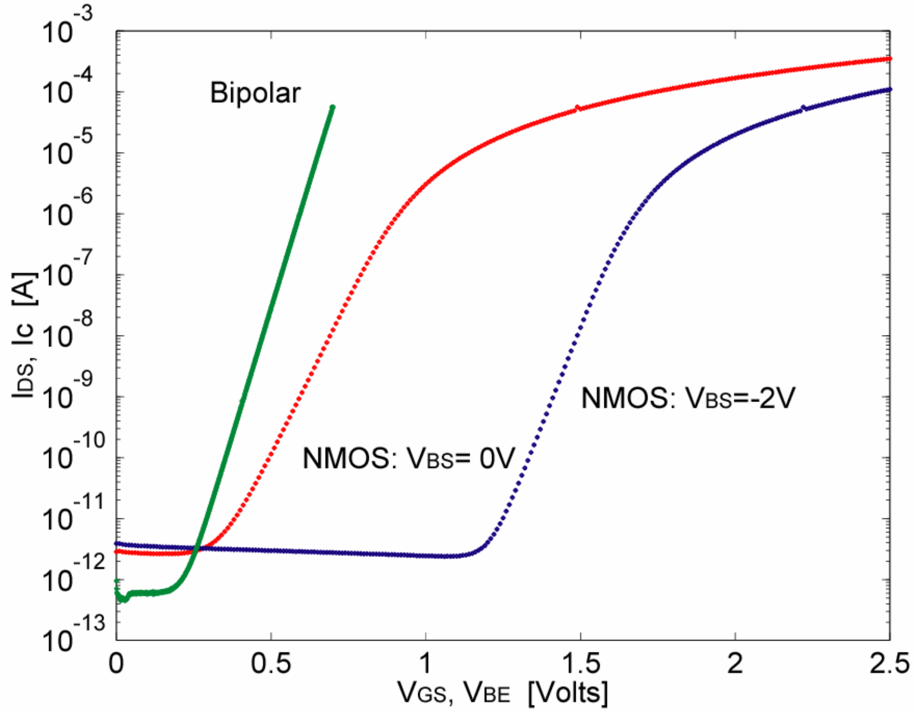
$$0.25\mu m \rightarrow 1.6GHz$$

subthreshold MOS and bipolar characteristics

$$I_D \equiv I_{DS} = S\, I_{n0} \exp\left(\frac{\kappa_n V_{GB}}{V_t}\right)\left[\exp\left(\frac{-V_{SB}}{V_t}\right) - \exp\left(\frac{-V_{DB}}{V_t}\right)\right]$$

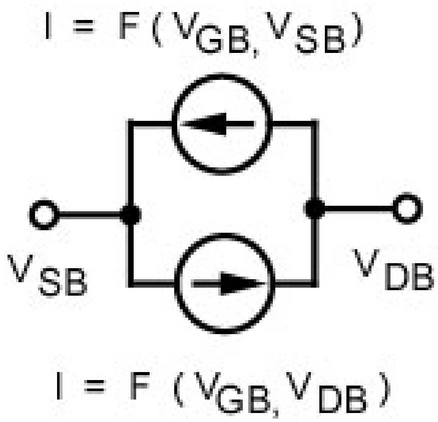
$$I_D \equiv I_{SD} = S\, I_{p0} \exp\left(\frac{-\kappa_p V_{GB}}{V_t}\right)\left[\exp\left(\frac{V_{SB}}{V_t}\right) - \exp\left(\frac{V_{DB}}{V_t}\right)\right]$$

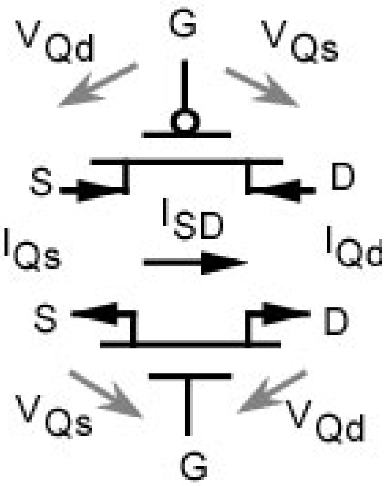




$$I_C = I_S \exp\left(\frac{V_{BE}}{V_t}\right) = I_S \exp\left(\frac{V_B - V_E}{V_t}\right)$$

symmetric MOS model





DIFFUSION

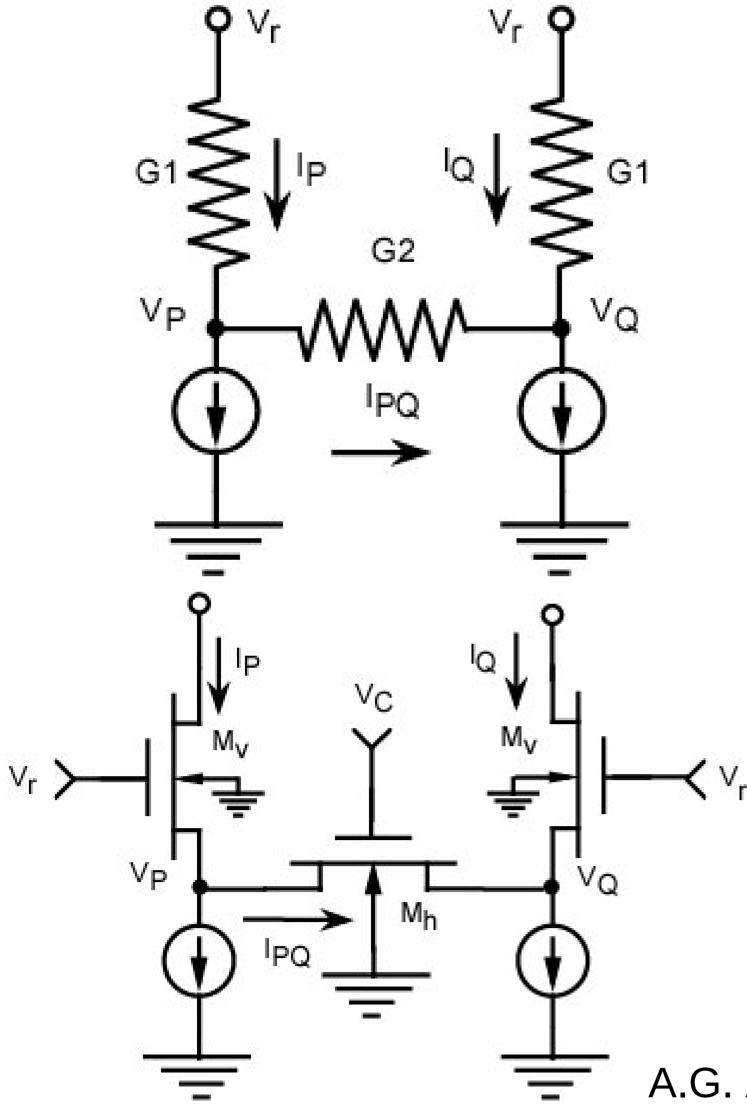
$$I \equiv I_{Q_S} - I_{Q_D} = \mu \frac{W}{L}\left[\left(\frac{1}{2}\frac{Q_S{}^2}{C_{ox}+C_{dep}} + \frac{kT}{q}Q_S\right) - \left(\frac{1}{2}\frac{Q_D{}^2}{C_{ox}+C_{dep}} + \frac{kT}{q}Q_D\right)\right]$$

DRIFT

$$I_{SD} \propto F\left(V_{GB}, V_{SB}\right) - F\left(V_{GB}, V_{DB}\right)$$

$$I_{SD} \propto G\left(V_{GB}\right)\left[H\left(V_{SB}\right) - H\left(V_{DB}\right)\right]$$

non-linear CMOS resistors and translinear grids



Linear conductances

$$V_r - V_P = G_1 I_P$$

$$V_r - V_Q = G_1 I_Q$$

$$V_P - V_Q = G_2 I_{PQ}$$

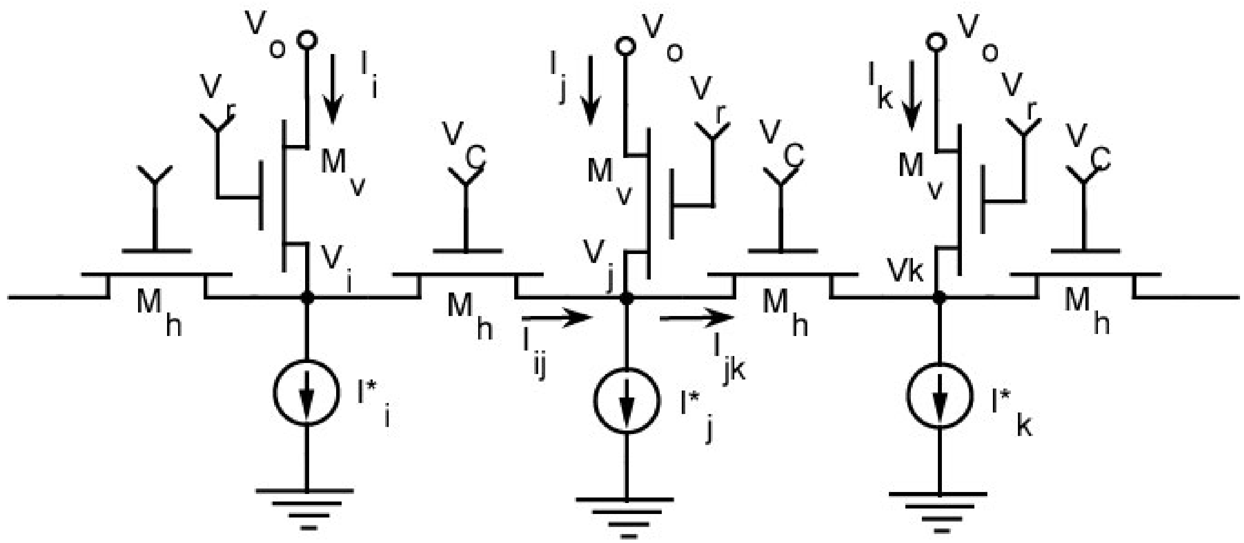
$$I_{PQ} = \left(\frac{G_1}{G_2}\right)\left(I_Q - I_P\right)$$

NMOS only “diffusor/conveyor”

$$I_{PQ} = \left(\frac{S_h}{S_v}\right)\exp\left[\frac{\kappa_n V_C - \kappa_n V_r}{V_T}\right]\left(I_Q - I_P\right)$$

A.G. Andreou and K.A. Boahen, “Translinear circuits in subthreshold CMOS,” *Journal of Analog Integrated Circuits and Signal Processing*, Vol. 9, pp. 141-166, March 1996.

1D spatial averaging network



Inputs:

$$I_i^*, I_j^*, I_k^*, I^*(x)$$

Outputs:

$$I_i, I_j, I_k, I(x)$$

At node V_j:

$$I_j^* = I_{ij} - I_{jk} + I_j$$

$$I_j^* = I_j + \left(\frac{S_h}{S_v}\right) \exp\left(\kappa_n v_C - \kappa_n v_r\right)\left(2 I_j - I_i - I_k\right)$$

