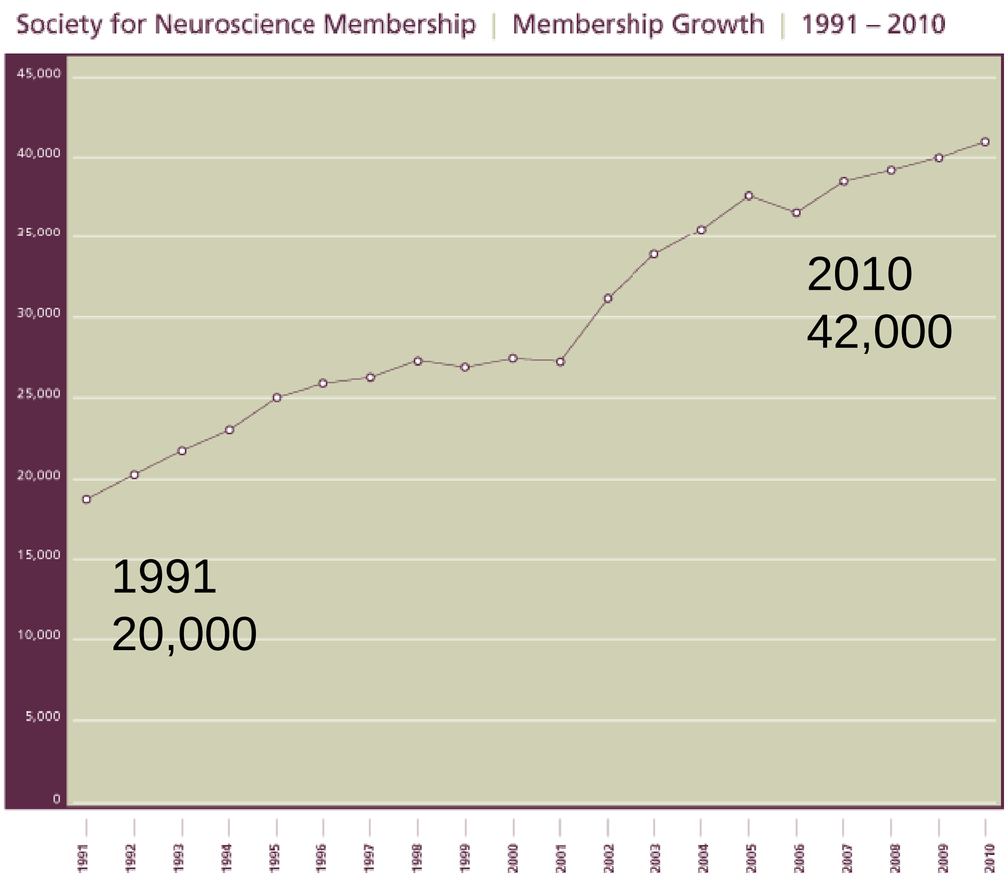
Prising the secrets of energy efficiency out of brains

Simon Laughlin
Department of Zoology
University of Cambridge UK

Principles of Neural Design,
P Sterling, S B Laughlin
MIT Press due Fall 2012

Neuroscience is BIG



Information Processing in Neural Circuits

- Identified neurons
- In intact circuits
- Relate signals to behavioural performance

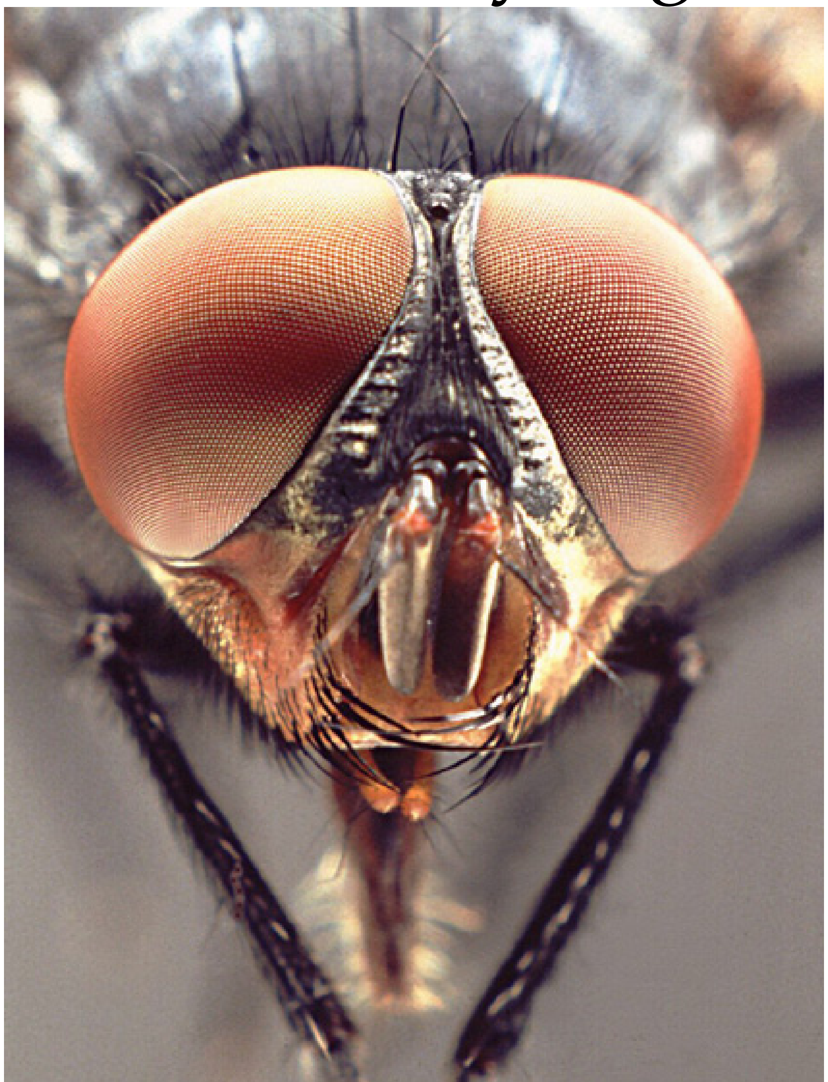
<u>Answer</u>

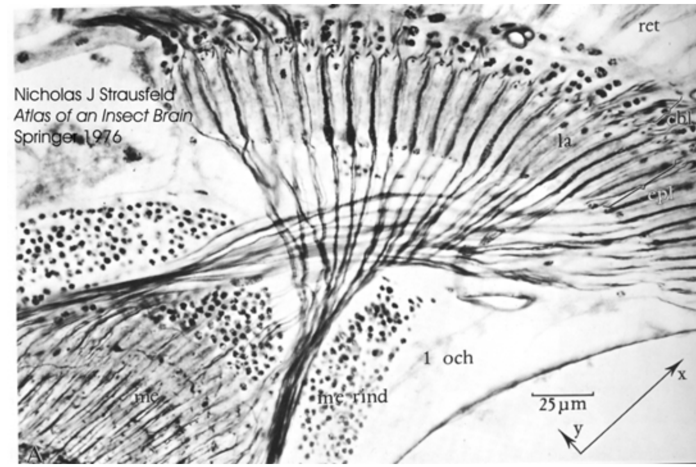
1. What?
2. How?
3. Why?

<u>See</u>

Design

Flies' compound eyes – model systems for analysing neural circuit design





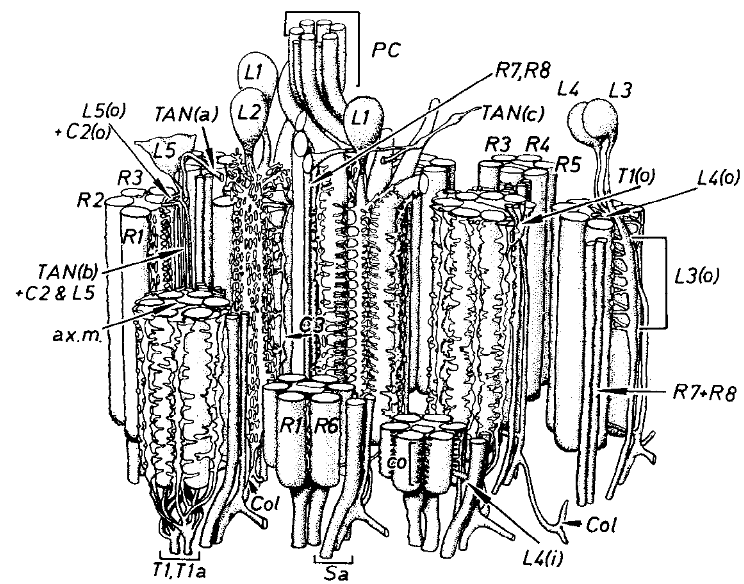
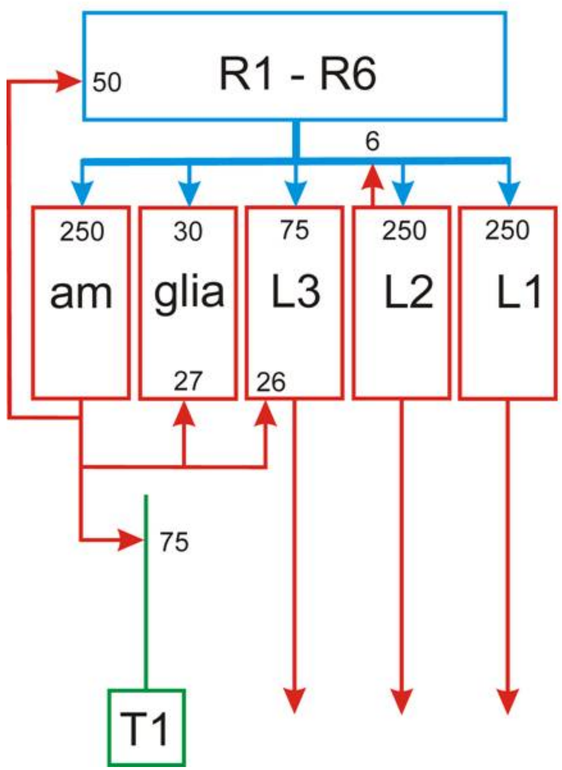
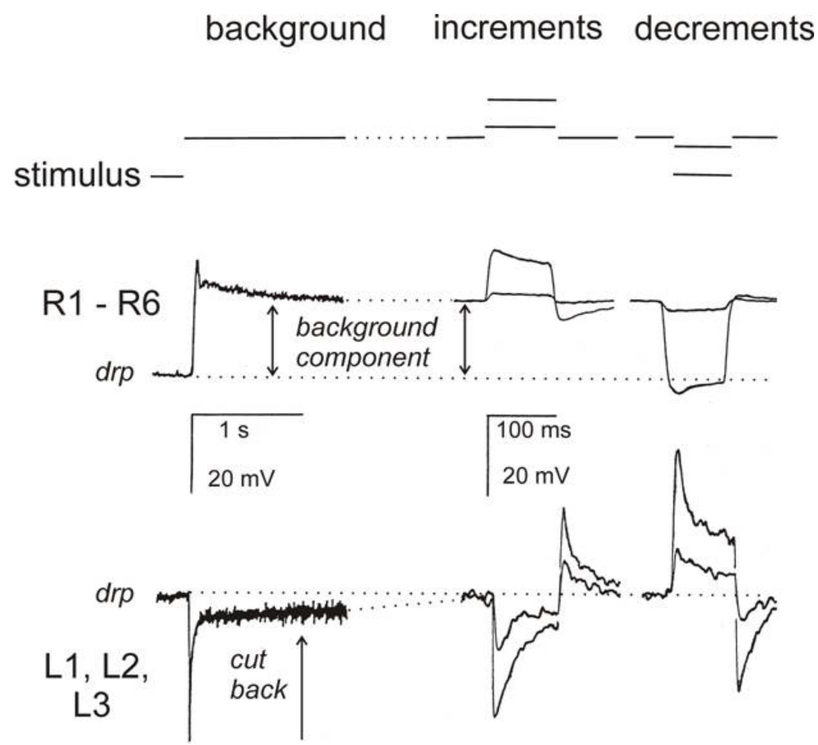


Fig. 1b.

Circuits and signals - fly compound eye





analogue signals

Secret 1

Mix analogue and pulsatile

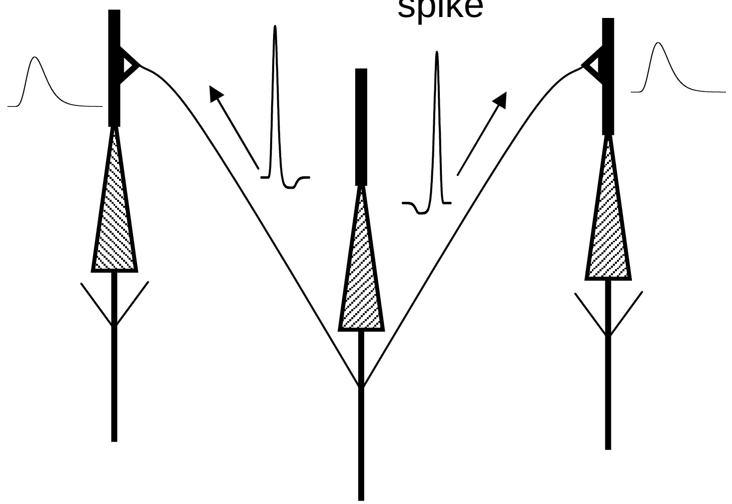
Hybrid computation *(mixing analog & pulsatile)* contributes to Energy Efficiency

Rahul Sarpeshkar, MIT

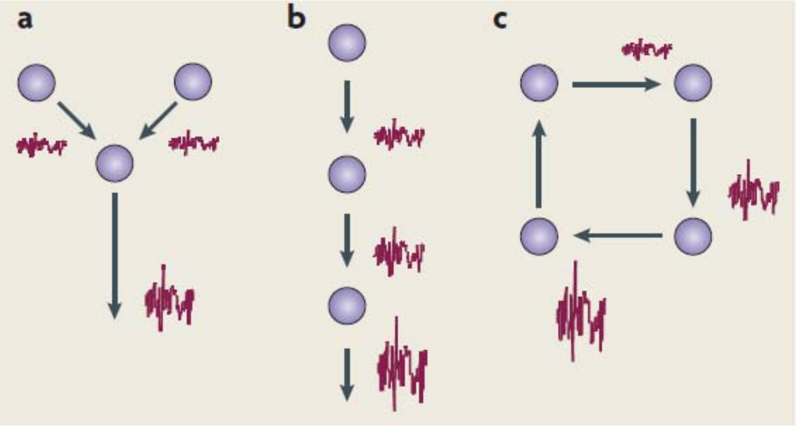
Sarpeshkar, R. *(1998). Analog versus digital: Extrapolating from electronics to neurobiology. Neural Computation* ***10****, 1601-1638*

His book *Ultra low power bioelectronics, C.U.P. 2010*

Independently reaches many of the conclusion of my talk



pyramidal neurons



stop noise accumulating

use efficient analogue operations to process information directly at nodes *(rich analogue primitives)*

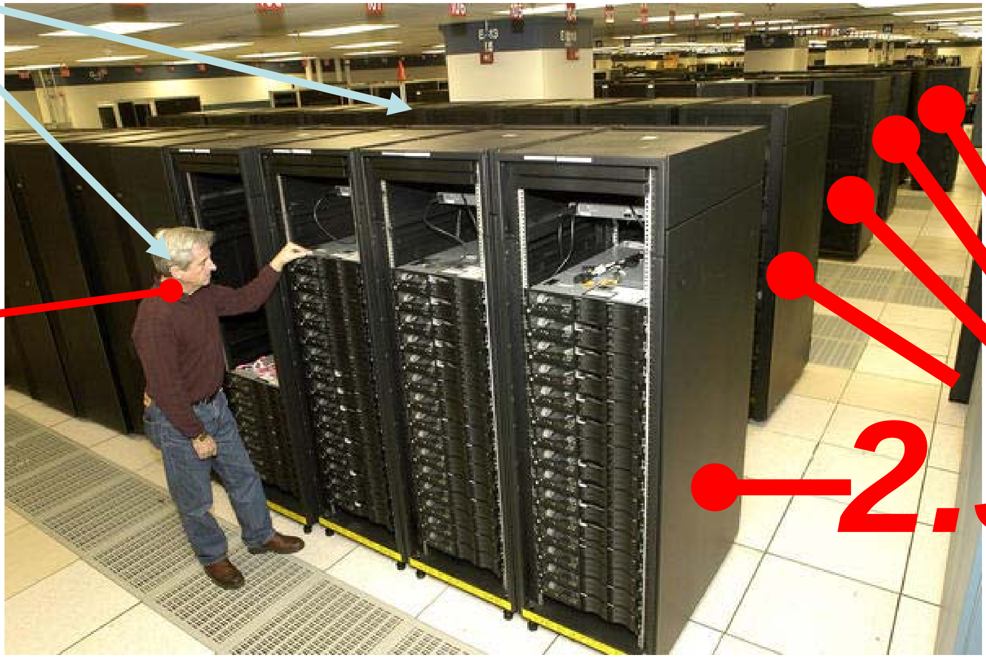
Question

Are brains efficient?

“Joe” with IBM Road Runner Supercomputer (2007)

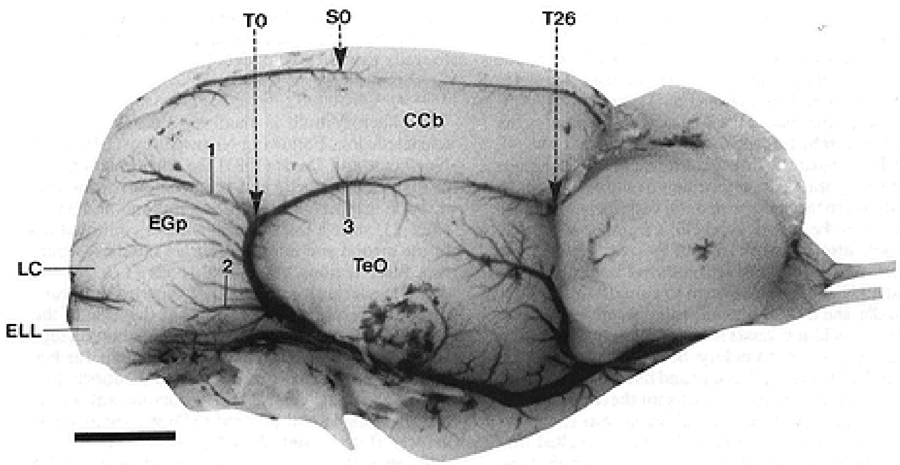
10^{15} events s^{-1}

20 watts



2.36 MW

Allocating
Materials and Space

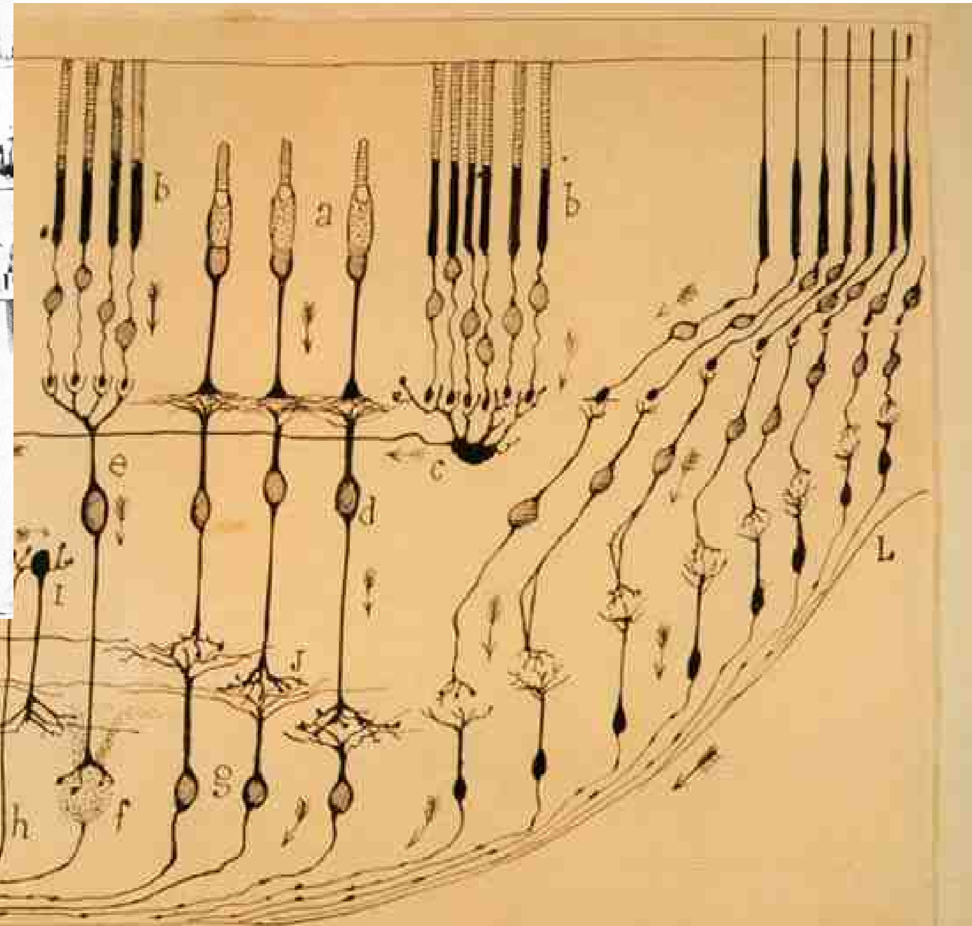


Electric fish brain

Naked mole rat

Secret 2

Allocate resource
according to need

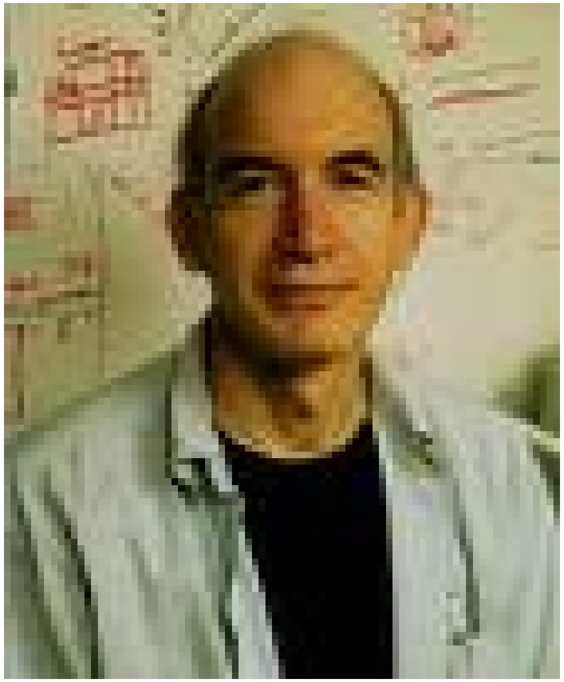


Adaptations that conserve ***space, materials, time***

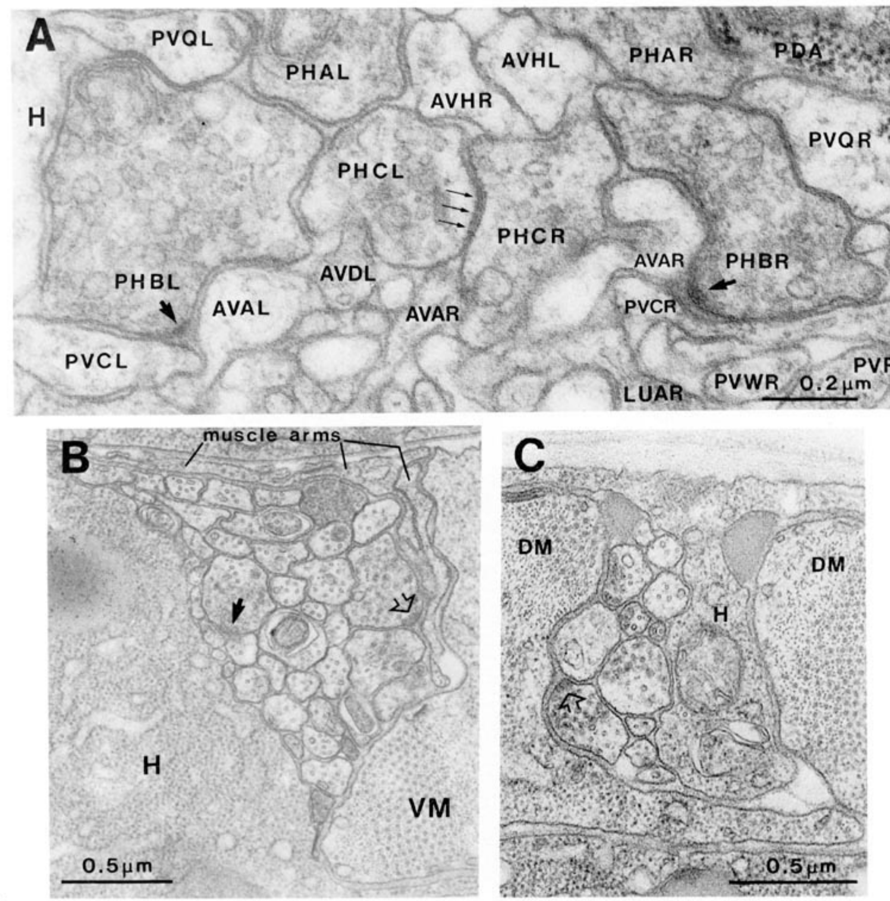
S.R. y Cajal Institute - CSIC - Madrid, Spain.

Minimal rationality

Christopher Cherniak

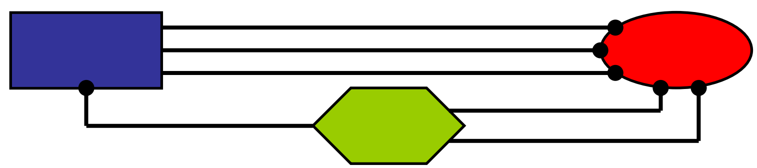


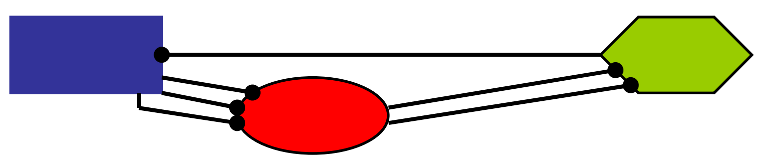
C elegans (aka “The Worm”)



Efficient layout reduces wiring costs

High wiring cost

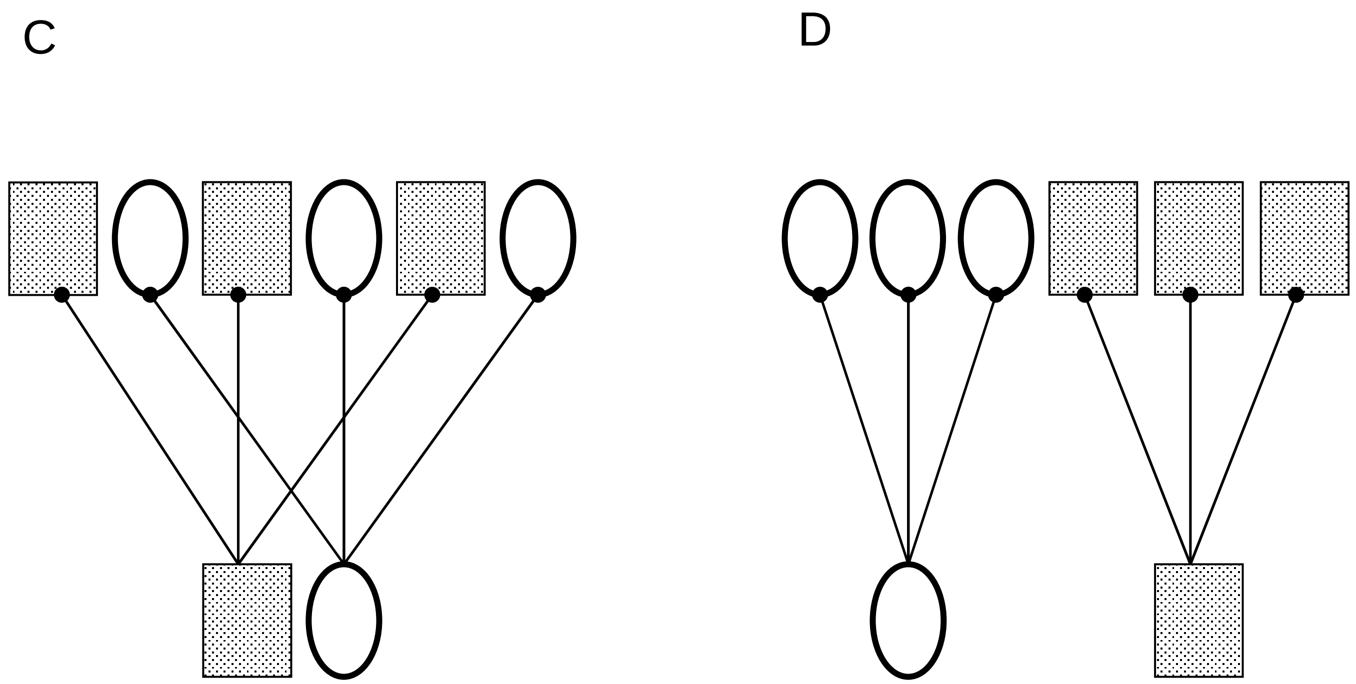




Low wiring cost

After Cherniak, 1992

Segregating neurons according to function reduces wire length



Mitchison 1992

Secret 3

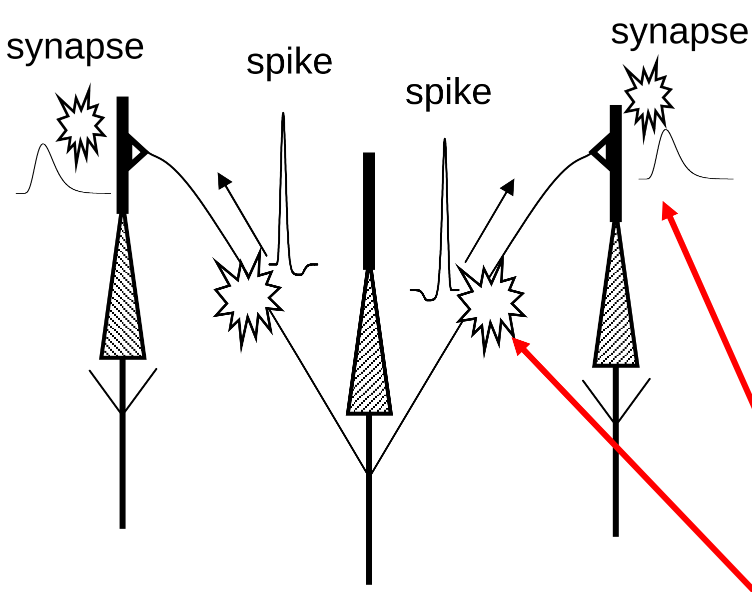
Minimise wiring costs

Brains are wired efficiently
Allocate materials efficiently

Do they need to be
Energy Efficient?