Normalizing inter-node distances to unity we write the above on the continuum

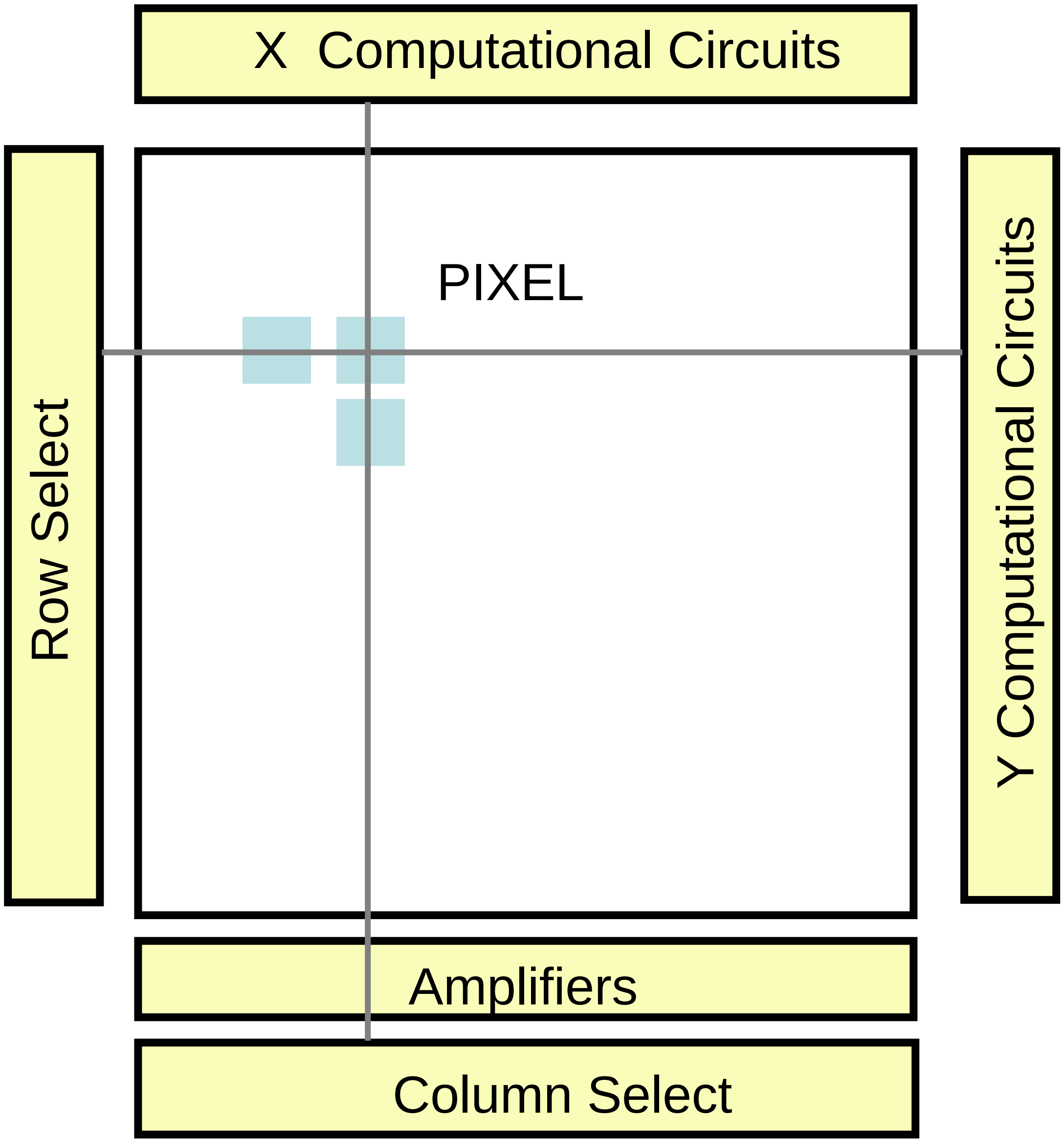
$$I^*(x) = I(x) + \lambda \frac{d^2 I}{dx^2}$$

where $\frac{d^2 I}{dx^2} \approx 2I_j - I_i - I_k$

Find the smooth function I(x) that best fits the data I(x) with the minimum energy in its first derivative.

λ The reqularization parameter cost associated with energy in the derivative relative to the squared error of the fit to the data

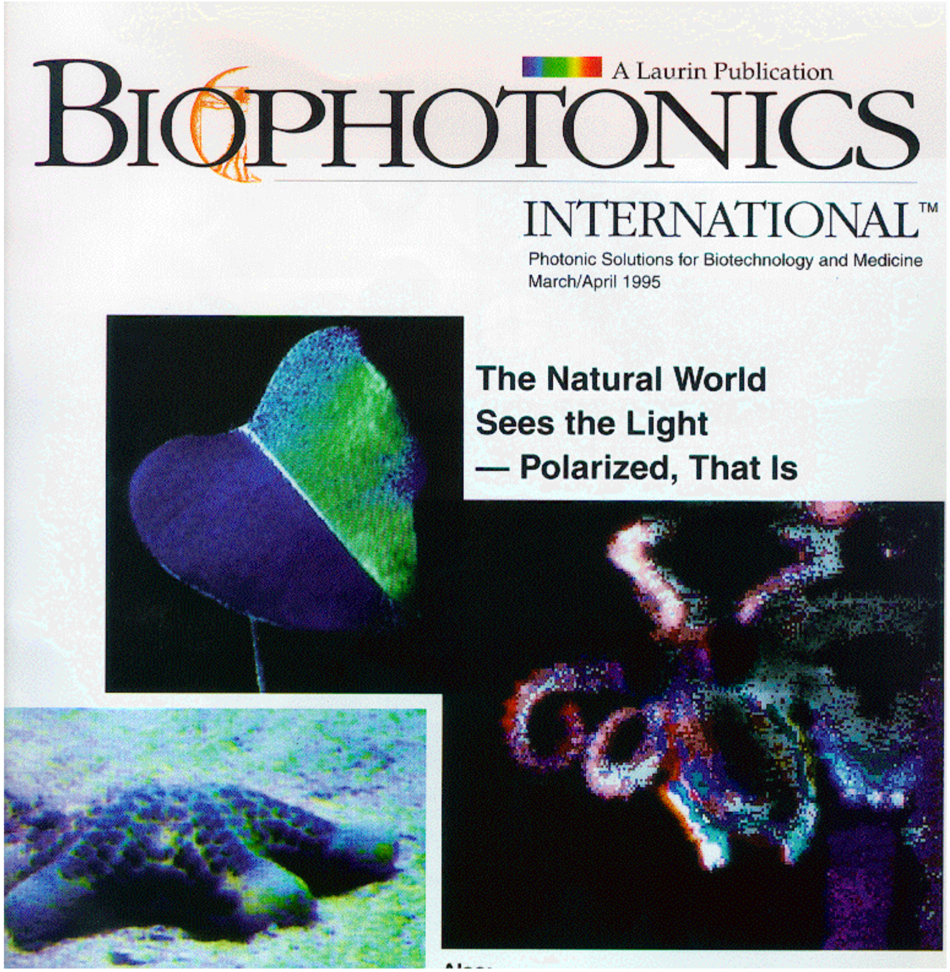
sensor level processing: what and where



Pixel:
transduction
amplification
gain control
quantization
non-uniformity correction
spatial filtering
temporal filtering

Periphery:
ego-motion
moments
global contrast
data-communication

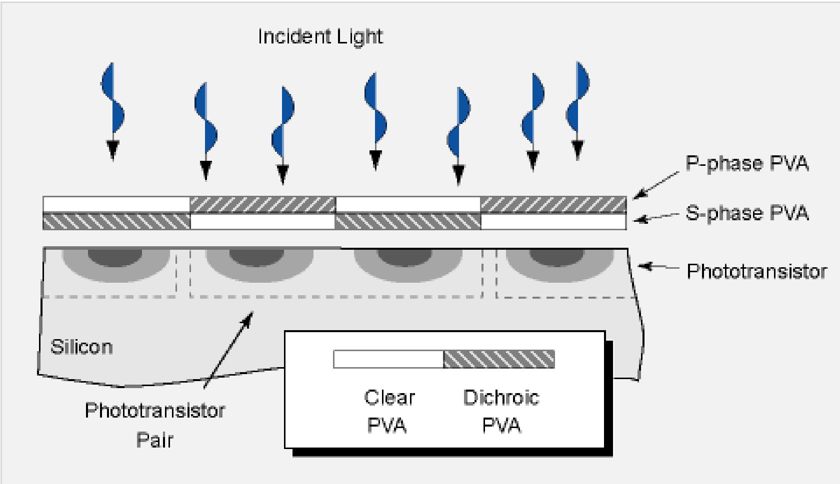
seeing in ways that we can't!

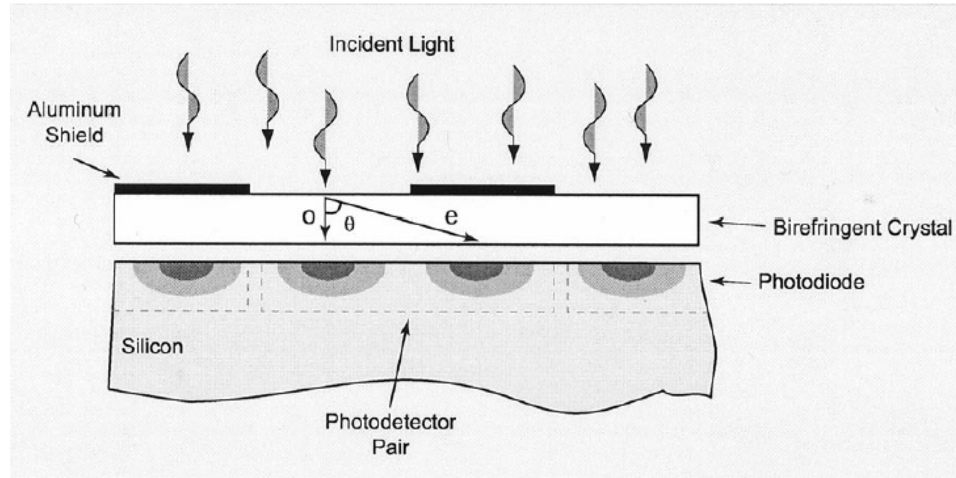


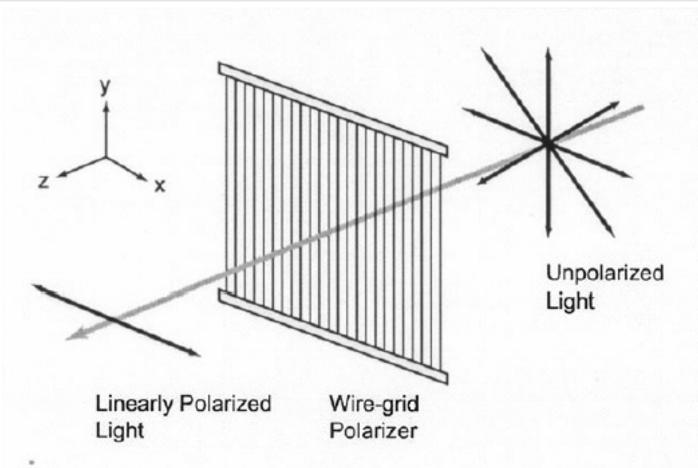
Mantis Shrimp

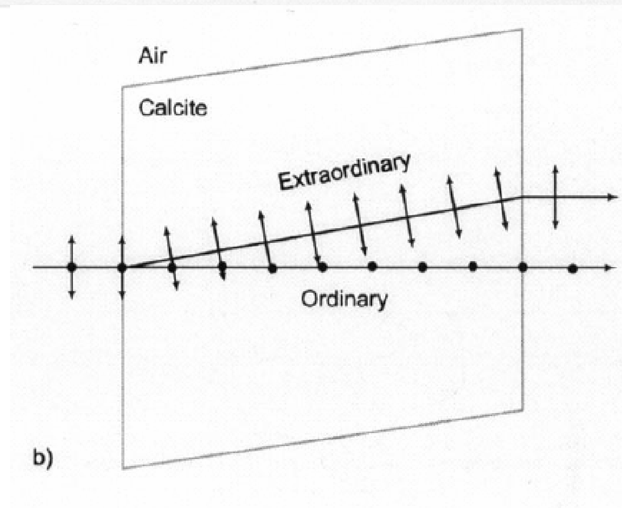
L.B. Wolff and A.G. Andreou, "Polarization camera sensors," *Image and Vision Computing*, Vol. 13, No. 6, pp. 497-510, August 1995.

doing things in front of the pixel: micropolarizers







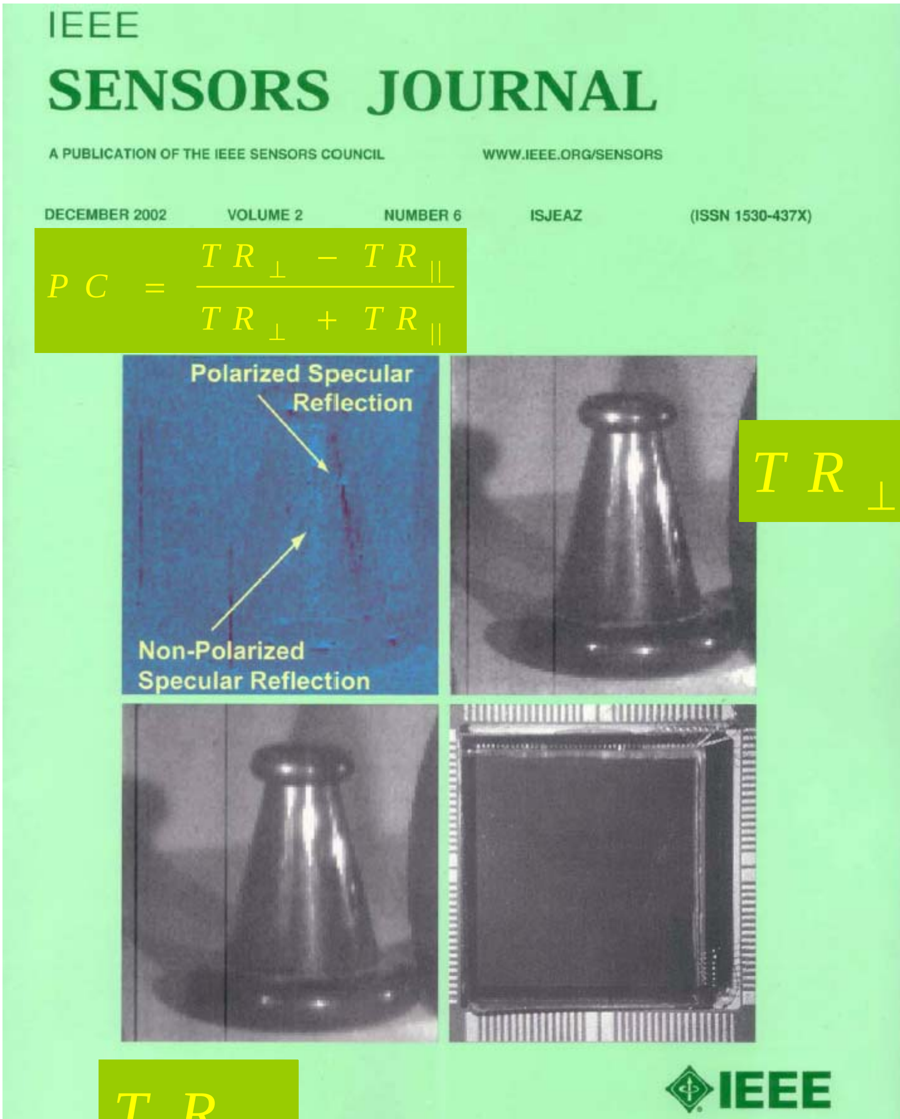


A.G. Andreou and Z.K. Kalayjian, "Polarization imaging: principles and integrated polarimeters," *IEEE Sensors Journal*, Vol. 2, No. 6, pp. 566-576, December 2002.