Brains need to be energy efficient because demand is high enough to limit signal traffic

Major sites of energy use



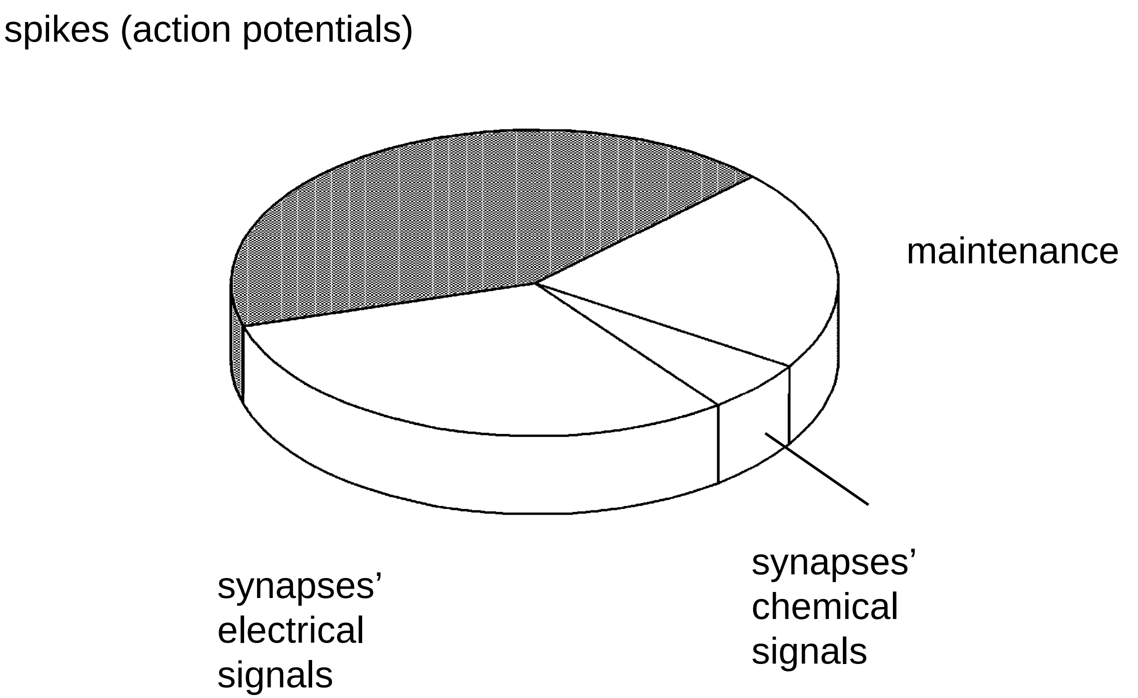
pyramidal neurons

The energy consumed by cerebral cortex
limits cortical signal traffic
to 1 – 10 spikes/neuron/sec

Attwell & Laughlin 2001

drive membrane resistance
charge membrane capacitance

Distribution of energy costs



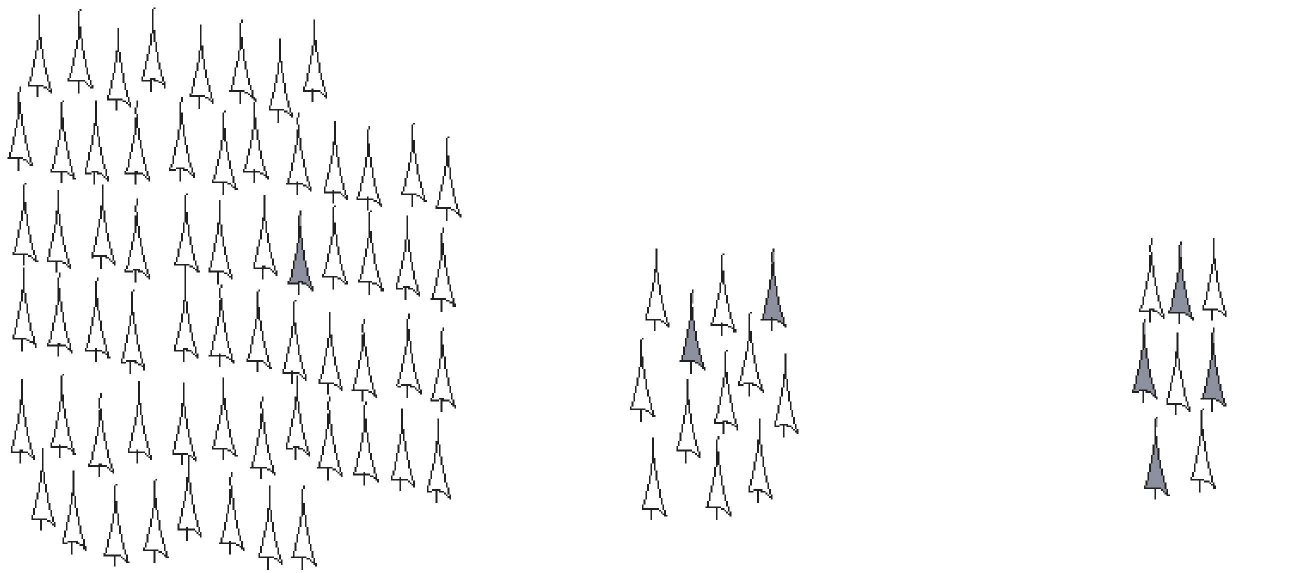
electrical – expensive
chemical - cheap

Secret 4

Distribute signals
sparsely

sparse coding is energy efficient

(after Levy & Baxter, 1996)



	1 active, 63 at rest capacity = 64			2 active, 10 at rest capacity = 66			4 active, 4 at rest capacity = 70		
	costs			costs			costs		
cost ratio signalling:fixed	signalling	fixed	total	signalling	fixed	total	signalling	fixed	total
100:1	100	64	***164**	200	12	212	400	8	408
10:1	10	64	74	20	12	***32**	40	8	48
5:1	5	64	69	10	12	***22**	20	8	28
1:1	1	64	65	2	12	14	4	8	***12**

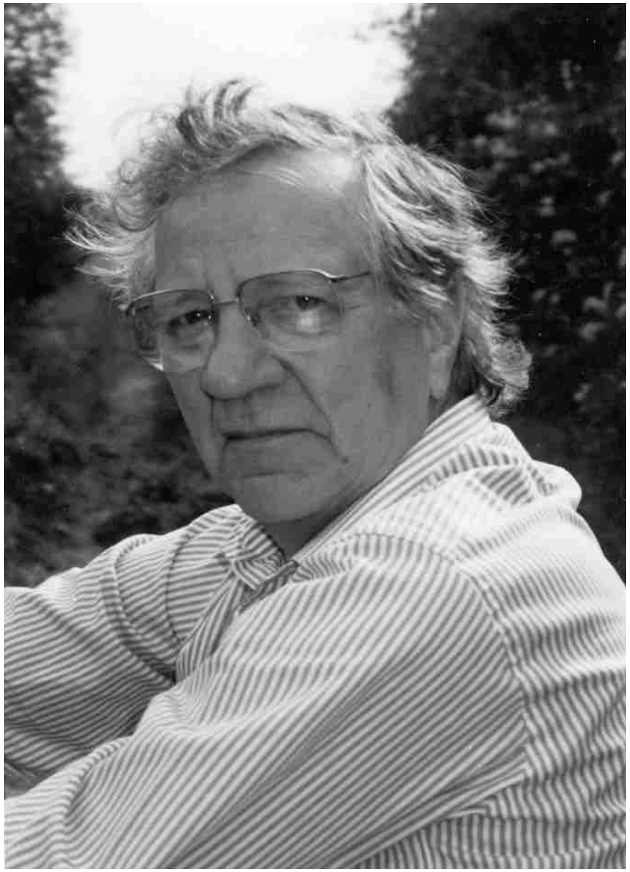
Secret 5

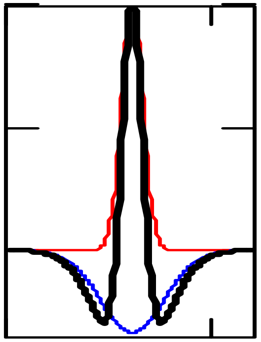
Send only what is needed

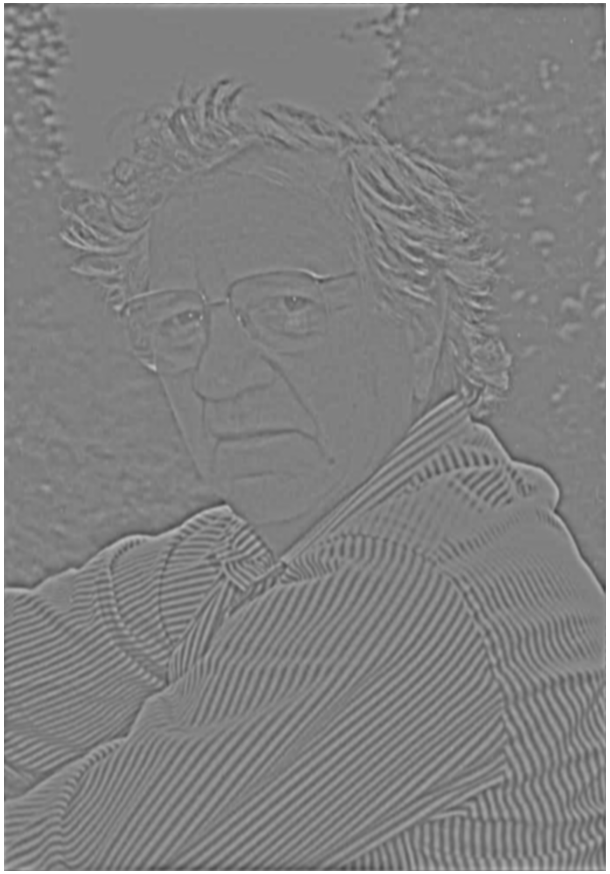
"The neat packaging of information"

Horace Barlow 1961

redundancy reduction as a goal of early sensory processing

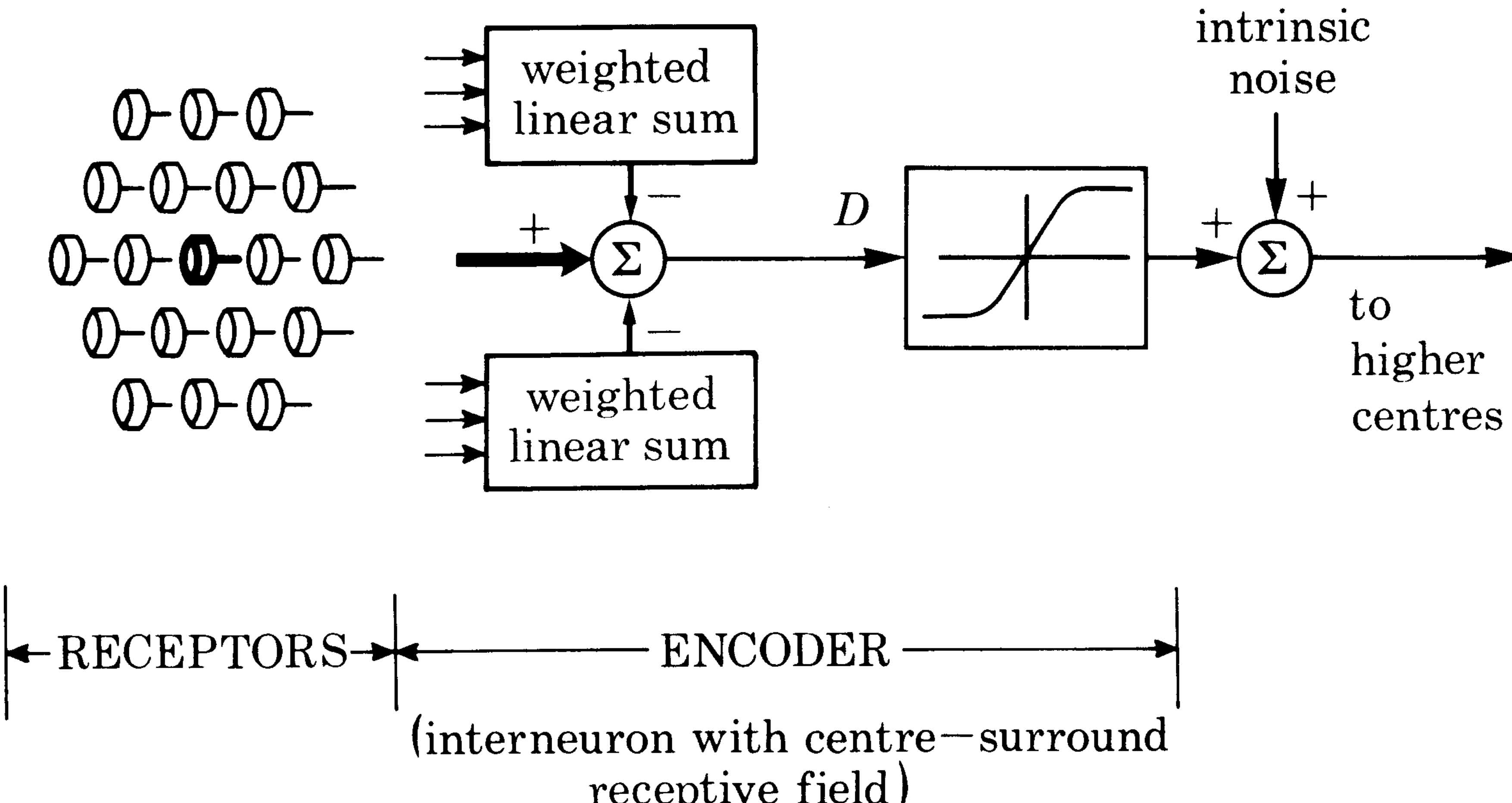






Predictive coding

Srinivasan, Dubs and Laughlin, 1982

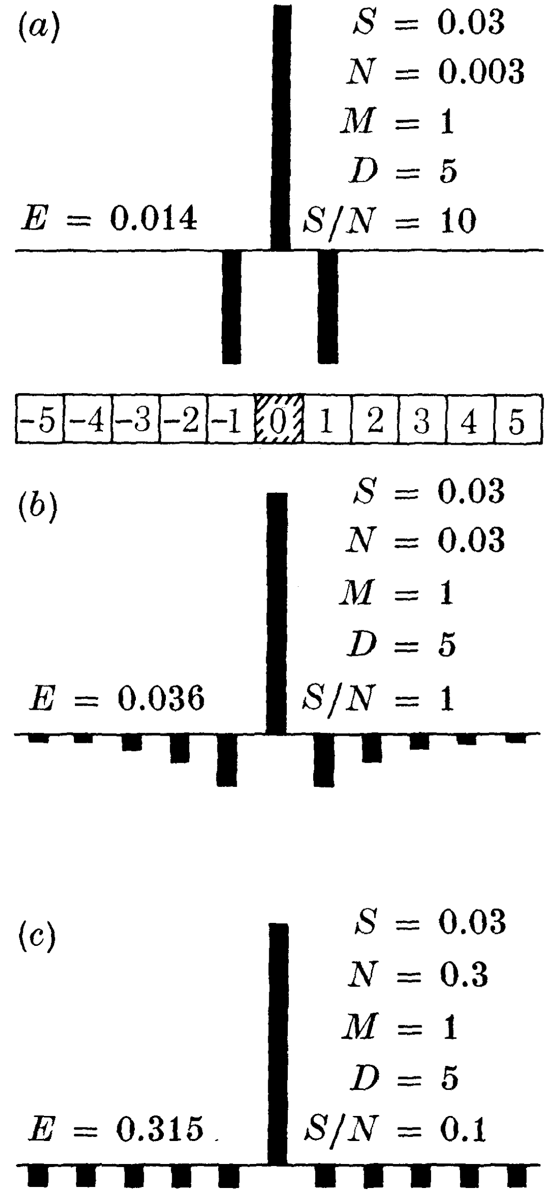


THEORY

(Srinivasan, Dubs and Laughlin, 1982)

Predictive coding requires an intensity dependent surround

Take wider samples when input is unreliable (photon noise)