Z. Kalayjian and A.G. Andreou, "Integrated imaging linear polarimeter," *ISA Transactions*, Vol. 38, pp. 203-209, 1999.

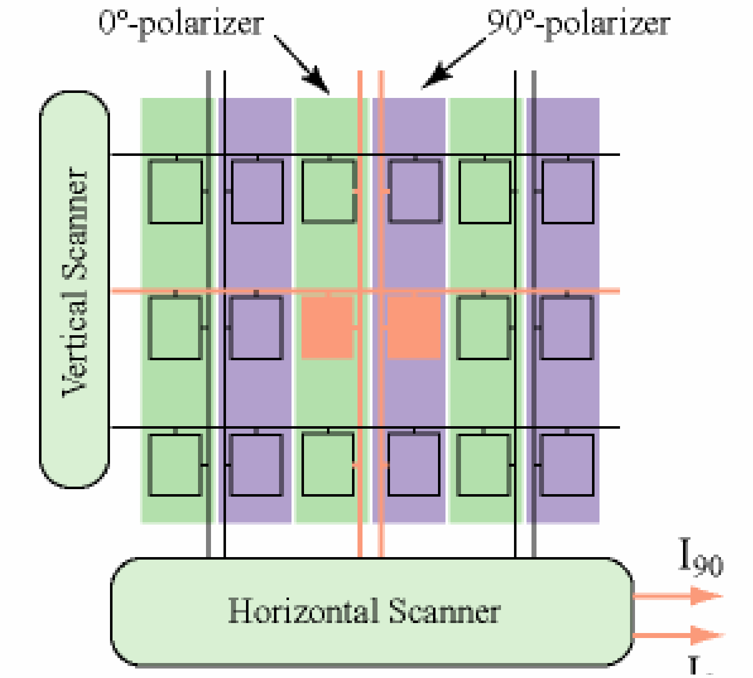
current-mode translinear processing

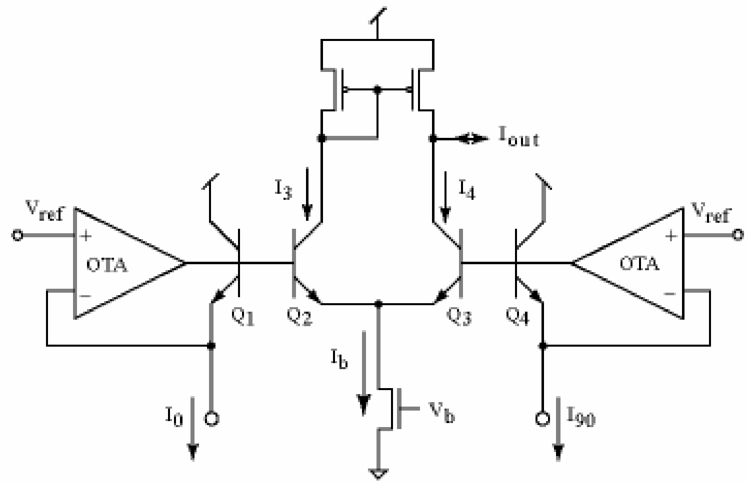
$$PC = \frac{TR_{\perp} - TR_{||}}{TR_{\perp} + TR_{||}}$$



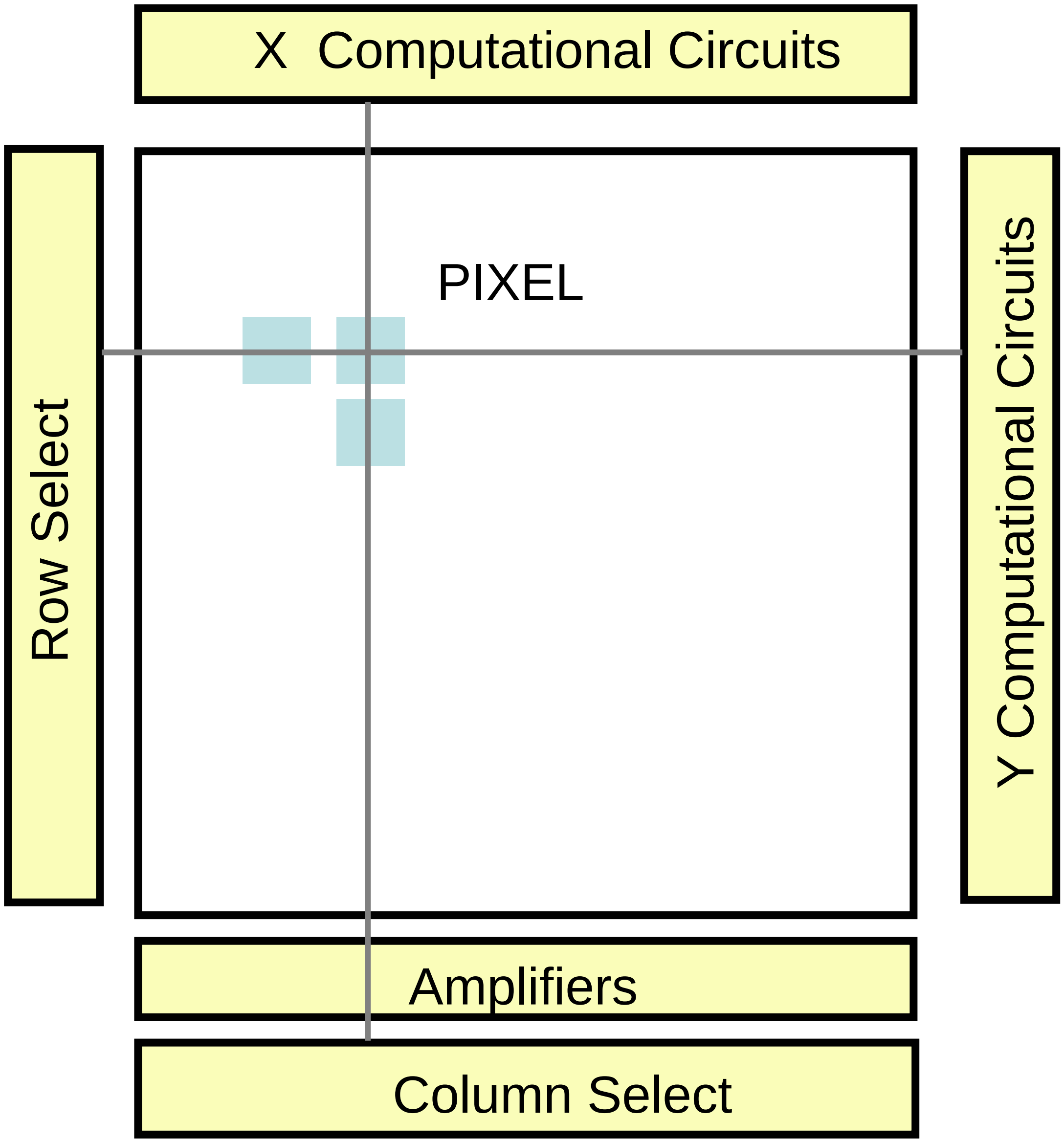
$TR_{\perp}$

$TR_{||}$





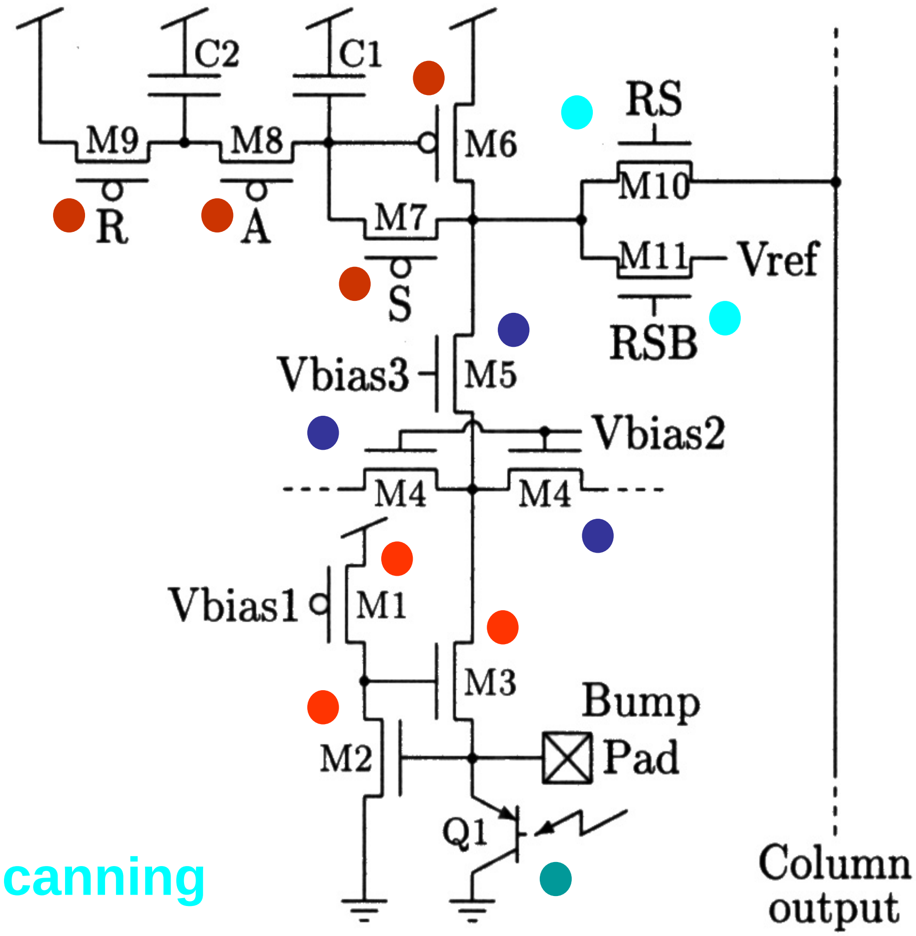
sensor level processing: what and where



Pixel:
transduction
amplification
gain control
quantization
non-uniformity correction
spatial filtering
temporal filtering

Periphery:
ego-motion
moments
global contrast
data-communication

spatial/temporal filter



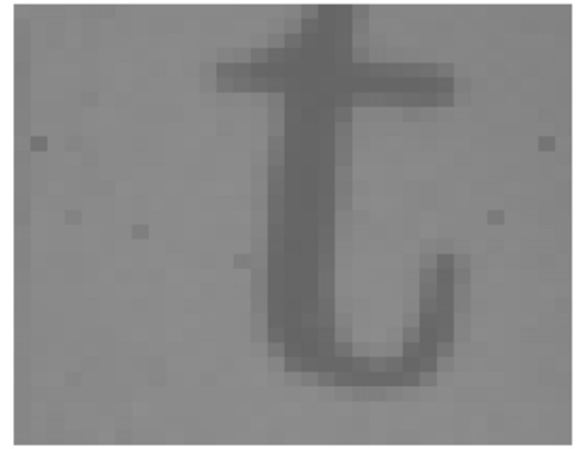
Scanning

Temporal Filtering

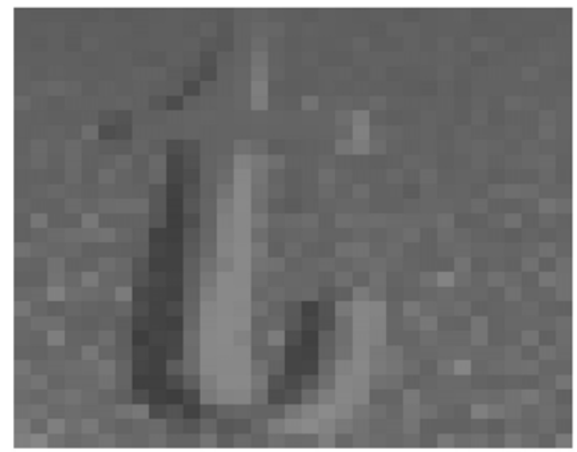
Spatial Filtering

Detection

Buffering / Amplification

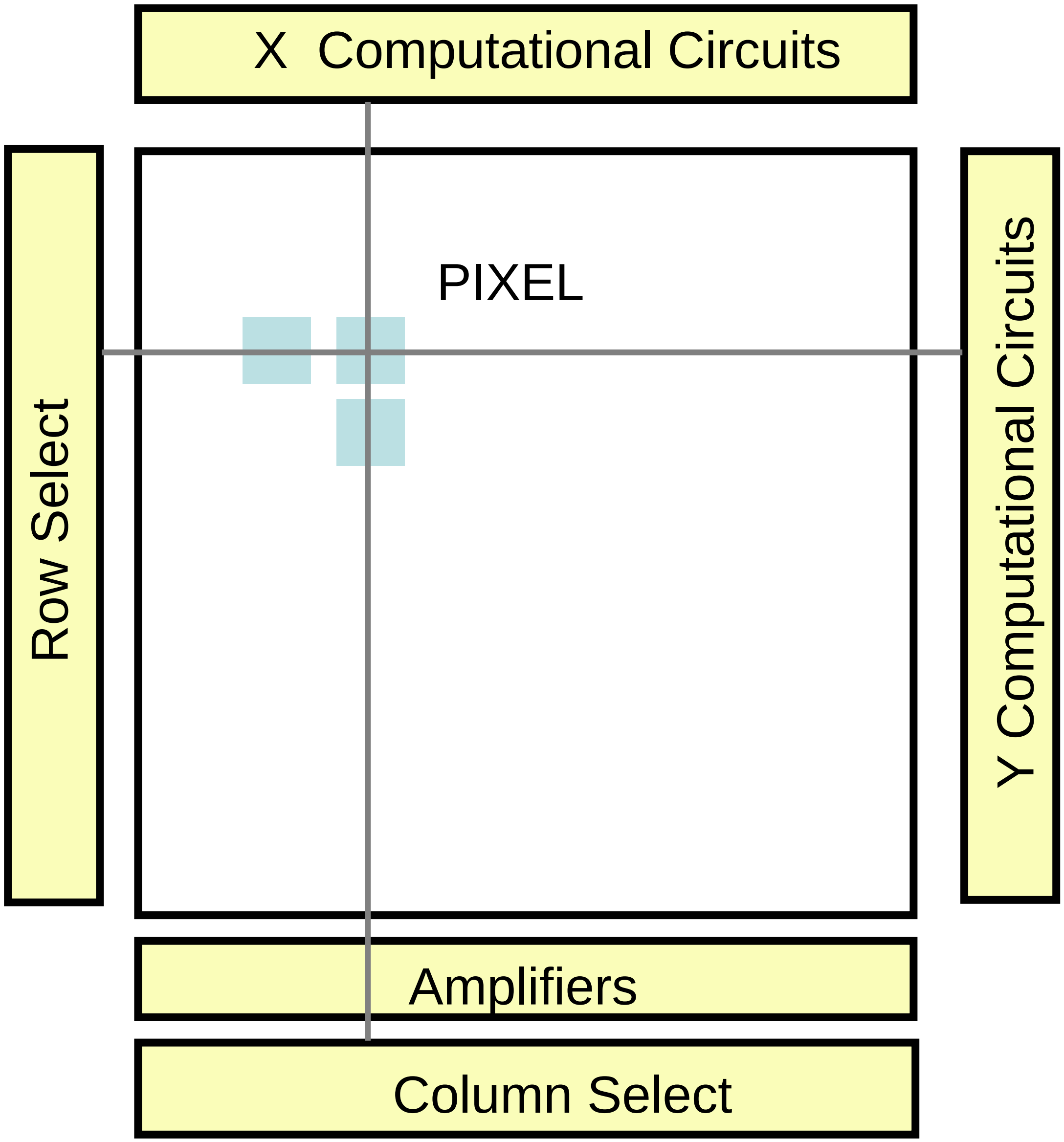


Moving “t”



33 x 30 pixels 0.5 micron
linear capacitor triple metal CMOS
50 micron cell pitch (2 x 2 mm die)

sensor level processing: what and where



Pixel:
transduction
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moments
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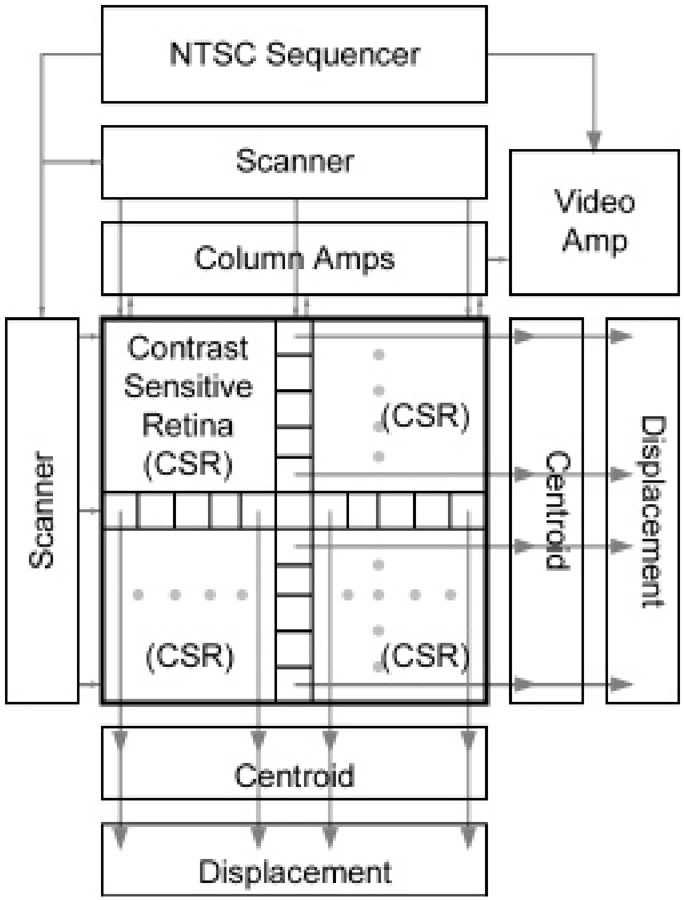
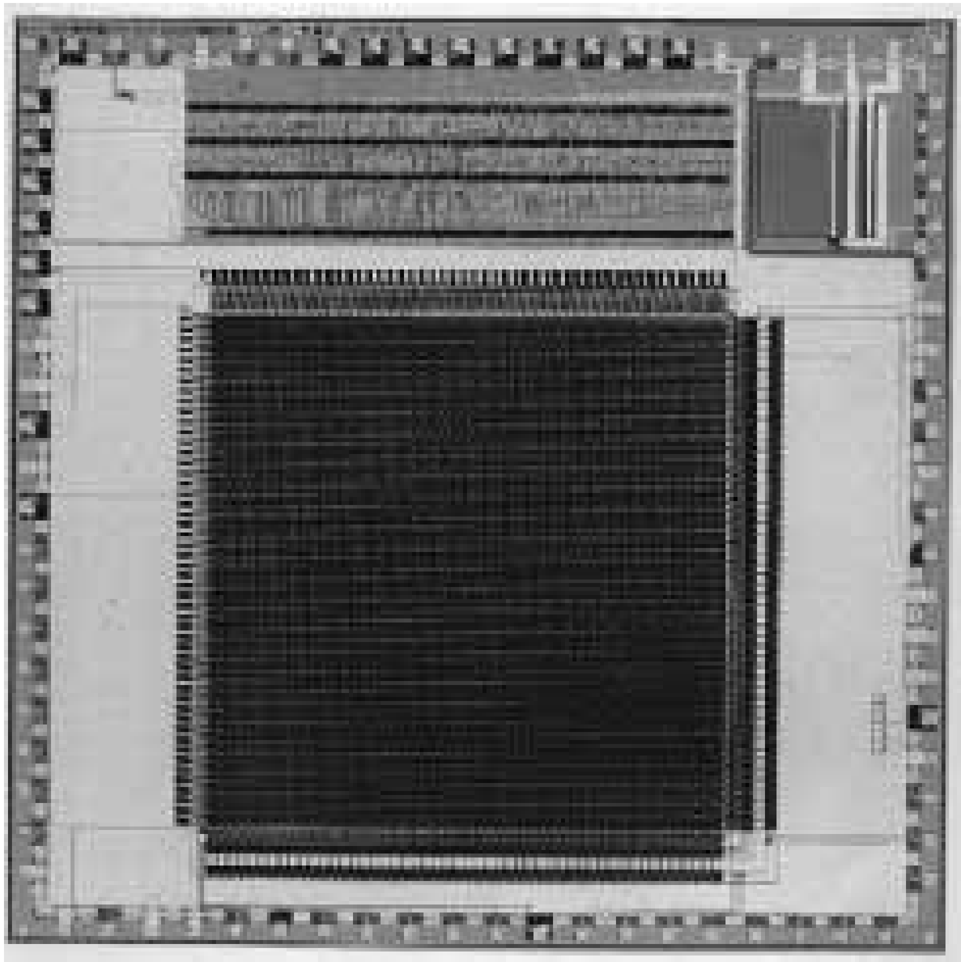
data-communication

doing things in the sides

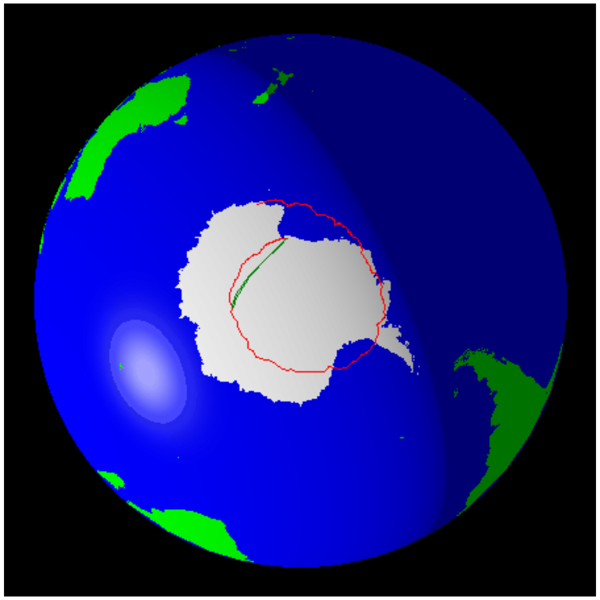




A.G. Andreou, R.C. Meitzler, K. Strohbehn and K.A. Boahen, "Analog VLSI neuromorphic image acquisition and pre-processing systems," *Neural Networks*, Vol. 8, No. 7-8, pp. 1323-1347, 1995.

Flare Genesis Observatory

http://sd-www.jhuapl.edu/FlareGenesis/flare.html



- Balloon based observatory
- Truly autonomous – low bit rate link -
  - A three stage hierarchical system of sun orientation and tracking
  - Two “Eyes” for finding the sun and motion stabilization + Kodak Megaplus CCD camera
- Solar power; command and control power budget ~1W

networks of nodes ….constraints ….

Image sensor constraints (1280x1024 pixels, 24 bit/pixel, 10000 frames/s)

Rates	Scanned	Anisochronous event based
Data rate (Mbits/s)	24,000	variable
Distance (m)	0.01	0.01
Energy per bit (pJ)	20 x (bits/frame)	20
Latency (ms)	0.1 (frame rate)	0.00001 (pixel)