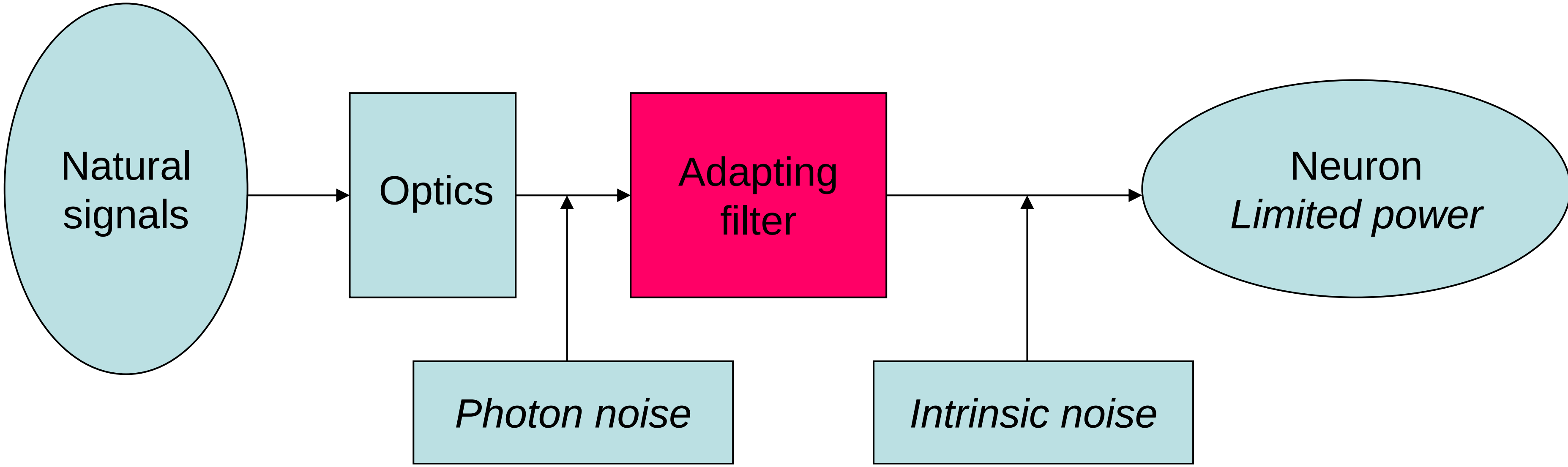
Hi S/N

Lo S/N

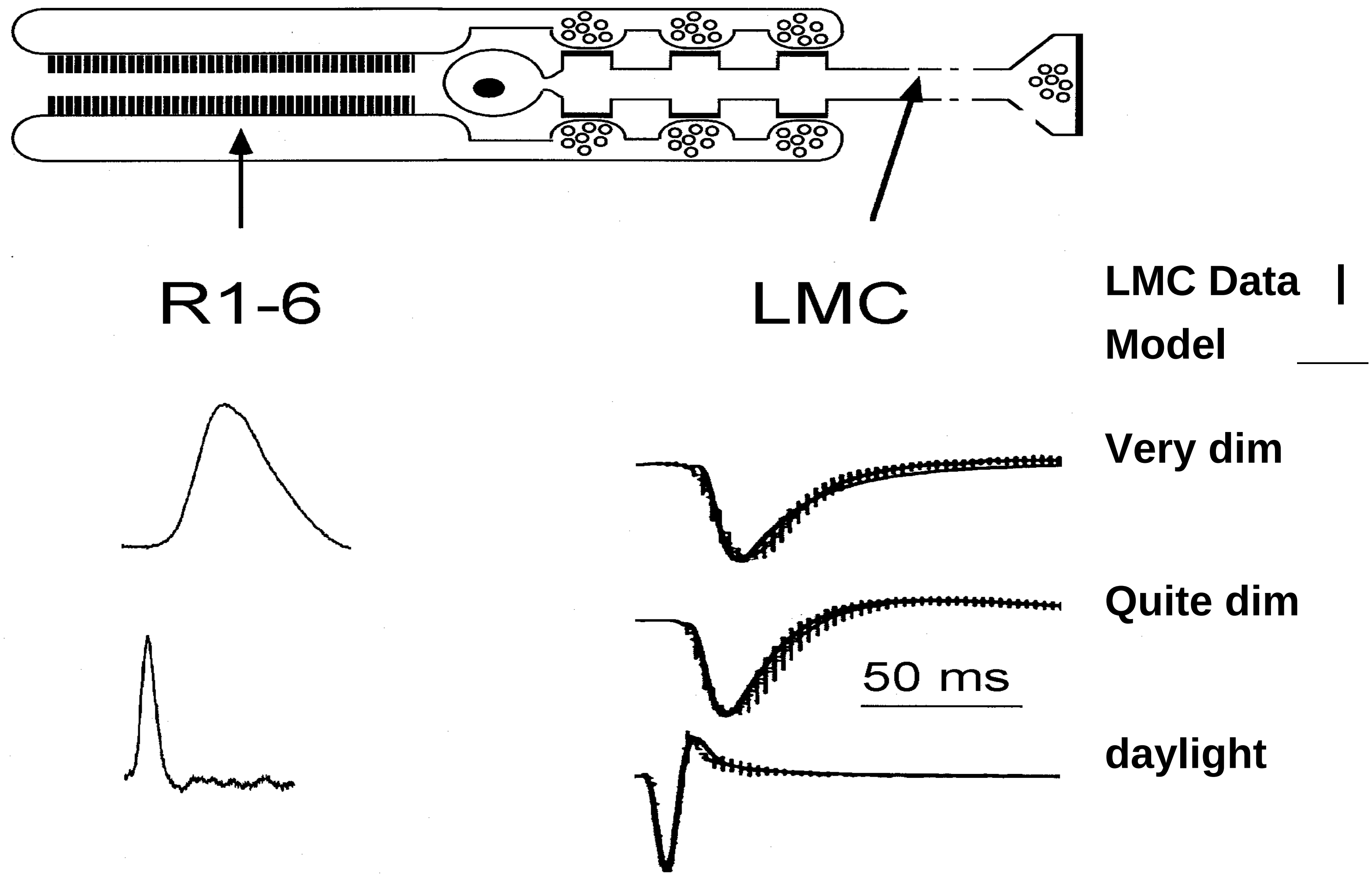
Maximise information coded in a channel limited bydynamic range and noise
(Hans van Hateren, 1992)

MODEL

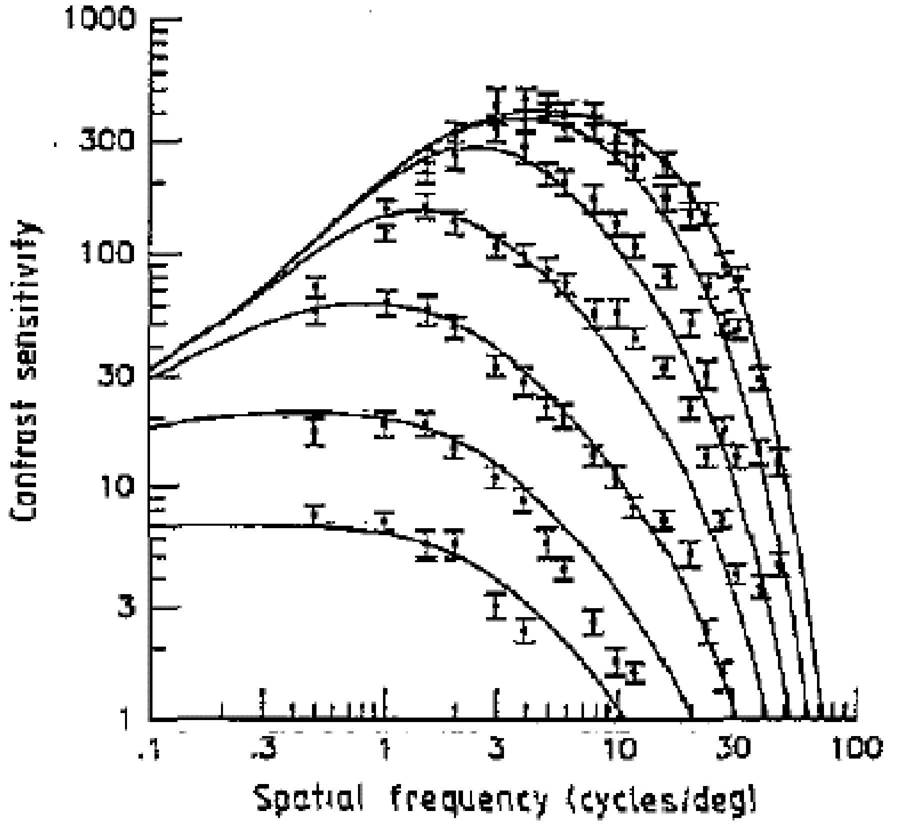
Input "naturalistic" 1/f statistics



Test model



Model generalises
Similar redundancy reduction model applied to human vision (Atick & Redlich, in Atick, 1992)



Data points = psychophysical data; Curves = redundancy reduction model

Secret 5
Send only what's needed

- eliminate redundancy
- improve SNR before transmission
- boil information down to *" what the destination needs to know, no less, no more"*

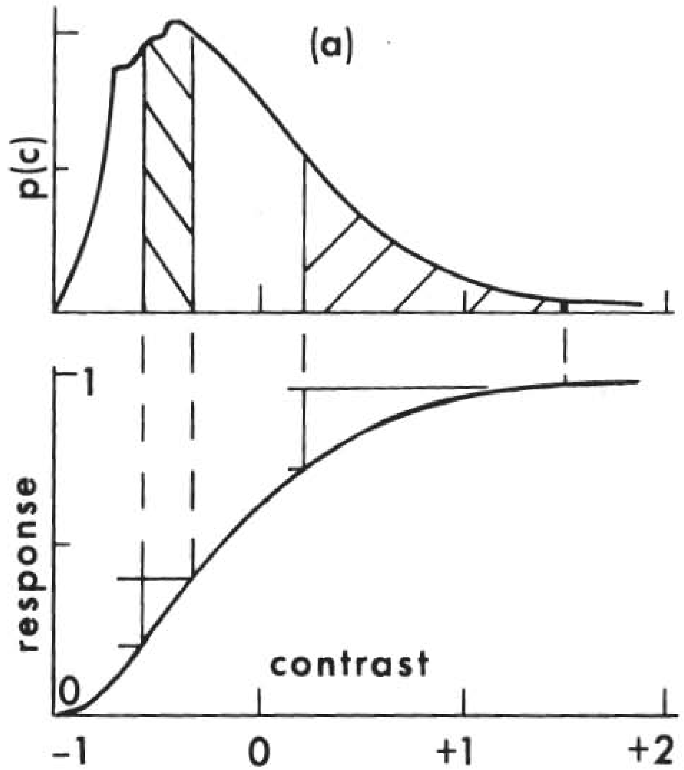
Secret 6

Match neural resources to natural distributions of signals and tasks. *Match* components across levels (*"symmorphosis"*)

Redundancy reducing adaptive filter matched to input SNR

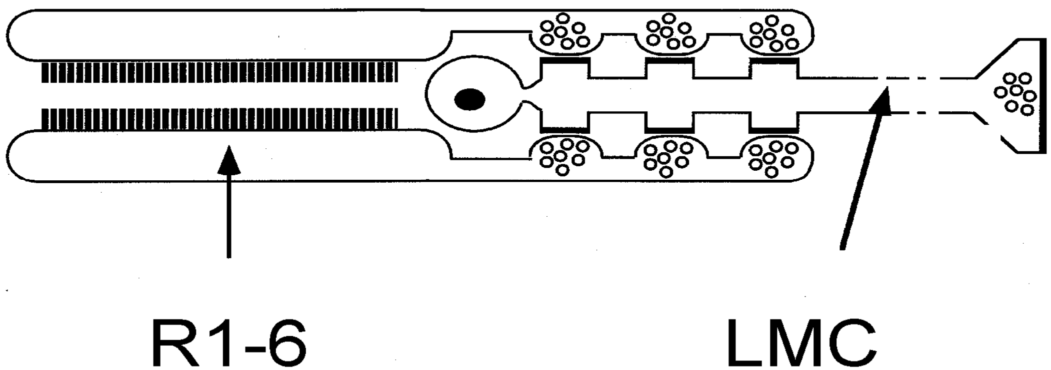
Gain adapted to input amplitude distribution

Amplifying signal to fill the response range HISTOGRAM EQUALISATION



(Laughlin, 1981)

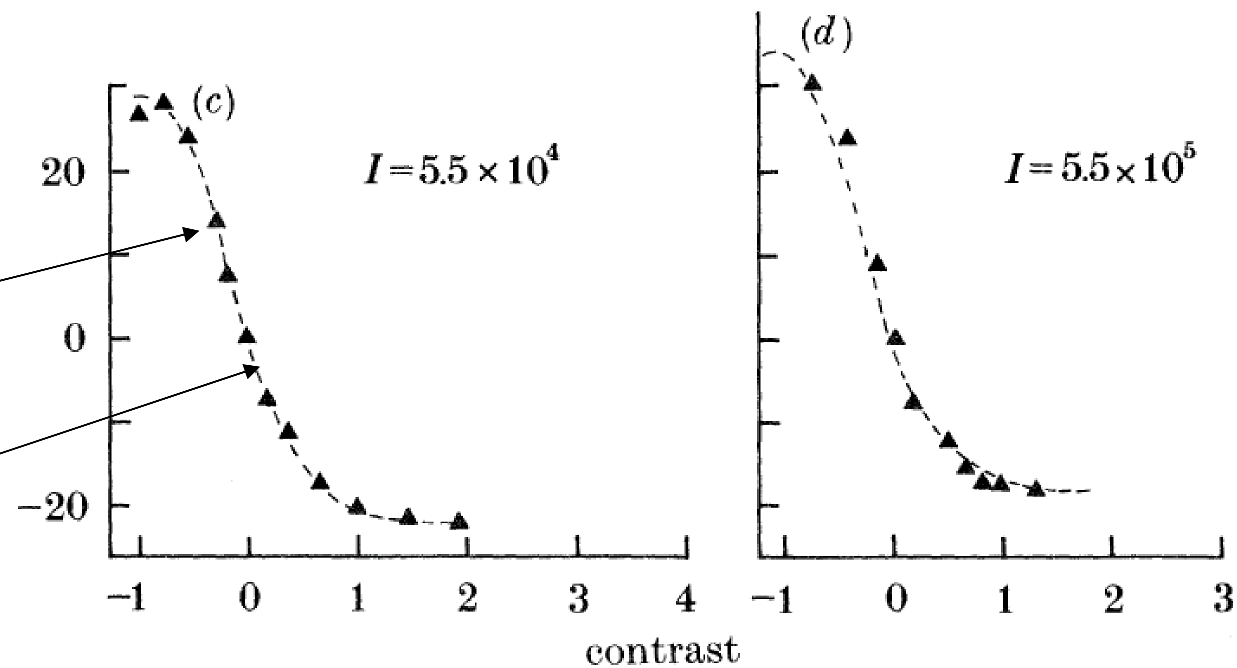
Histogram equalisation at the photoreceptor – LMC synapse



Measurements

Response

Histogram
(cum. prob.)



Equalising the response histogram in *Drosophila* olfactory glomeruli

Bhandawat et al 2007

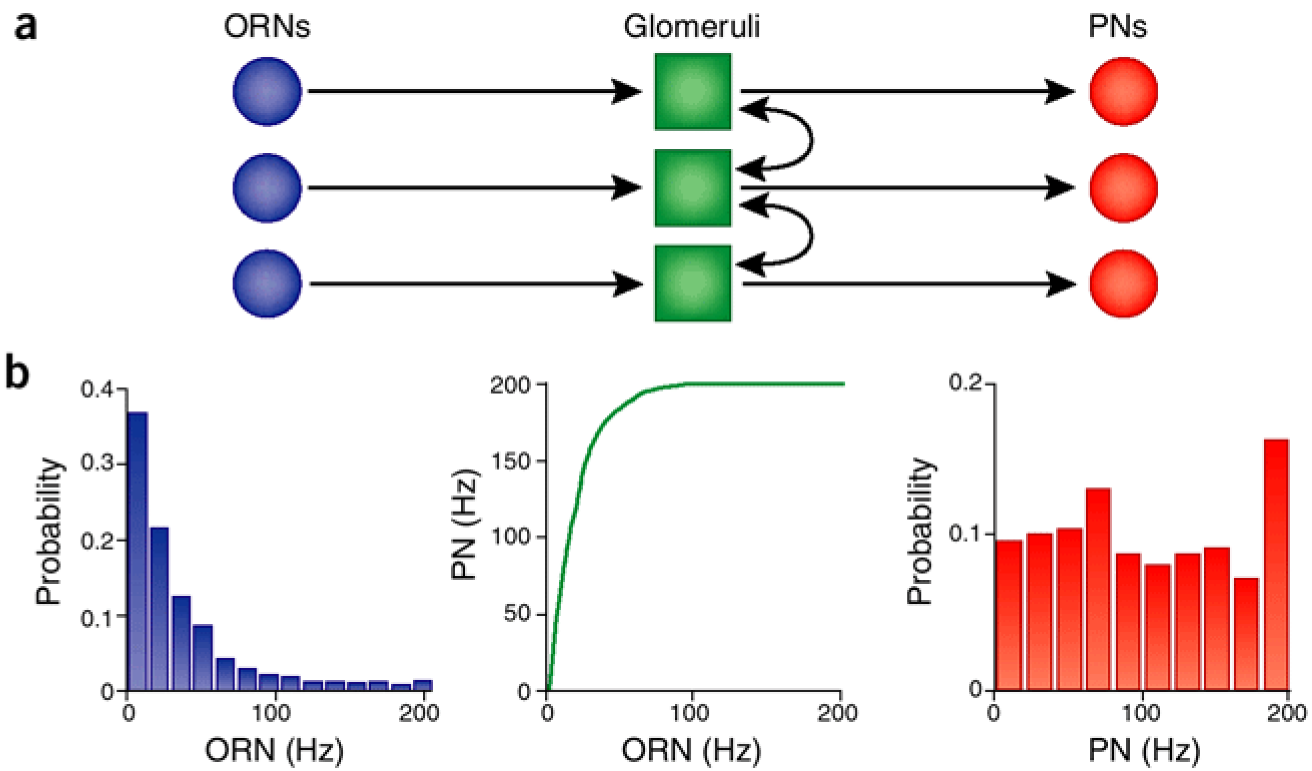


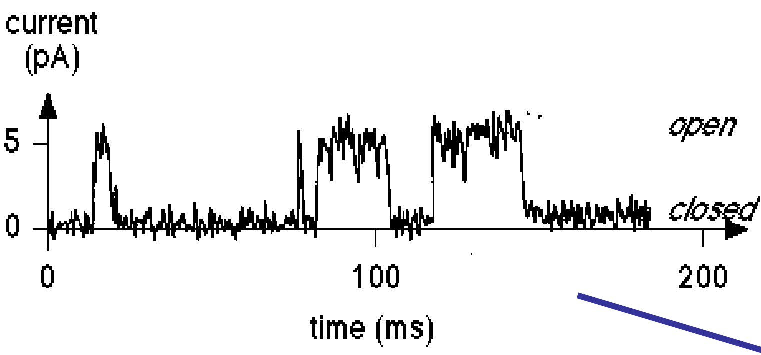
Figure from Abbott & Luo, Nature Nsci News and Views 2007