RF link constraints

Rates	UWB (Multiband OFDM)	COTS (Chipcon 24xx)
Data rate (Mbits/s)	200	1
Distance (m)	10	100
Energy per bit (nJ)	10	100
Latency (ms)	0.01	100s

analog, digital and all that …

CVDT

Continuous-Value
Discrete-Time

CCD
Switched Capacitor

CVCT

Continuous-Value
Continuous-Time

Linear and non-linear analog

Binary digital
Multivalue digital

Discrete-Value
Discrete-Time

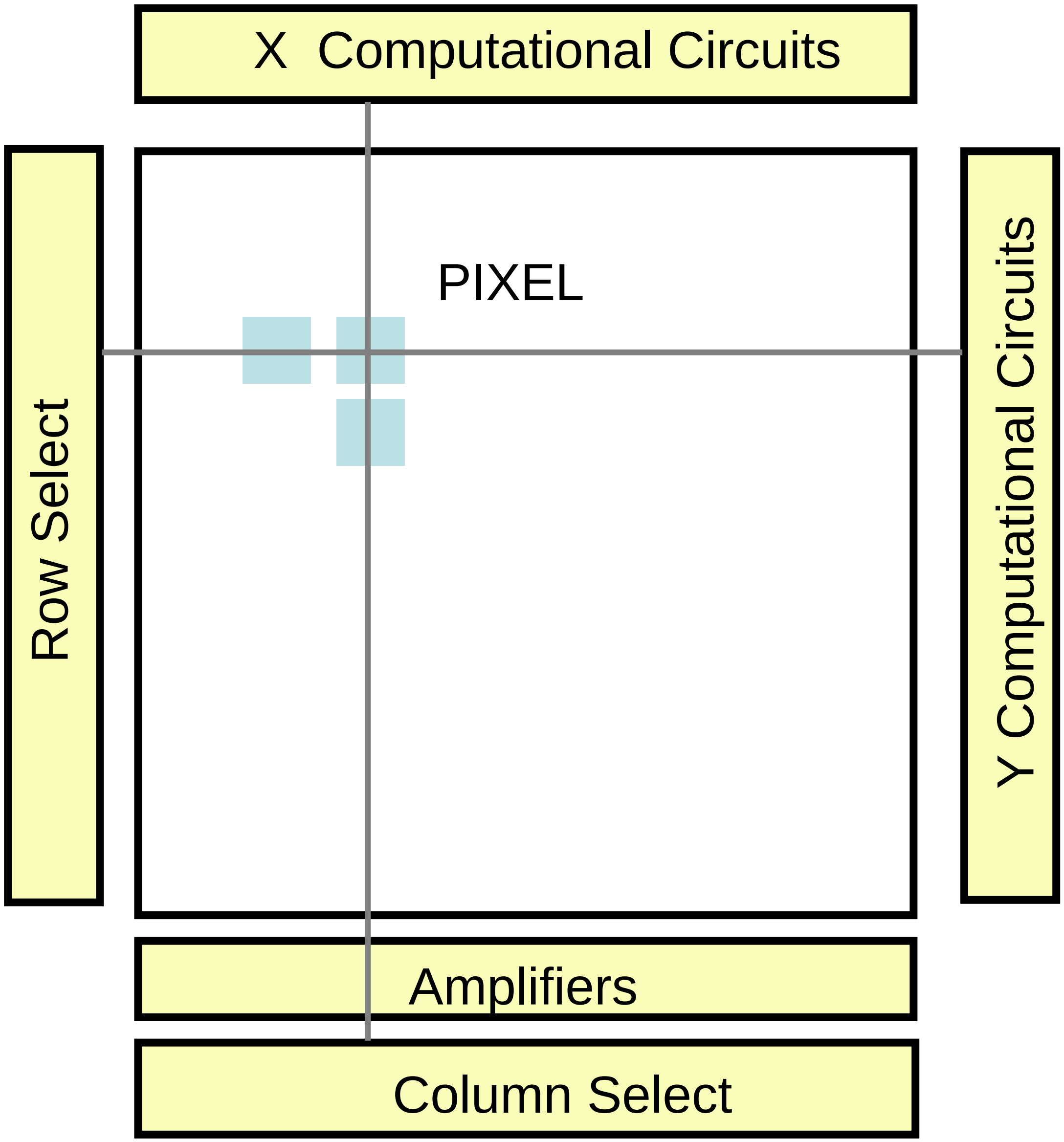
DVDT

Asynchronous digital
Neuron spikes
Anisochronous Pulse Time Modulation

Discrete-Value
Continuous-Time

DVCT

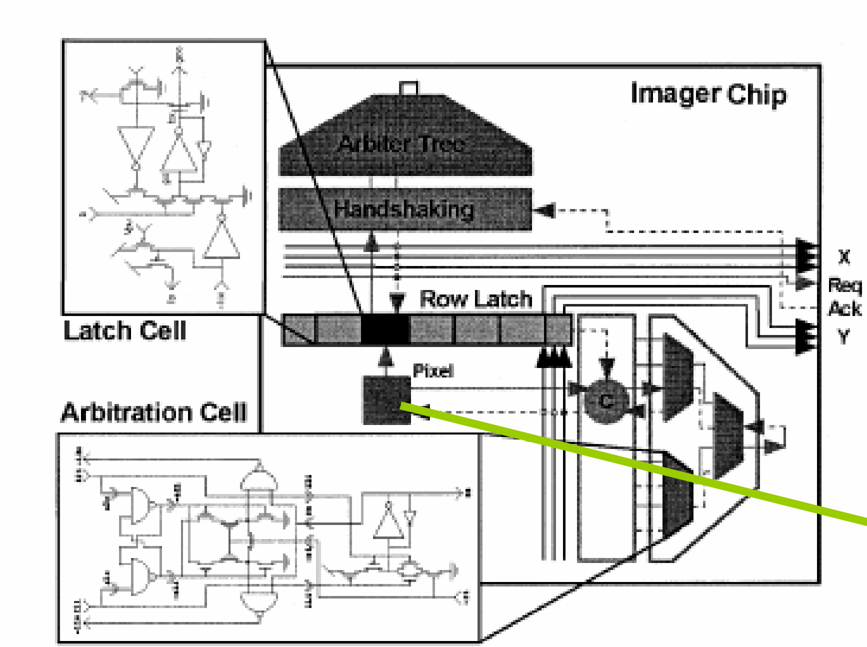
event based systems



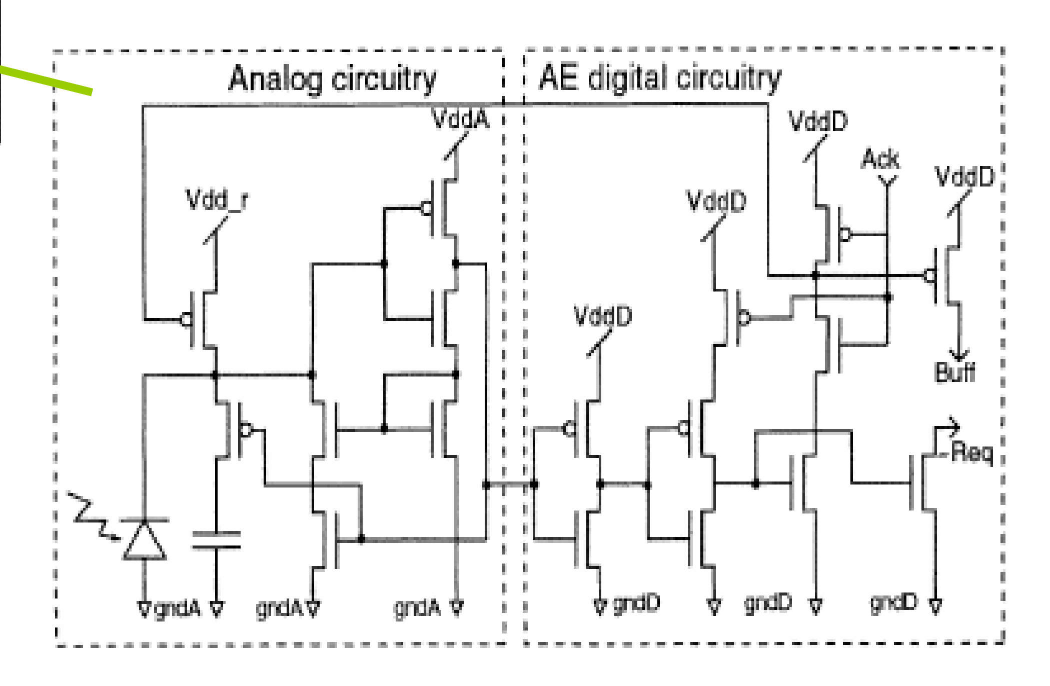
Pixel:
transduction
amplification
gain control
quantization
non-uniformity correction
spatial filtering
temporal filtering

Periphery:
ego-motion
moments
global contrast
data-communication

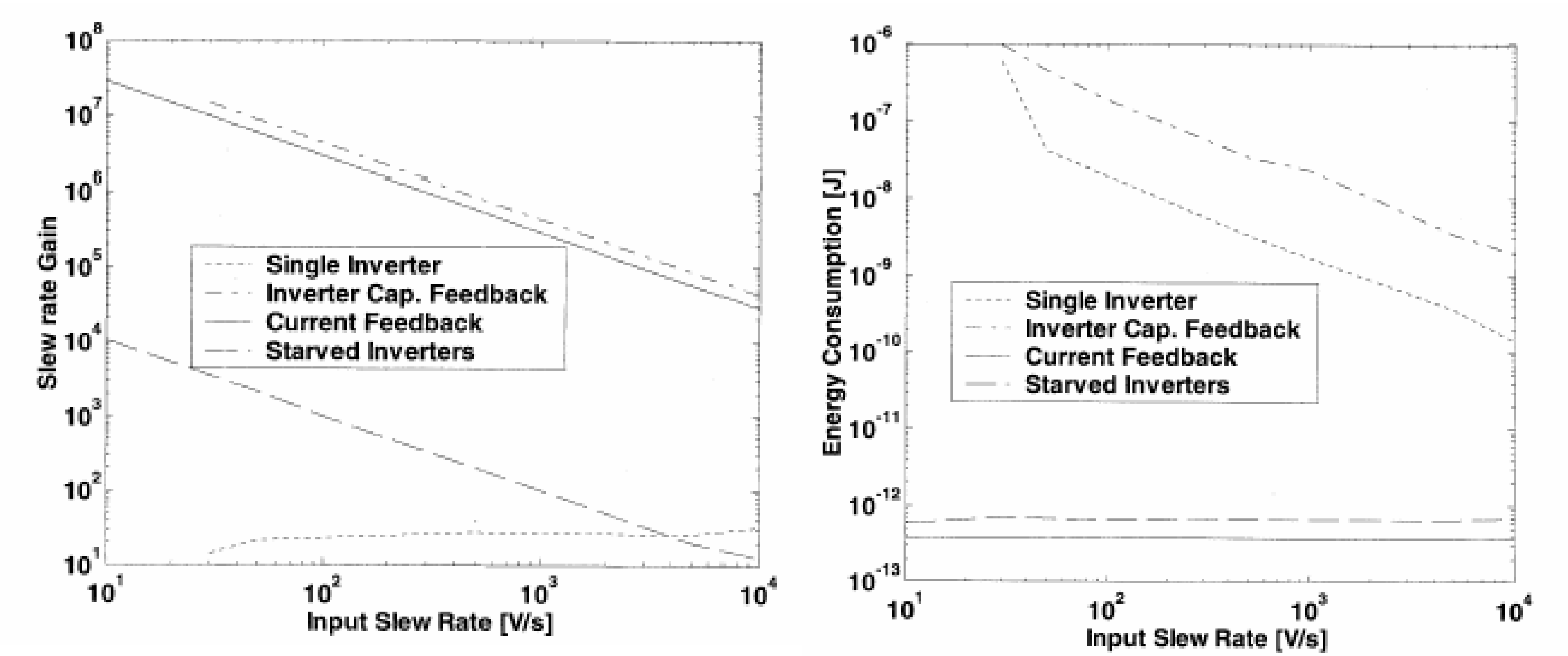
digital event based imager



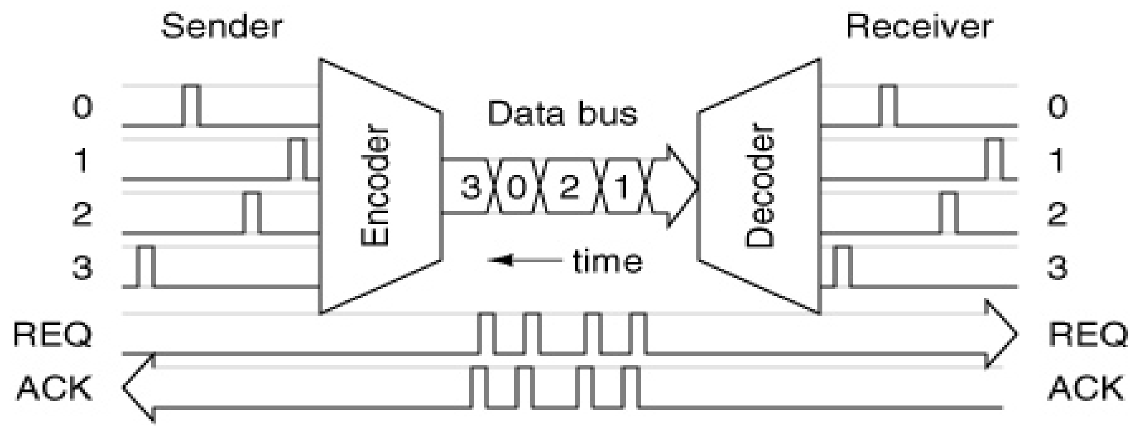
K. A. Boahen E. Culurciello, R. Etienne-Cummings, "A biomorphic digital image sensor," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 2, pp. 281 –294, February 2003.