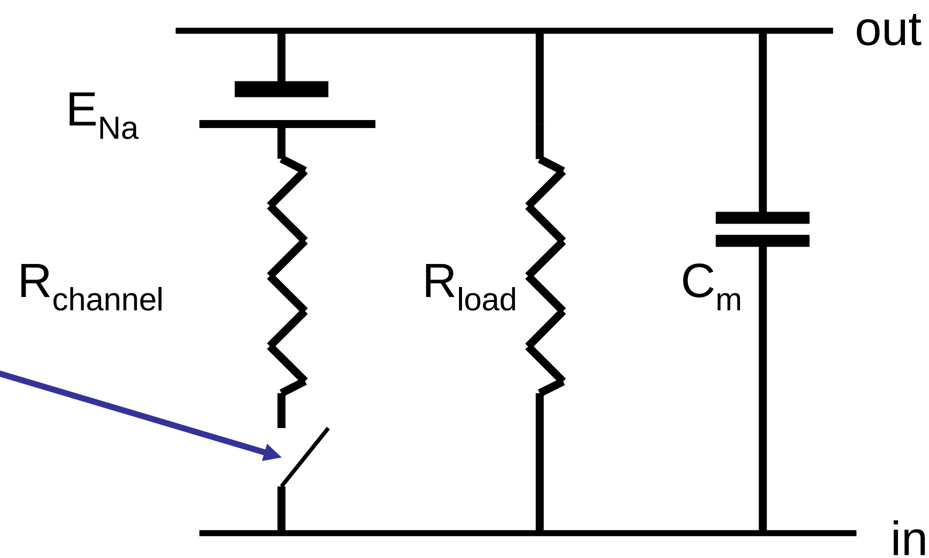
Working efficiently within device constraints

electrical signalling

Signal quality in single neurons

basic biophysics – graded responses





Noisy signals

$R_{channel} = 10^{11}$ Ohms

$E = 10^{-1}$ V

$R_{load} = 10^{9}$ Ohms

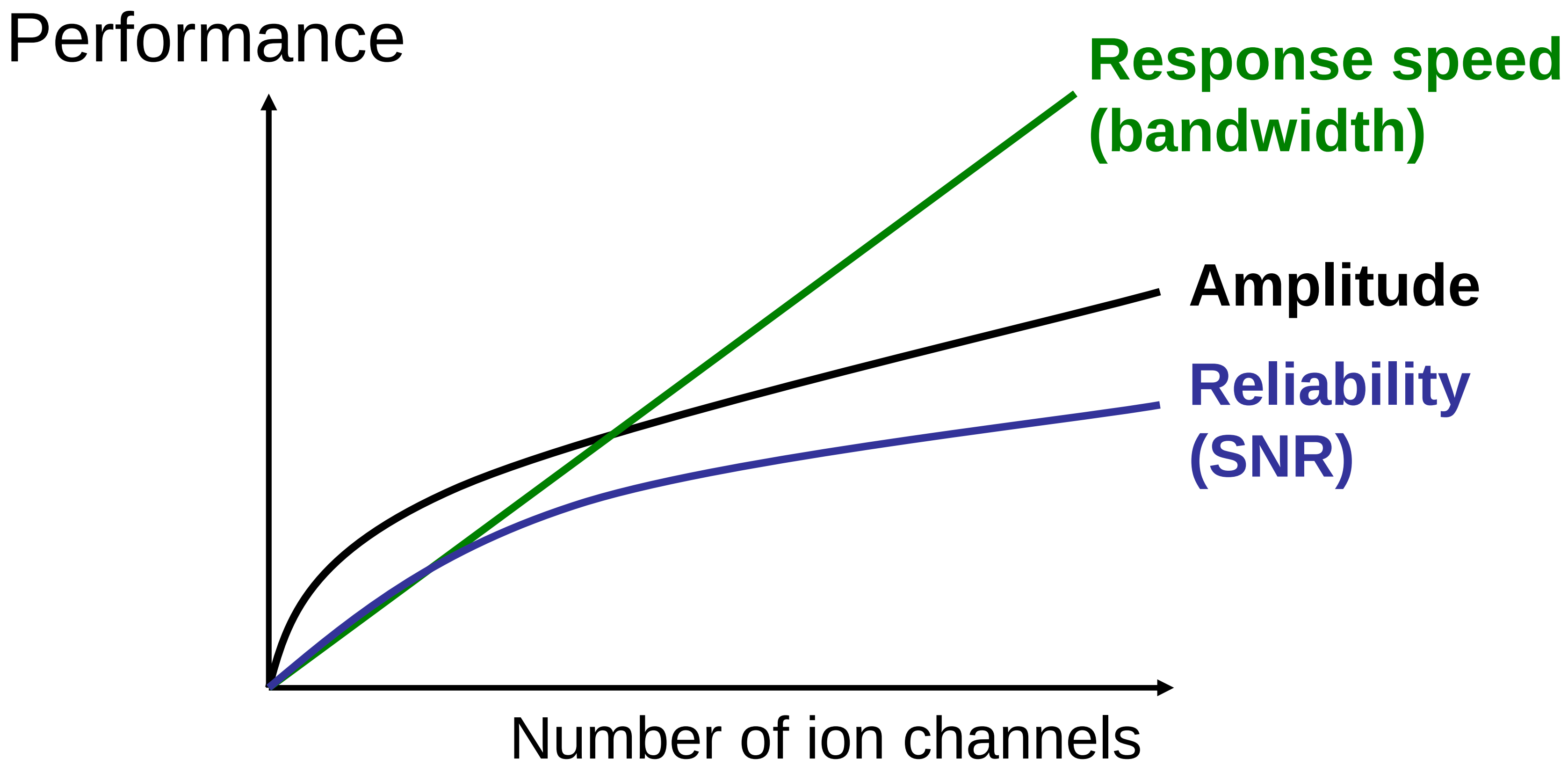
C_m is significant

R_m is high

Small signals ***Slow signals***

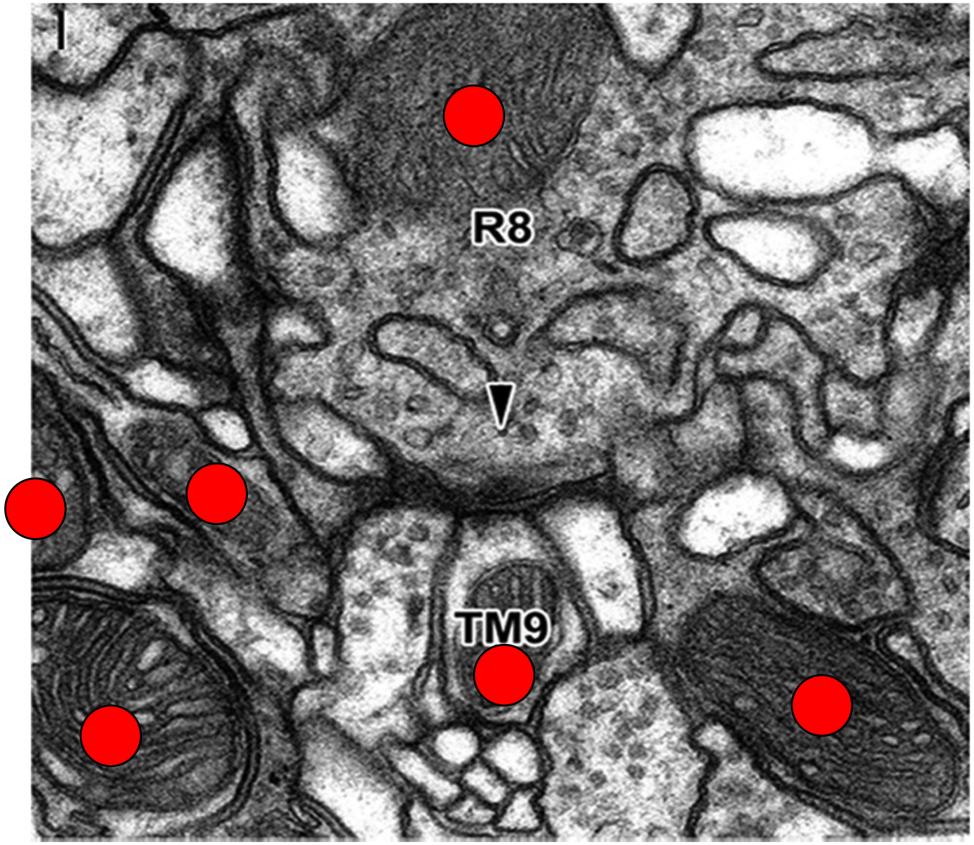
Decaying signals

More ion channels – better performance



Energy costs;
plus space and materials

Energy takes space
mitochondria in neurons



Gao *et al, Neuron* 2008, *Drosophila* medulla

500 *nm*

Secret 7

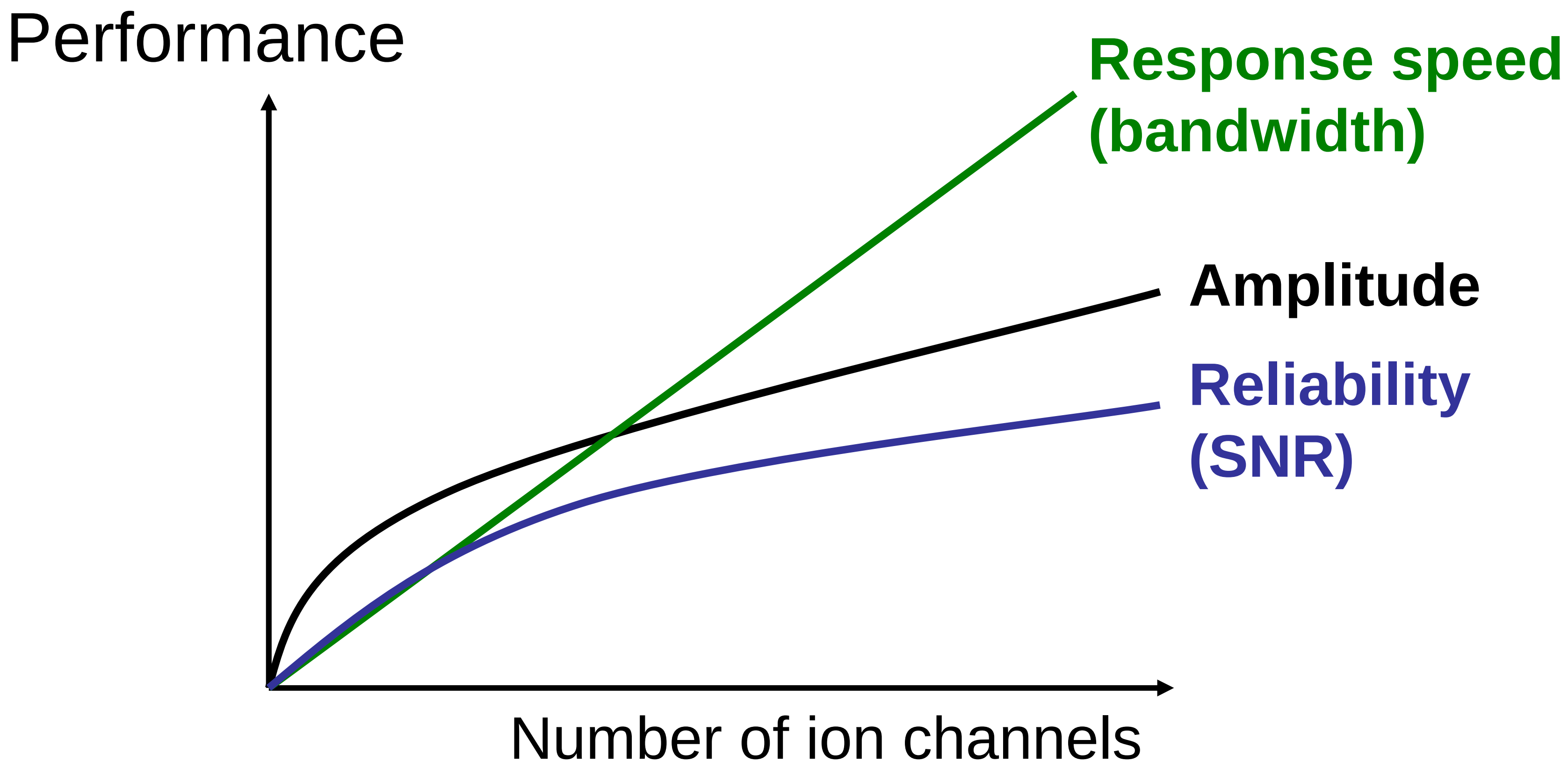
Reduce voltage and increase resistance

Secret 8

send information at the lowest rate

(minimise bandwidth and precision)

More ion channels – better performance



Energy costs;
plus space and materials

Testing for a Law of Diminishing Returns

bit cost vs capacity (max rate)

Sarcophaga carnaria

Calliphora vicina

Drosophila melanogaster

Drosophila virilis

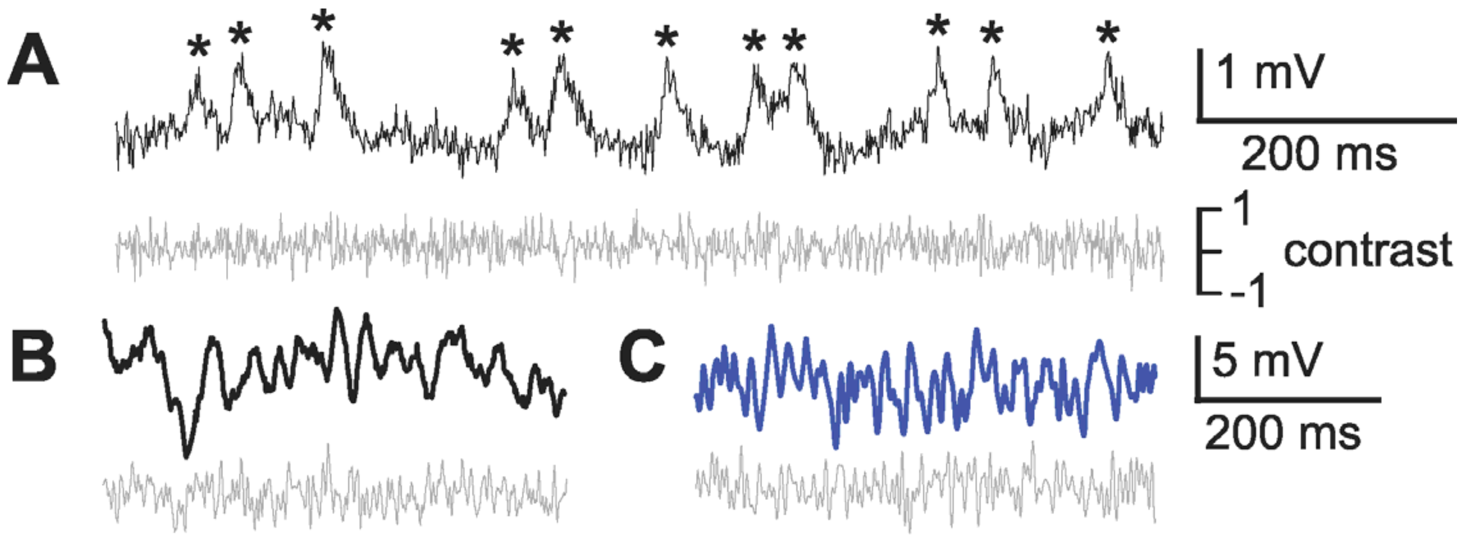
Jeremy Niven, John Anderson and Simon Laughlin PLoS Biol 2007

The data

Quantum bumps

Response

White-noise stimulus



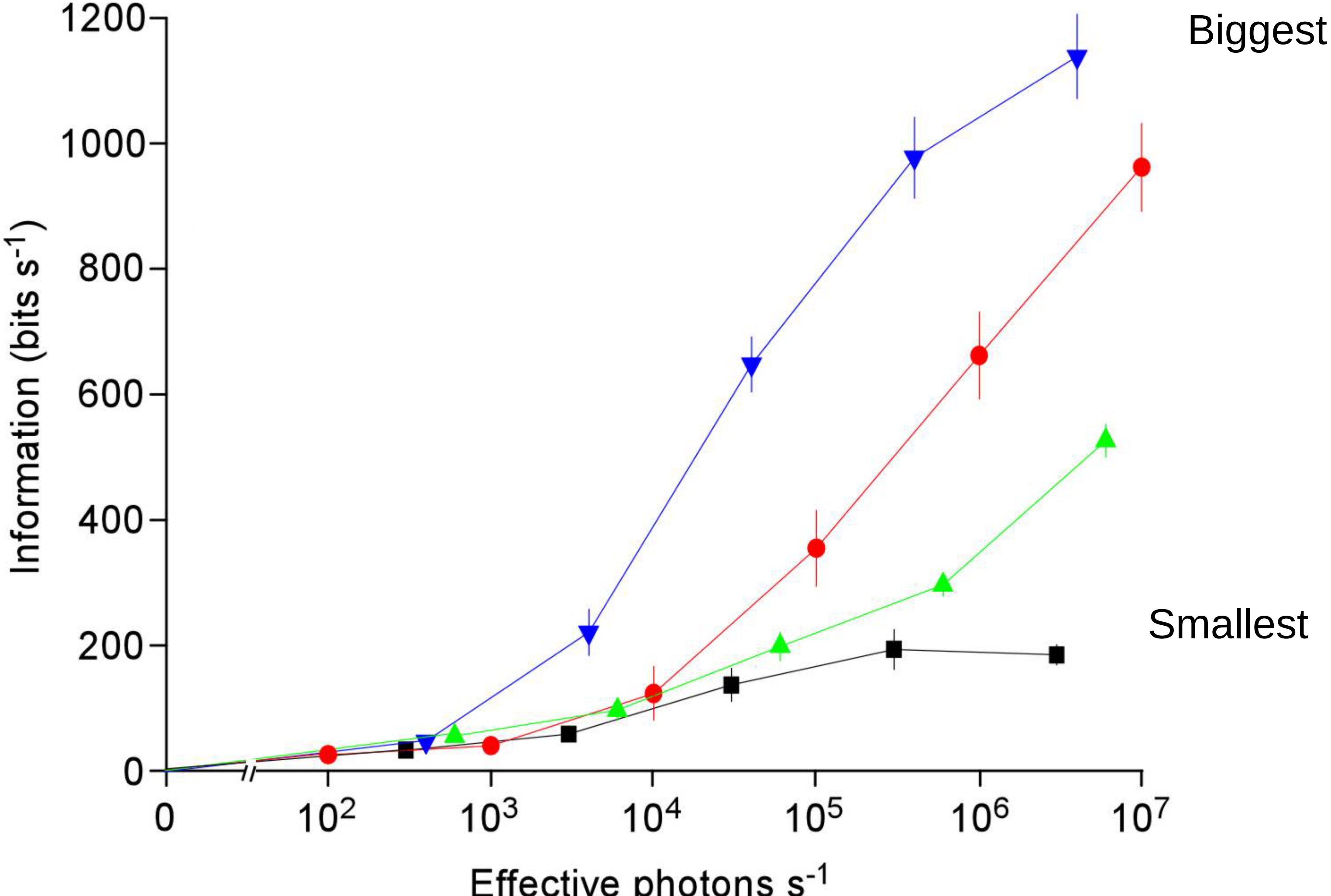
D. melanogaster

Sarcophaga

Capacity increases with bandwidth and precision

$$I = \int_{0}^{co} \log_2[1 + S(f) / N(f)] \cdot df$$

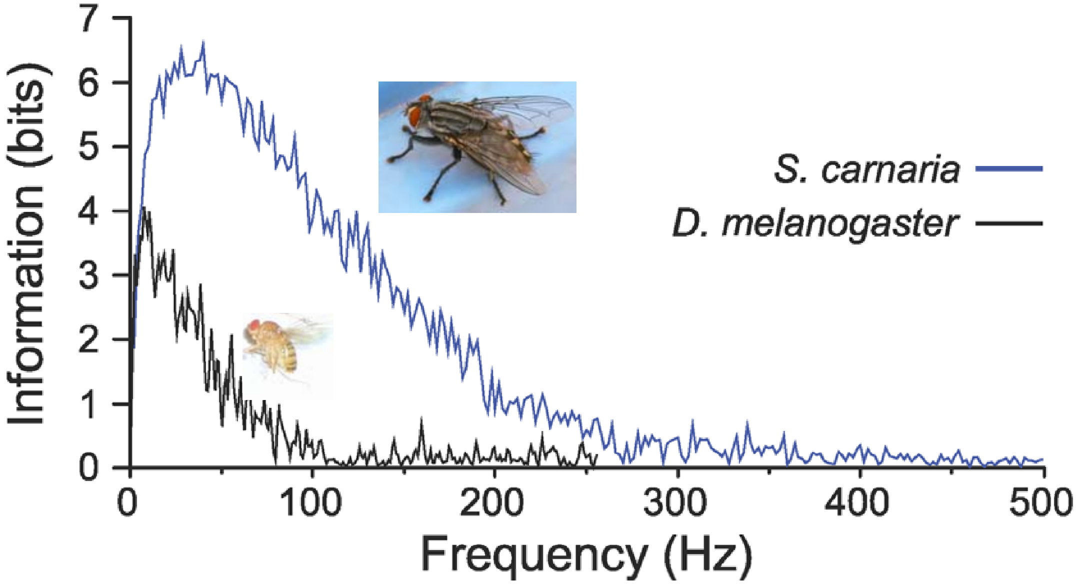
Larger cells - higher capacities



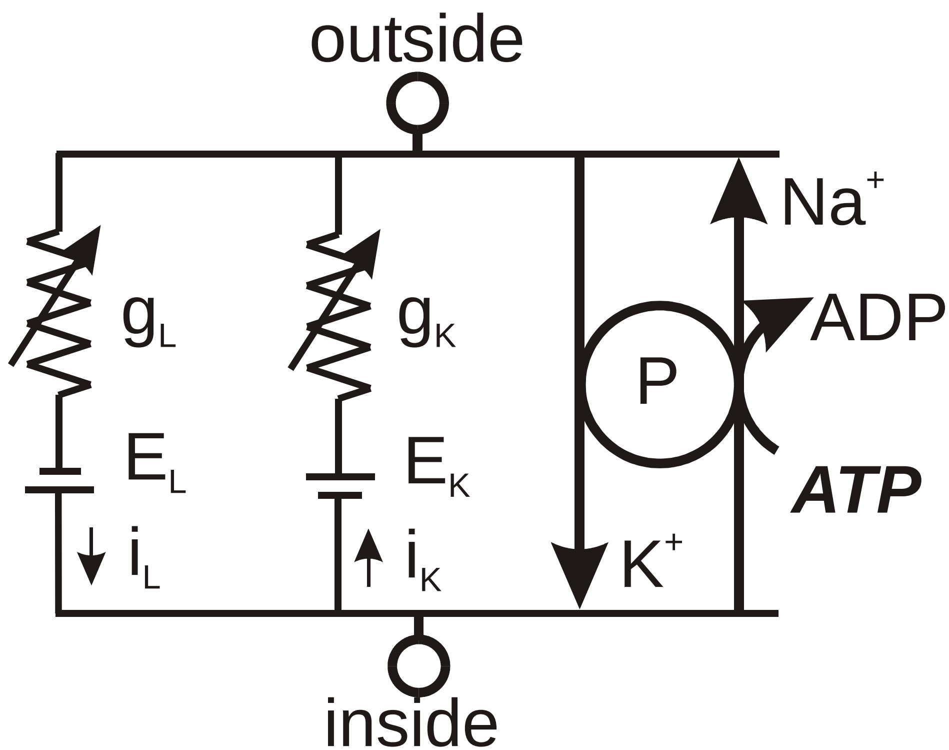
Big cell are faster and more precise

$log_2[1 + S(f)/N(f)]$

D

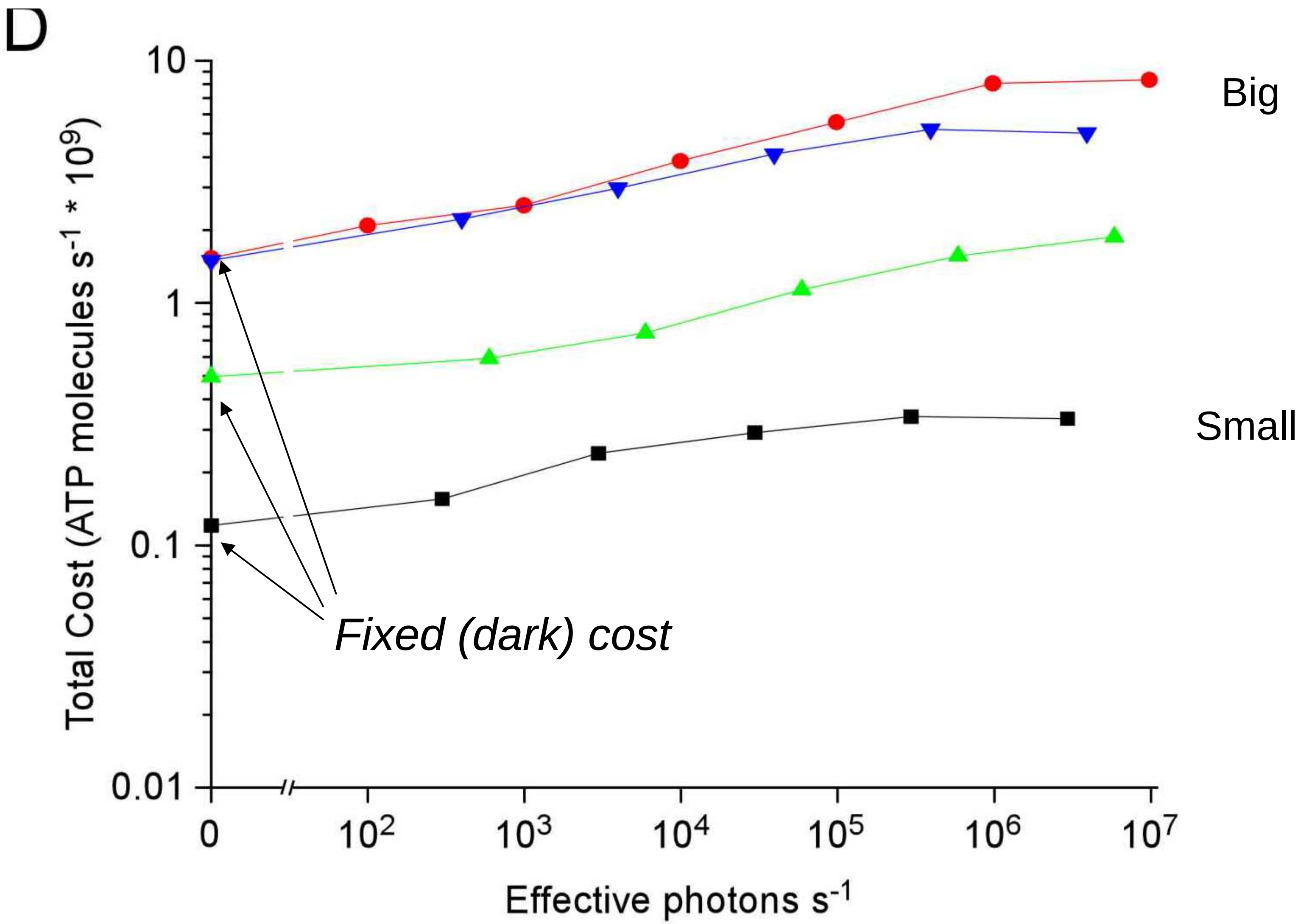


Membrane model gives energy consumption

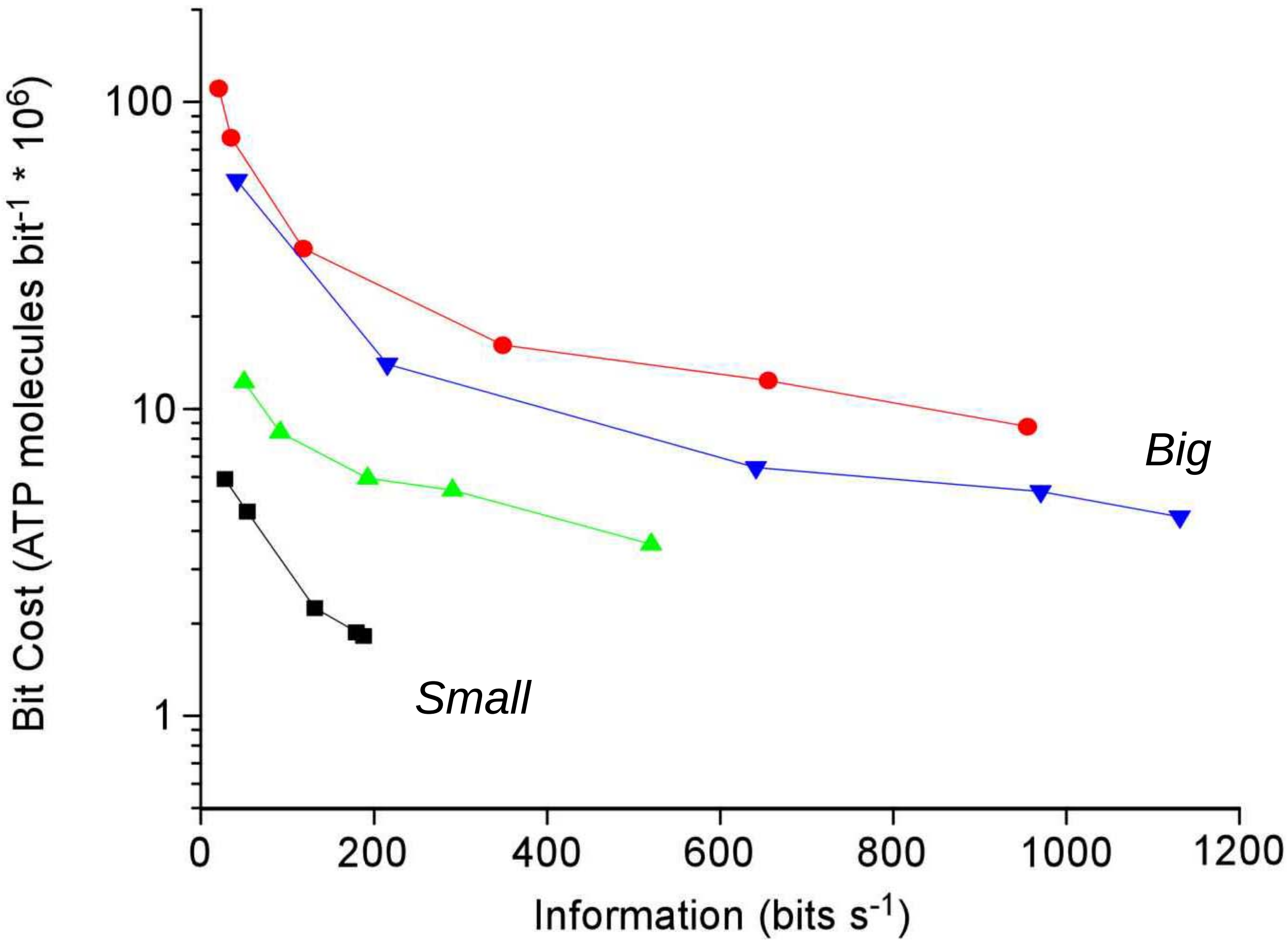


Laughlin et al, Nature Nsci 1998

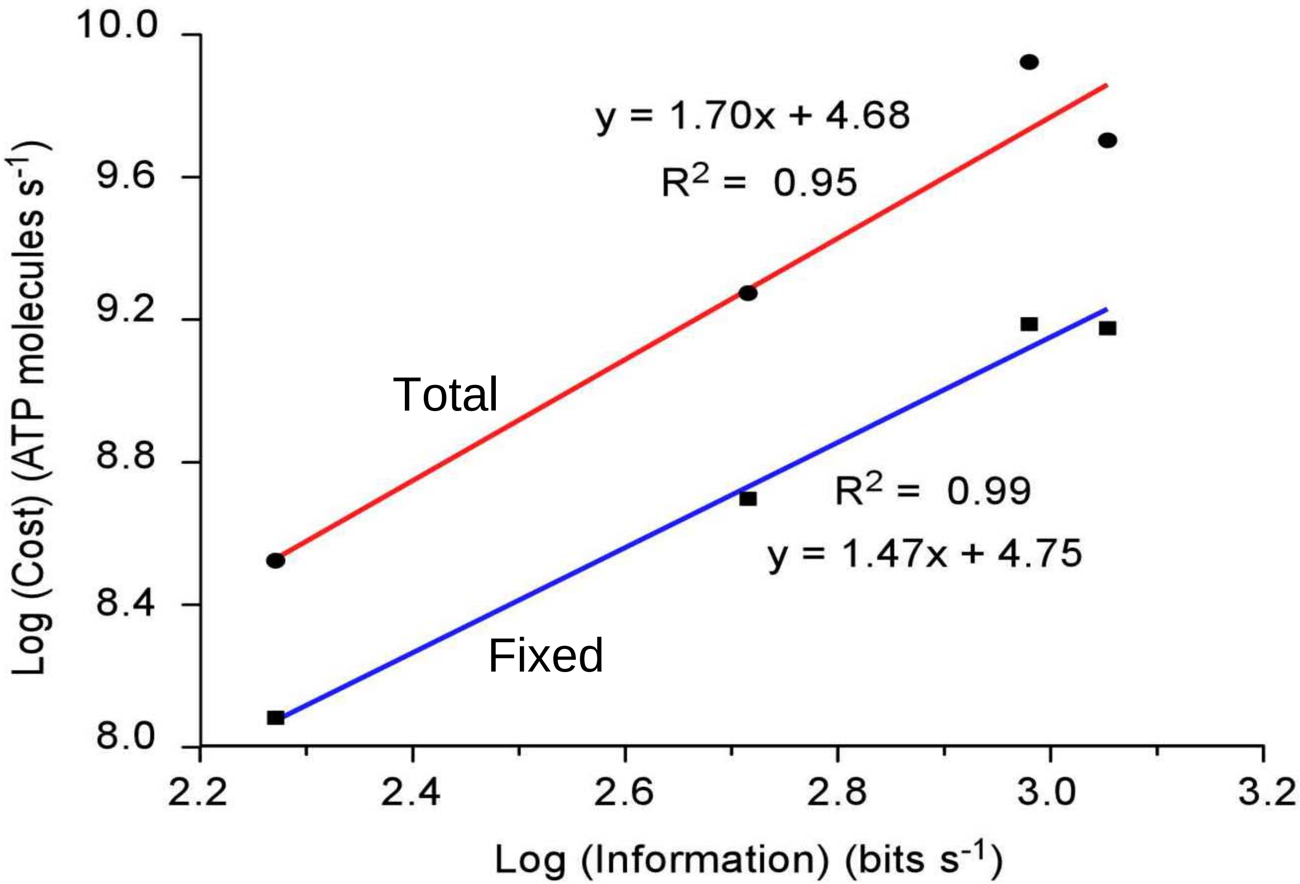
Different levels of energy consumption



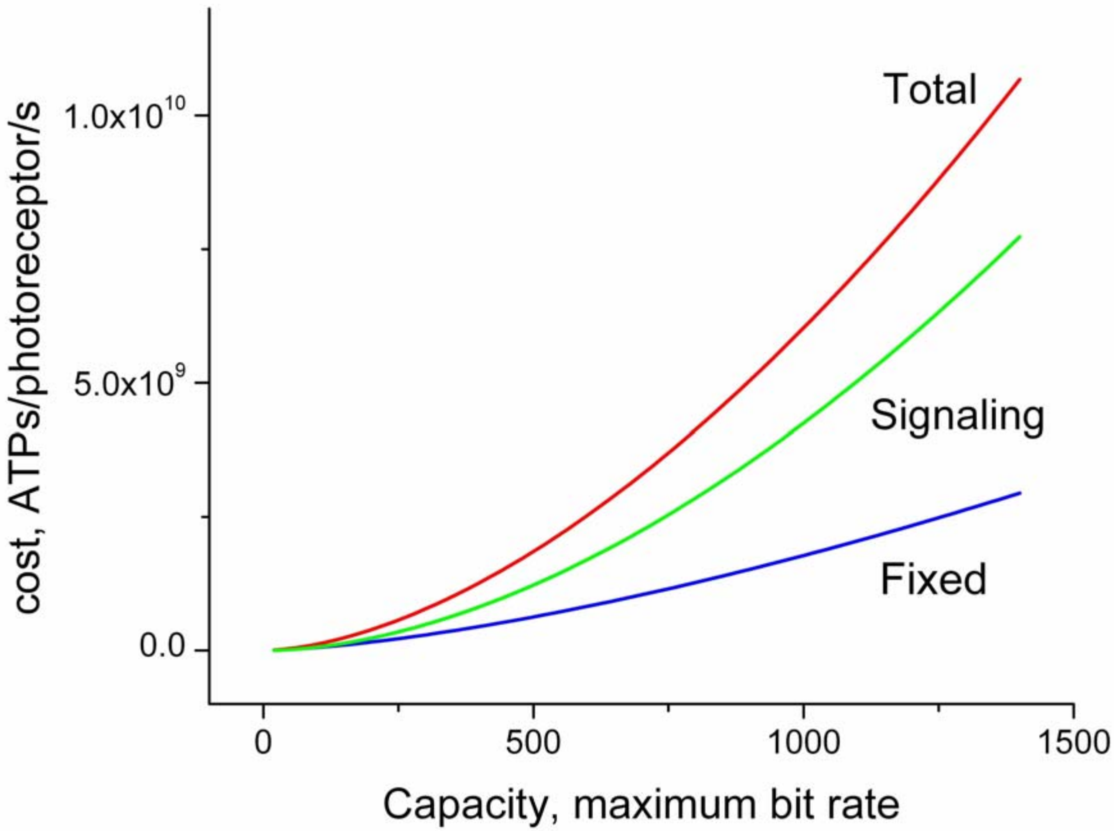
Bigger cells are less energy efficient
(they have traded economy for capacity)



Cost increases out of proportion to capacity