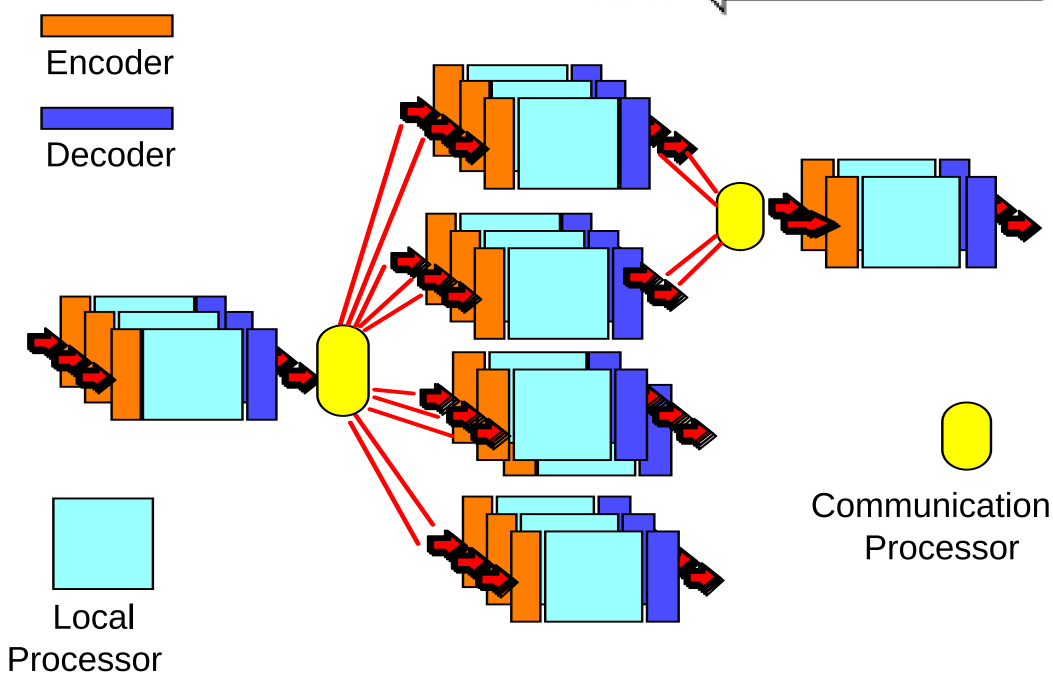


high slew rate gain at low energy costs



the network is the architecture



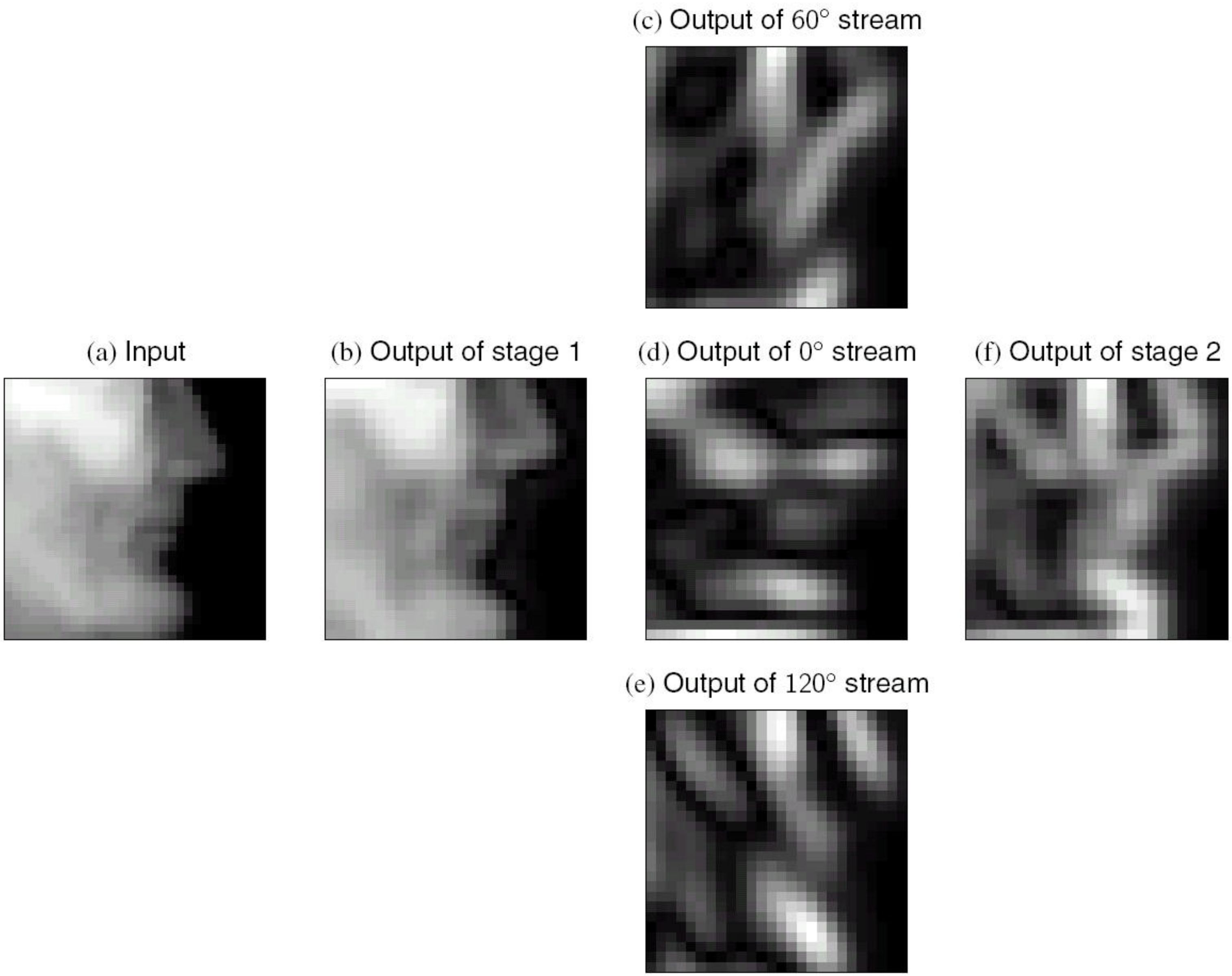


ALL COMPUTATION DONE ON THE ADDRESSES OF THE EVENTS

distributed network processing

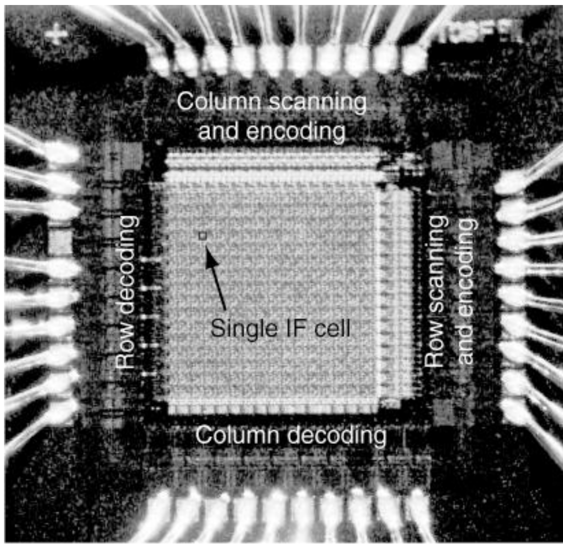
- Information is encoded in a stream of events, the address of each pixel node
  - Address Event Representation
  - Asynchronous on demand
- Programmable communication processors transform and route the events
- Local Processors perform spatial/temporal integration and normalization
- Point-to-point and broadcast links provide high speed interconnects

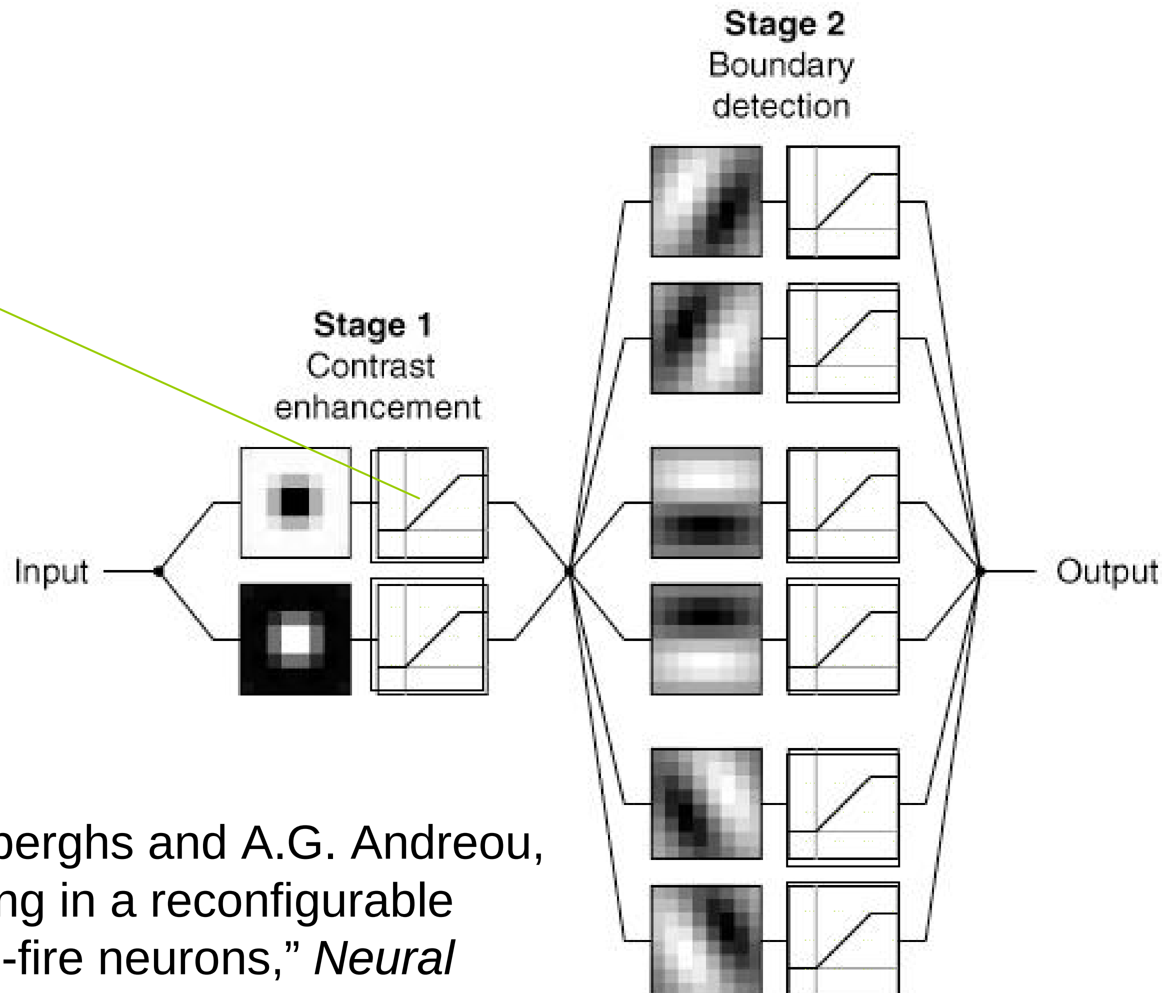
simulation …


(c) Output of 60° stream
(a) Input
(b) Output of stage 1
(d) Output of 0° stream
(f) Output of stage 2
(e) Output of 120° stream

feature extraction through projective fields

Think of computation as
part of the MAC layer

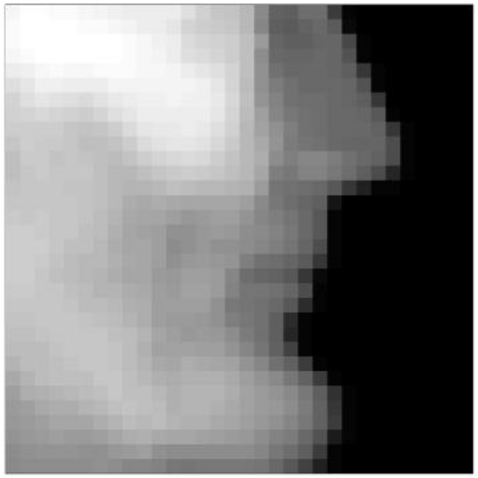




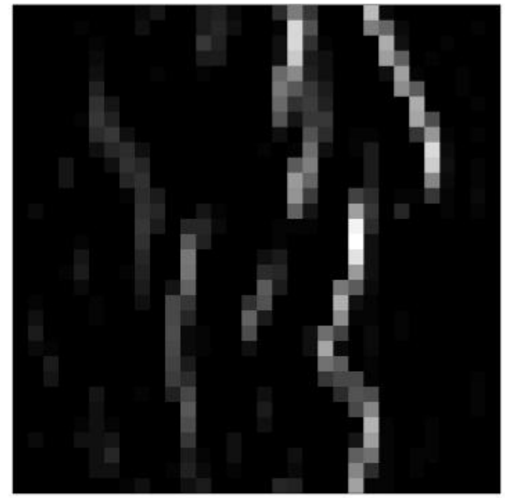
D.H. Goldberg, G.C. Cauwenberghs and A.G. Andreou, "Probabilistic synaptic weighting in a reconfigurable network of VLSI integrate-and-fire neurons," *Neural Networks*, Vol. 14, No. 6-7, pp. 781-793, July 2001

results

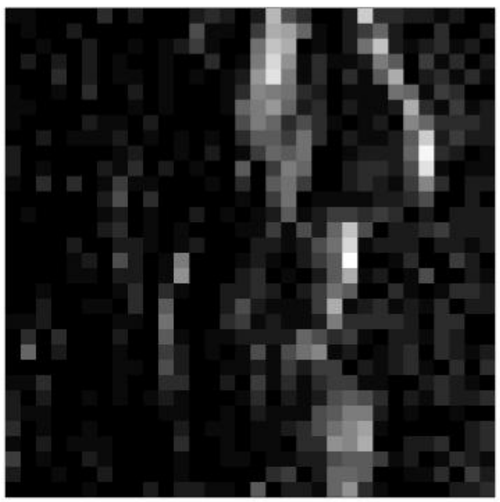
Input



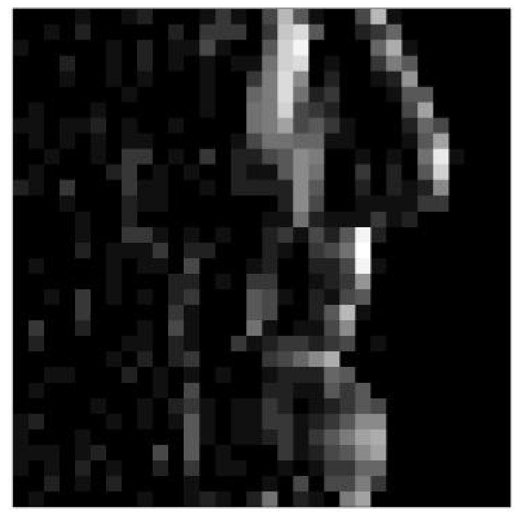
Rectifed
Laplacian
(Matlab)