The Law of Diminishing Returns



How to implement
Send at the lowest rate

- Distribute information and processing tasks among parallel low rate channels
  - *sparse coding, parallel pathways*
- Only use high speed/precision where it is essential
  - *small number of high speed/precision streams*
  - *larger number of low speed/precision stream*

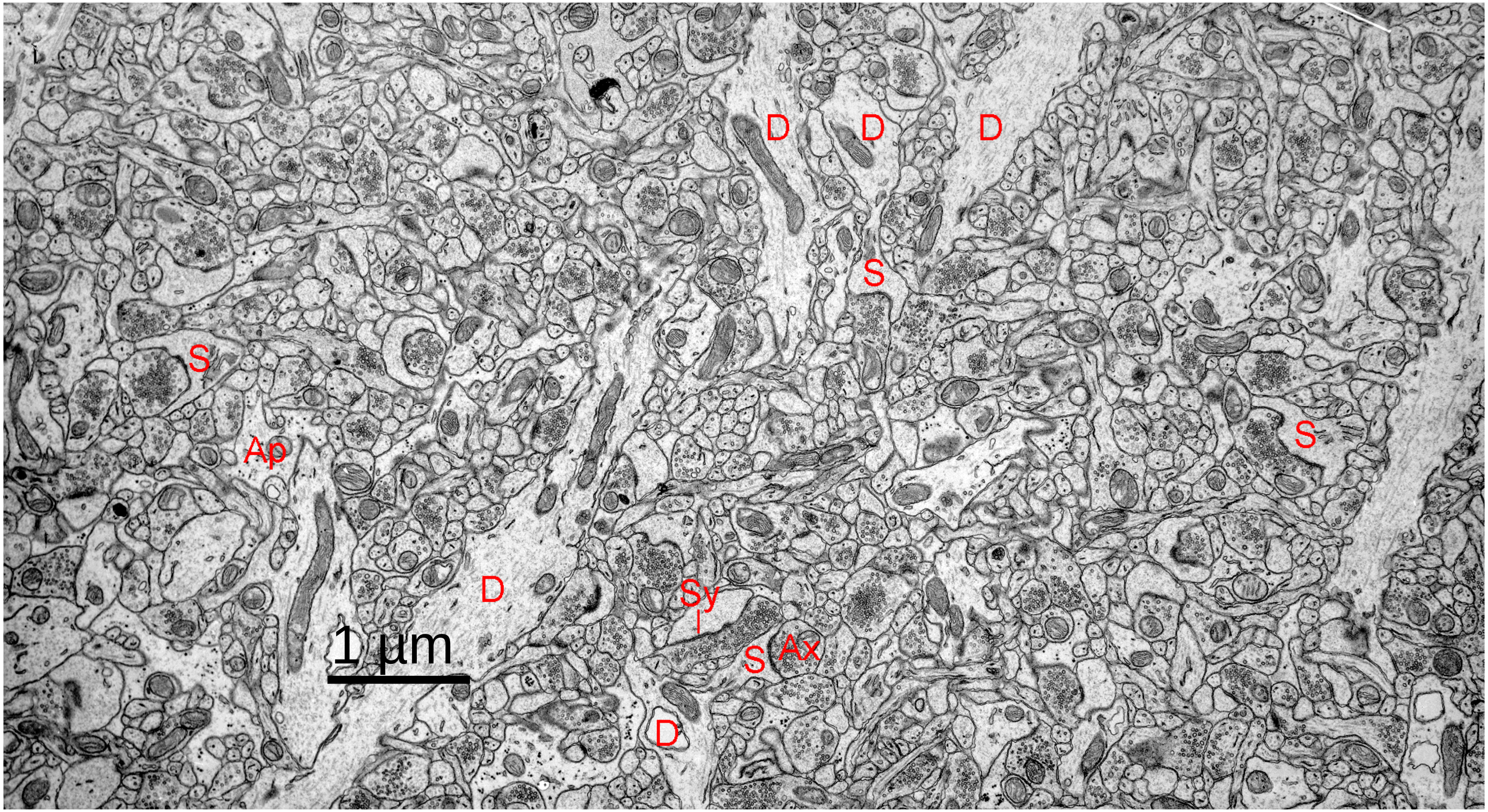
Massively parallel processing in low rate channels each dedicated to small part of the task

Secret 9

Nanofy!

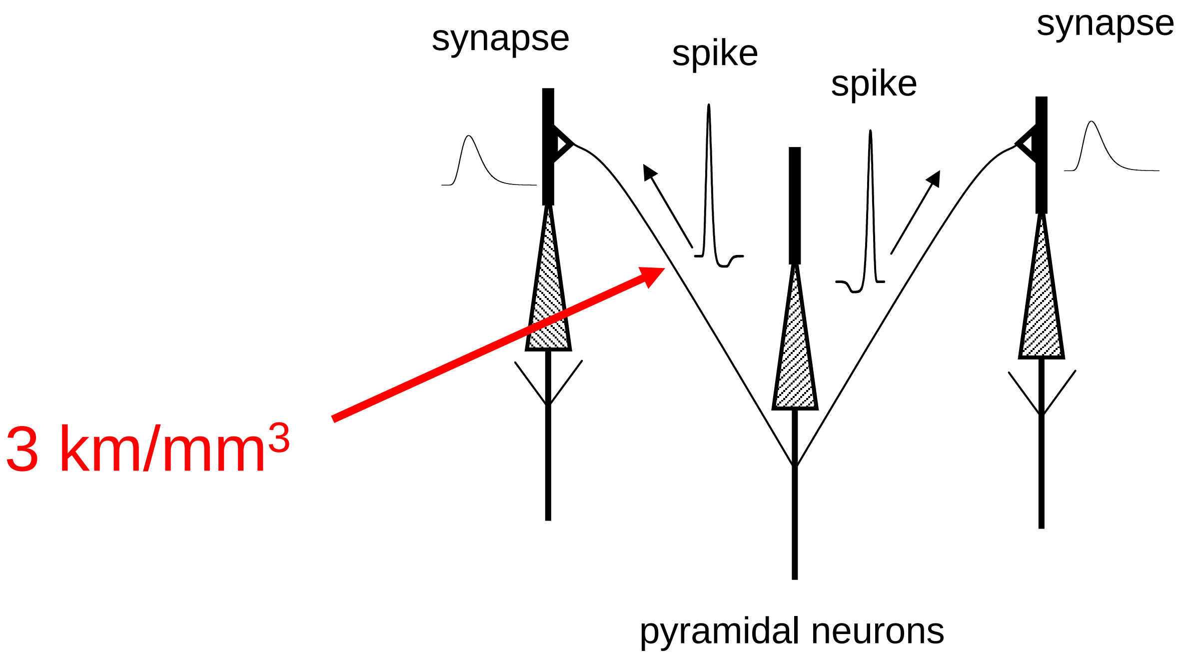
(reduce to the irreducibly small)

Miniaturisation



Dendrites (D) of CA1 pyramidal cells – EM section by Dr J. Spacek, Charles Univ Czech Rep. Visit *Synapse Web* for more details

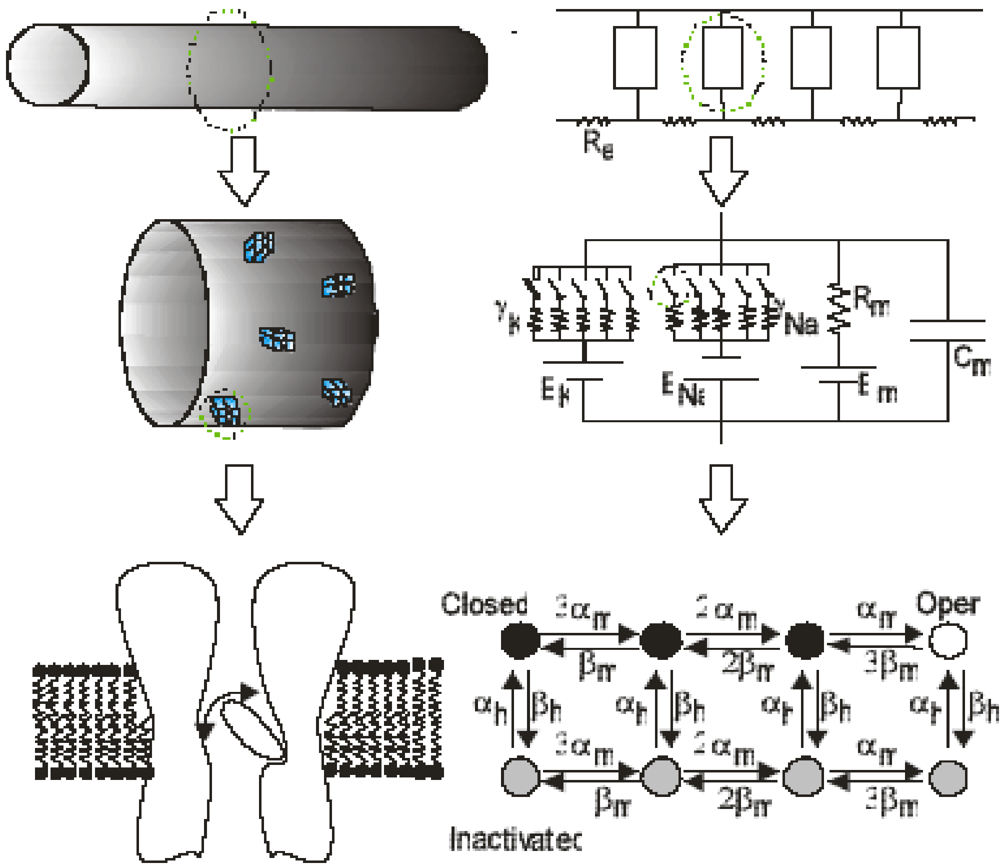
What is this spaghetti?