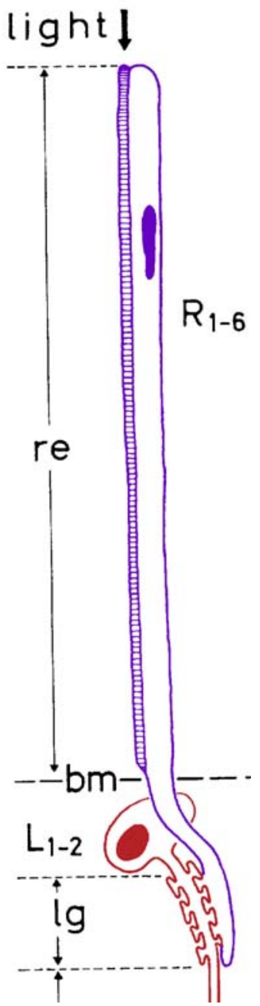
PrAER
chip

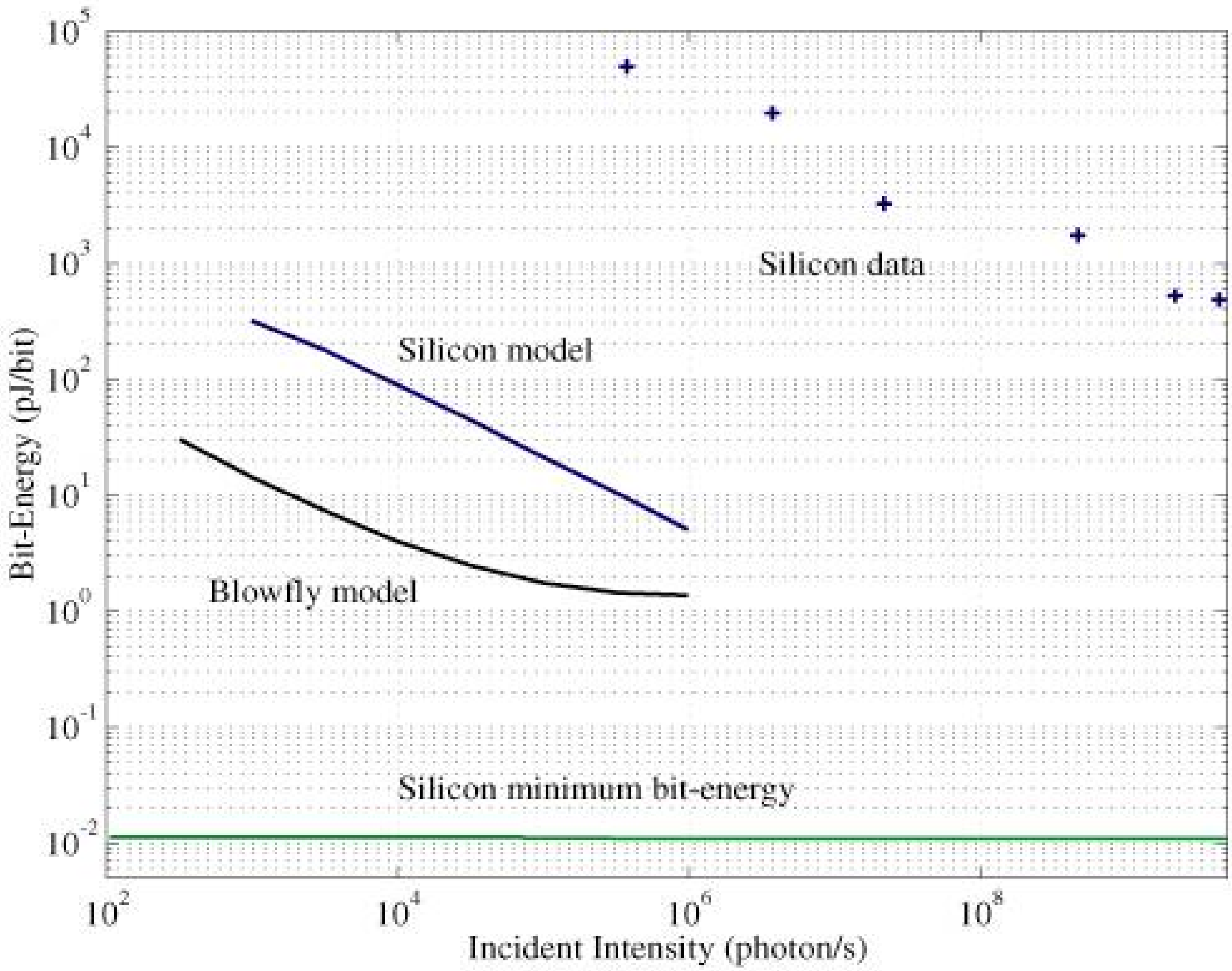


PrAER
(Matlab)



and something about biology: blow-fly photoreceptor





P.A. Abshire and A.G. Andreou, "Capacity and energy cost of information in biological and silicon photoreceptors ," *Proceedings of the IEEE*, Vol. 89, No. 7, pp. 1052-1064, July 2001.

some final thoughts

- One size perhaps does not fit all!
- With multiple interacting points of view, is worth revisiting "polarization vision".
- Asynchronous on demand systems may be preferable to random access or scanned for giving information to the question: "is there anything of interest out there ?"
- CMOS imagers can be cheap and can be designed to specific applications; 0.5 micron CMOS may be a sweet spot for garden variety "eyes".
- Increased physical complexity; more than just visible; large area sensor devices conformal to non planar surfaces.
- What good are "eyes" without optics or when they can't move?…. Good questions! "eye" designers have plenty things to do.

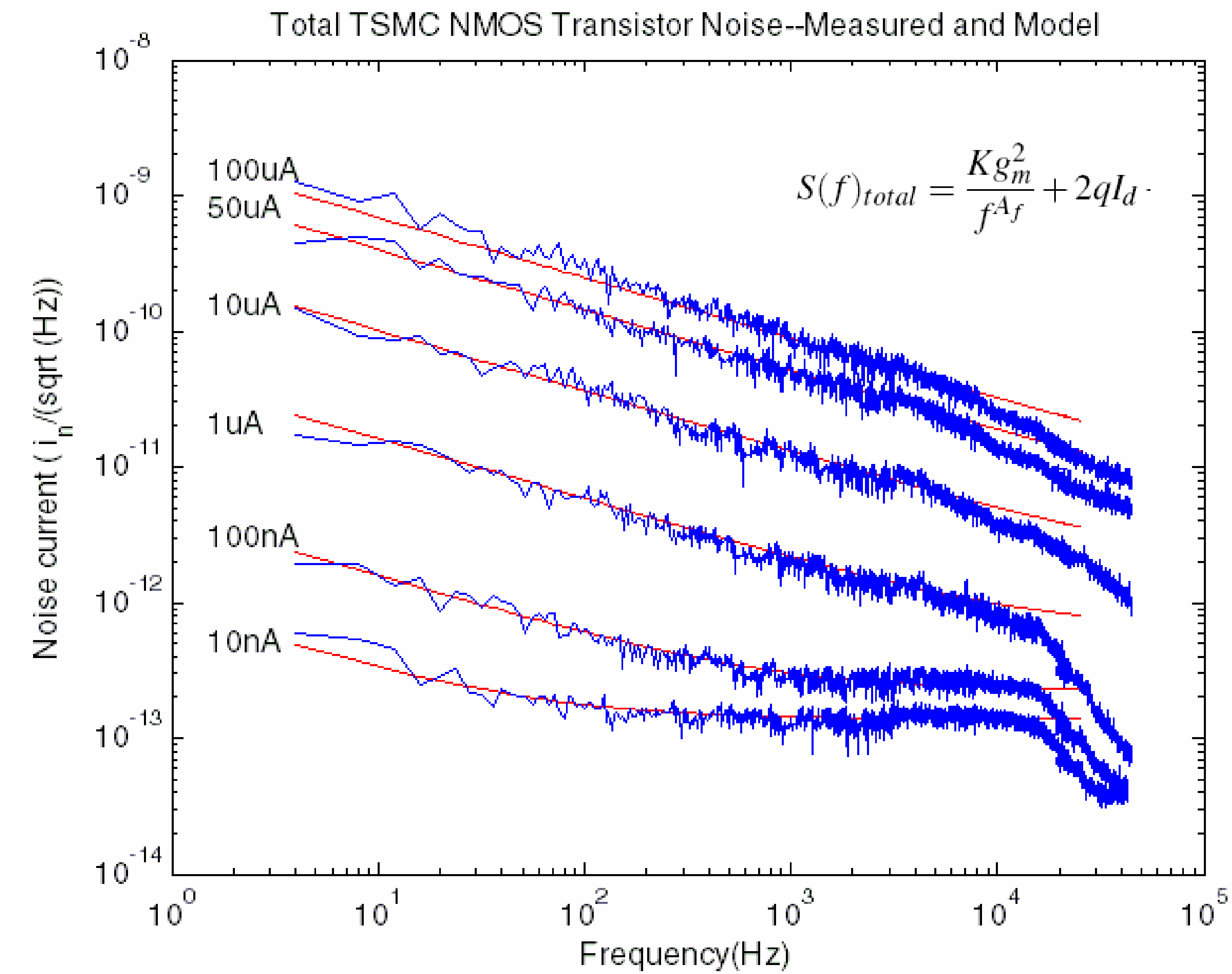
acknowledgments:

- DARPA N0014-00-C-0315 *Acoustic Microsensors*
- NSF-ECS-0010026: *Microscale adaptive optical wavefront correction*
- NSF-EIA-0130812: *A comparative study of information processing in biological and bio-inspired systems: performance criteria, resources tradeoffs and fundamental limits.*
- NVSED *Smart focal planes*

Philippe Pouliquen
Rich Meitzler
Zaven Kalayjian
Pamela Abshire
Kwabena Boahen
Marc Cohen
Bernabe Linares Barranco

Teresa Serrano
Kim Strohbehn
Larry Riddle
Gert Cauwenberghs
David Goldberg
Pedro Julian
Pablo Mandolesi
Eugenio Culurciello

subthreshold CMOS challenges: noise



energy costs per pixel

$P: power \quad (Watts)$

$\xi: pixel\ activity\ factor$

$N: number\ of\ pixels$

$N_{\mathrm{ker}\,nel}: number\ of\ pixels\ in\ the\ computational\ \mathrm{ker}\,nel$

$I_{bg}: mean\ photocurrent\ (A)$

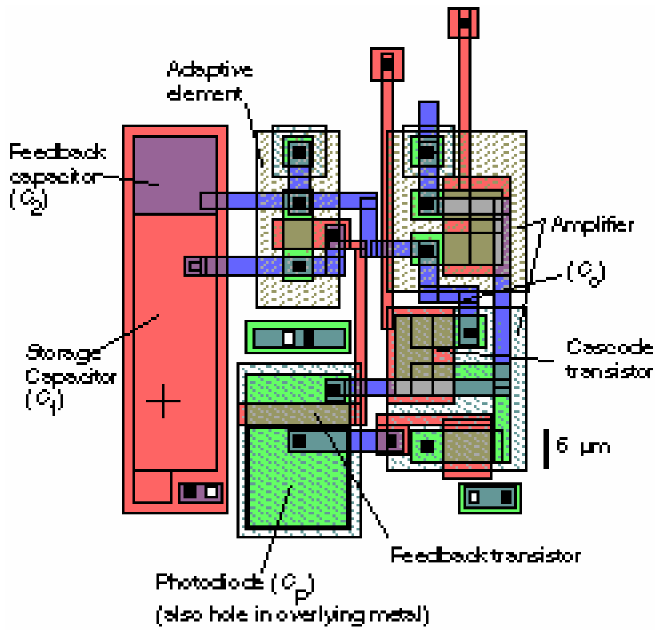
$I_{comp}: computational\ branch\ current\ (typically\ 10-100nA)$

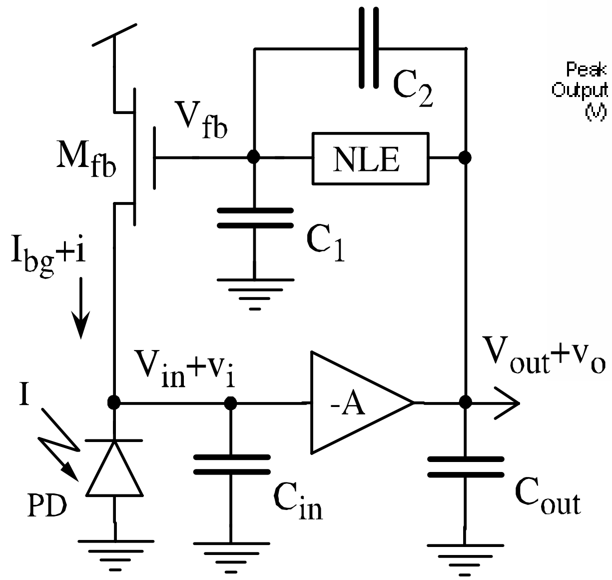
$V_{pd} = V_{scale}: phototransduction\ branch\ voltage\ (typically\ (0.3) = 0.3\,Volts)$

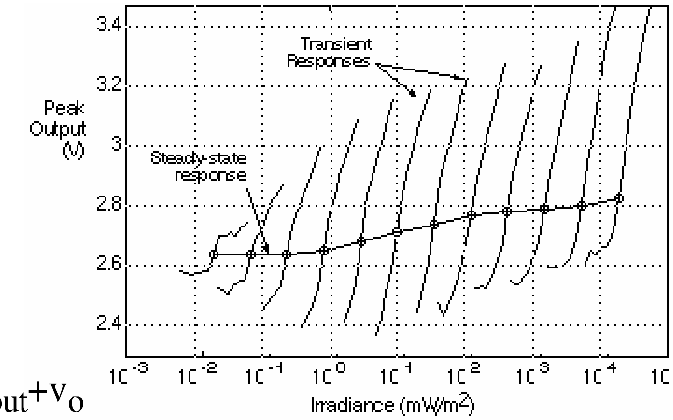
$V_{comp} = V_{scale} + V_{sat}: computational\ branch\ voltage\ (typically\ (0.3+0.2) = 0.5\,Volts)$

- Bandwidth scales linearly with computational branch current
- Power will scale linearly with computational branch voltage

Transduction and Dynamic Range Compression (I): Temporal







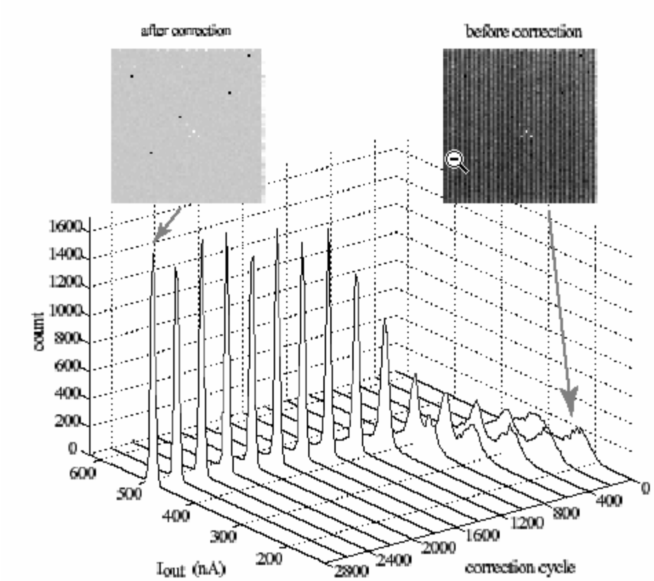
Delbruck and Mead 96

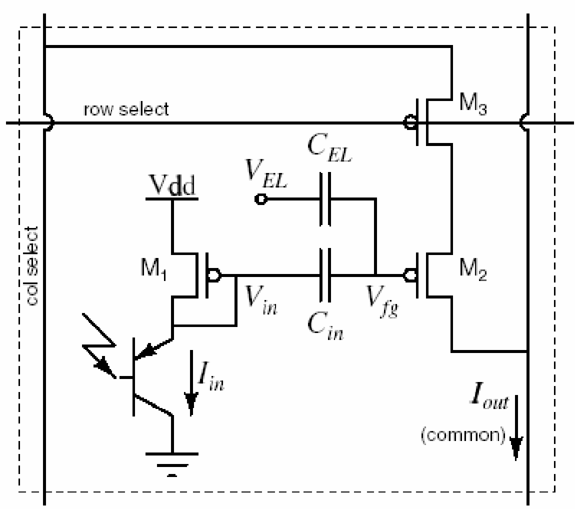
1. Average signal in time and store the state -range- on a quasi floating gate (Vfb)
2. Employ negative feedback to position the DC operating point.
3. Amplifier-computational branch-: single stage biased in substhreshold (100nA)

$$P = (\xi I_{bg} V_{pd} + I_{comp} V_{comp}) N$$

$$(0.1 \times 10^{-8} \times 0.3 + 10^{-7} \times 1) = 10^{-7} W \quad per \quad pixel$$

Non-Uniformity Correction Using FGMOS





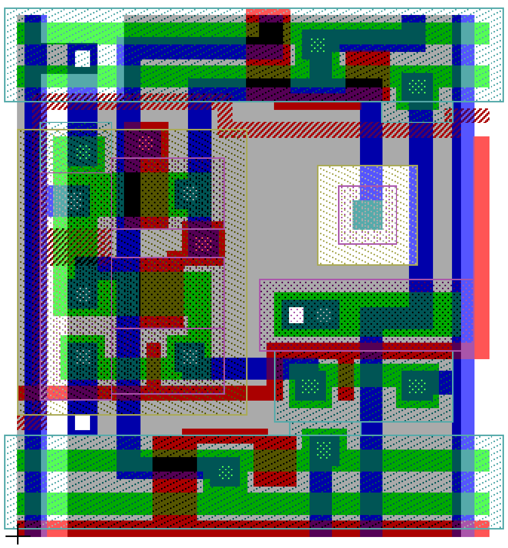
Cohen & Cauwenberghs 2001

- An MOS mirror with FGMOS transistor (M2) injected using impact ionization (tunneling will work as well).
- NO power cost during operation.
- Technique can be applied to both current mode and voltage mode pixels
- Energy cost only with initial calibration
- Calibration takes ~2000 iterations for all pixels on the chip and each pixel takes about 1sec

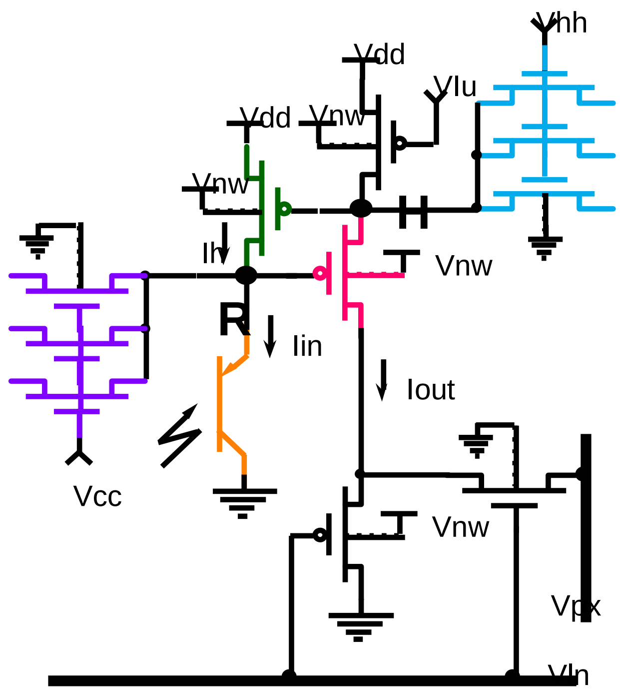
$$E_{adapt} = P \times T = N \times (I_{in} V_{pd} + I_{out} V_{comp}) \times T$$
$$= (10^{-8} \times 0.3 + 10^{-8} \times 10) \times 1$$
$$= 10^{-7} \quad Joules \quad per \quad pixel$$

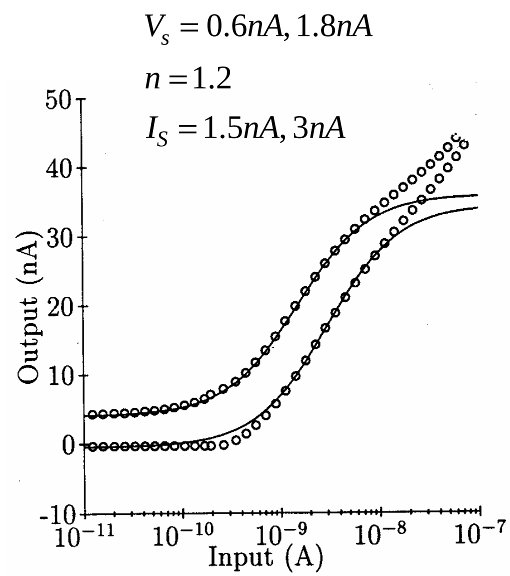
Transduction and Dynamic Range Compression (I): Spatial -network based-

1. Average using a shunting network
2. Employ negative feedback and log-antilog amplifier to do the ratio computation
3. Note! kernel size does not matter as we normalize everything to the computational current and this gets steered from one pixel to the other.
4. Compression function not *tanh* but something that can be synthesized in CM circuits!



Boahen and Andreou 92



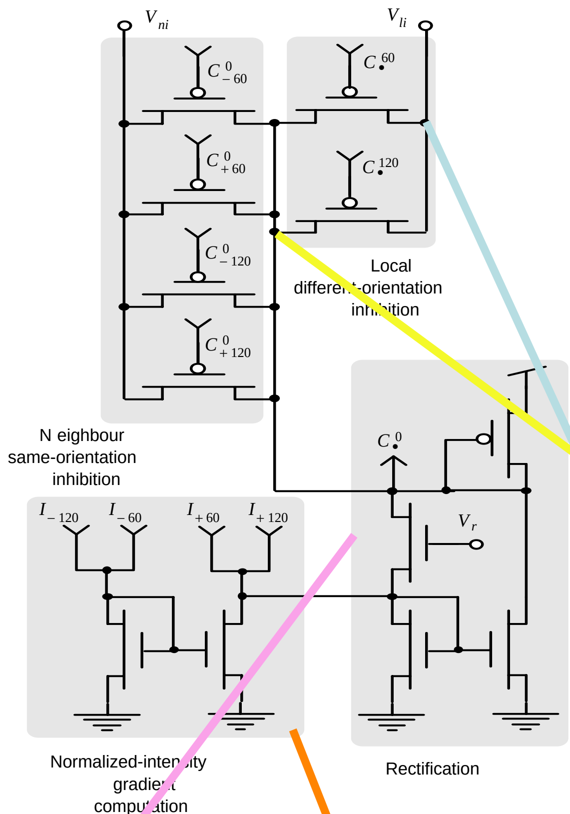


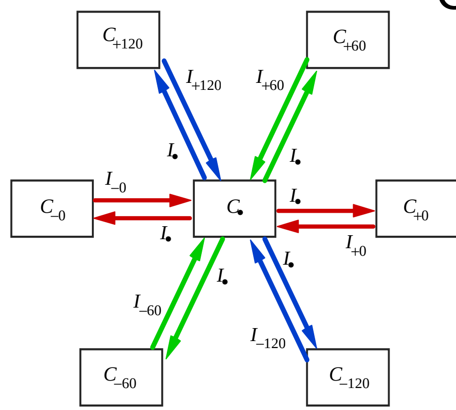
$$I_{out} \rightarrow I_{comp} \qquad I_{in} \rightarrow I_{bg} \qquad P = (\xi I_{bg} V_{pd} + I_{comp} V_{comp}) N$$

$$\frac{V}{V_s} = \frac{I^n}{I^n + I_s^n}$$

Center-ON-OFF surround with local competition and rectification

Cauwenberghs and Waskiewicz 1999





1. An alternative to resistive grids we can explicitely compute the Laplacian using simple scaled mirrors and summing the currents.
2. Added local wiring complexity

$$C^0_\bullet = \left| \left(I^0_{+60} - I^0_{-60} \right) + \left(I^0_{+120} - I^0_{-120} \right) \right| - \alpha \left(C^{60}_\bullet + C^{120}_\bullet \right) - \beta \left(C^0_{+60} + C^0_{+120} + C^0_{-60} + C^0_{-120} \right)$$

$$P = (\xi \times 4 \times I_{comp} V_{comp}) N \qquad (4 \times 10^{-8} \times 1) = 10^{-7} W \quad per \quad pixel$$