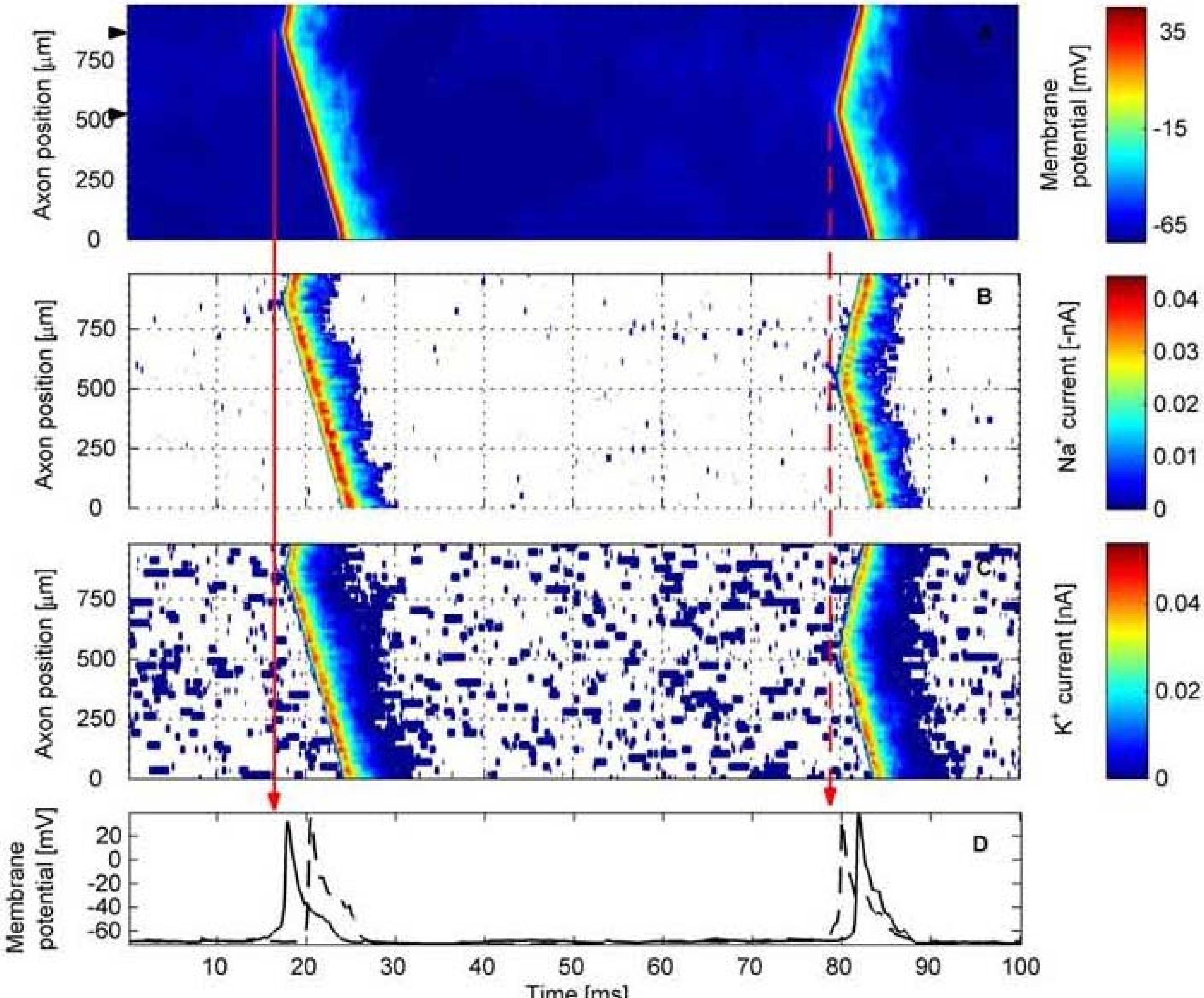


A channel noise limit to axon miniaturisation

Aldo Faisal, John White and Simon Laughlin 2005

stochastic axon model

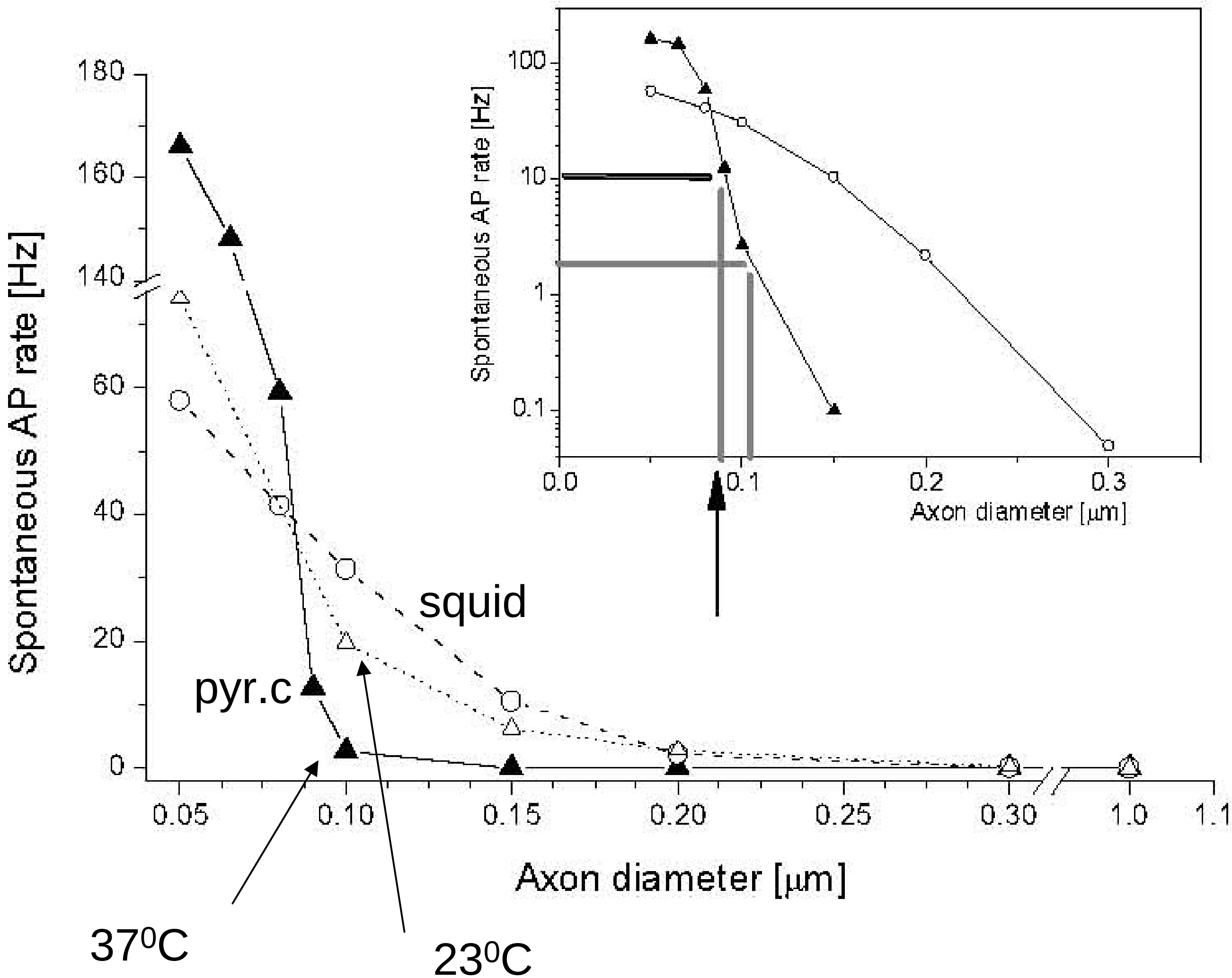




A.Faisal

Faisal, White & Laughlin Current Biology 2005

Spontaneous rate increases rapidly with decreasing diameter, below 0.2 µm



To be efficient
brains push down to
the molecular limits
of information transfer

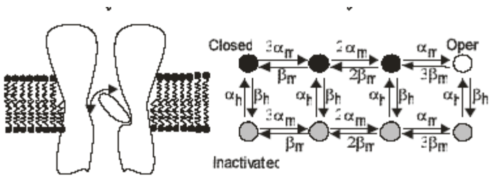
Secret 10

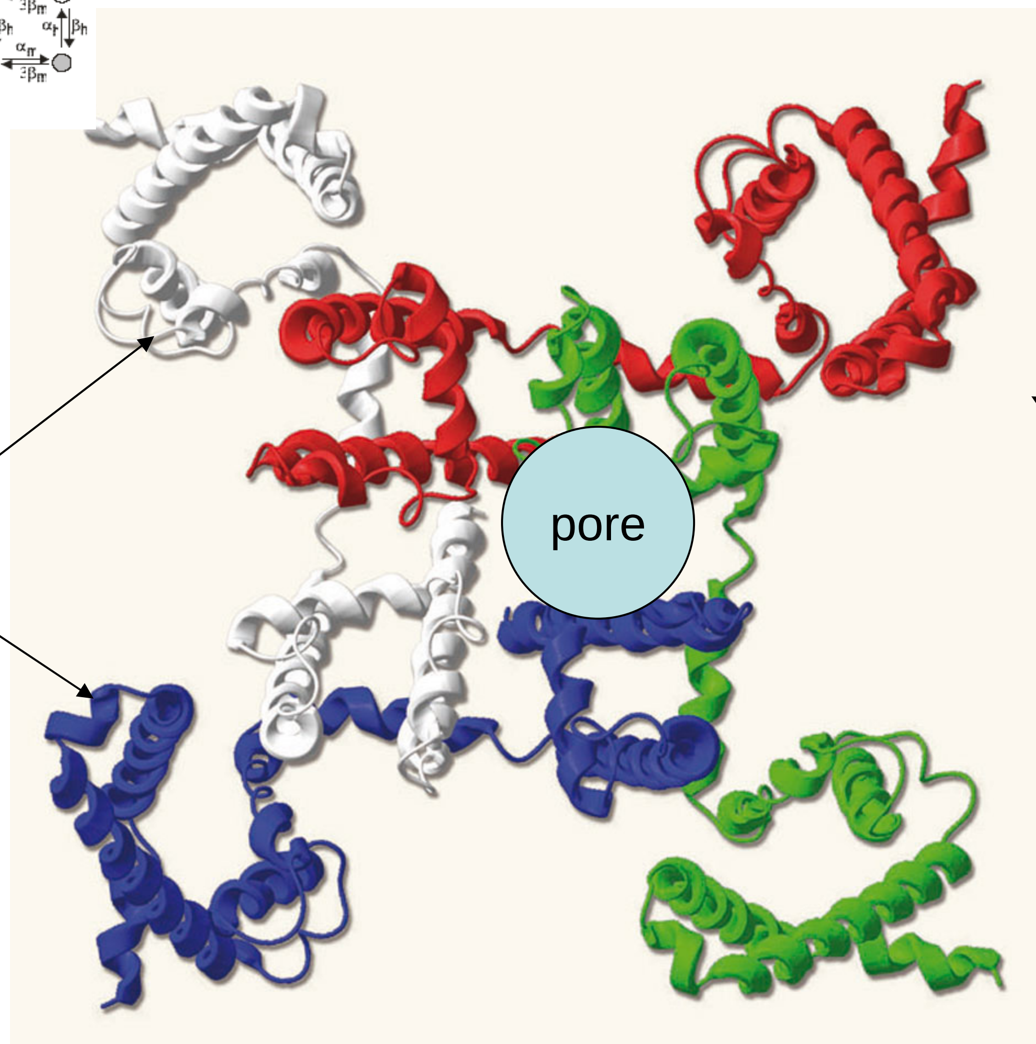
Do it with chemistry

(because ye have flesh)

The voltage sensitive sodium channel

a molecular machine





Voltage sensors

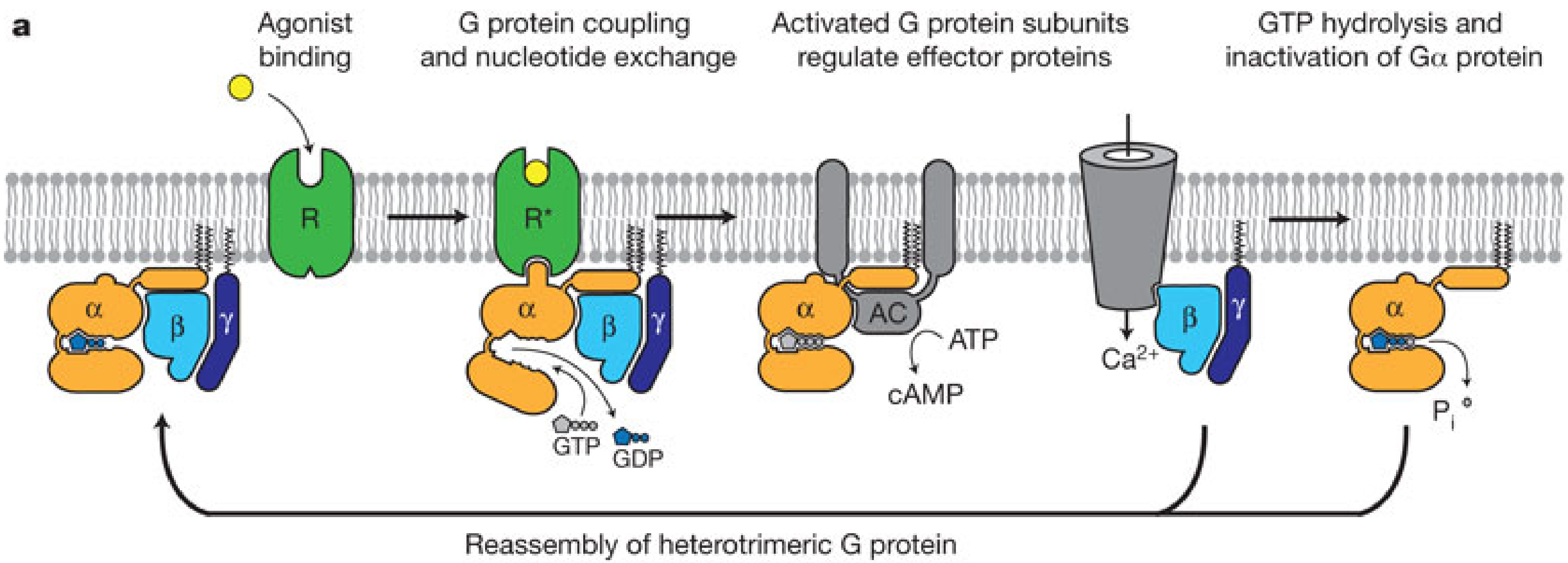
Voltage sensors

From Horn, *Nature* 2011
summarising Payandeh *et al, Nature* 2011

Protein power

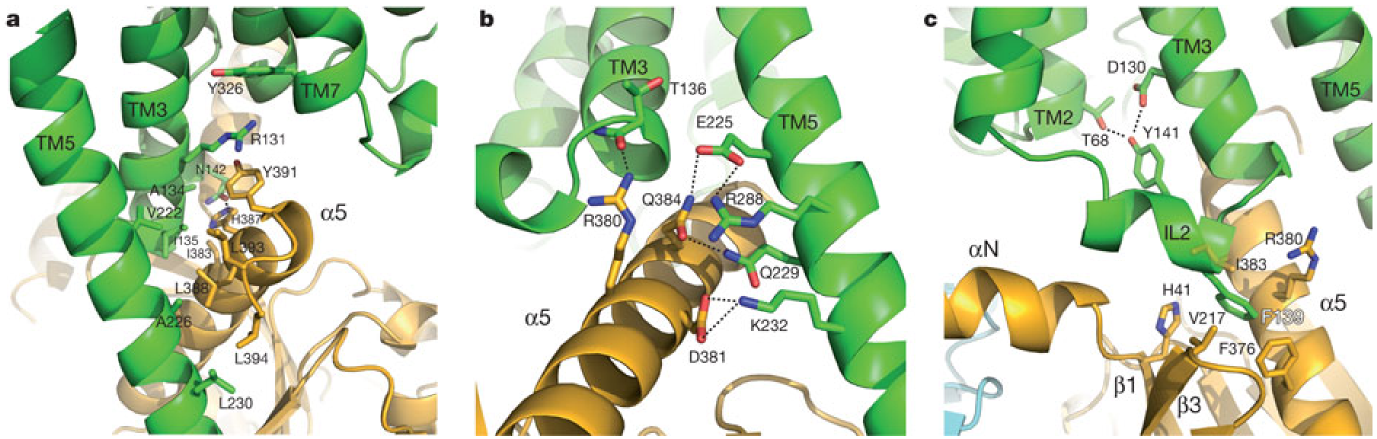
Nano (single molecule) finite state machines switching by conformational changes

G protein cycle for the β_2AR–Gs complex.



SGF Rasmussen *et al. Nature* **000**, 1-7 (2011) doi:10.1038/nature10361

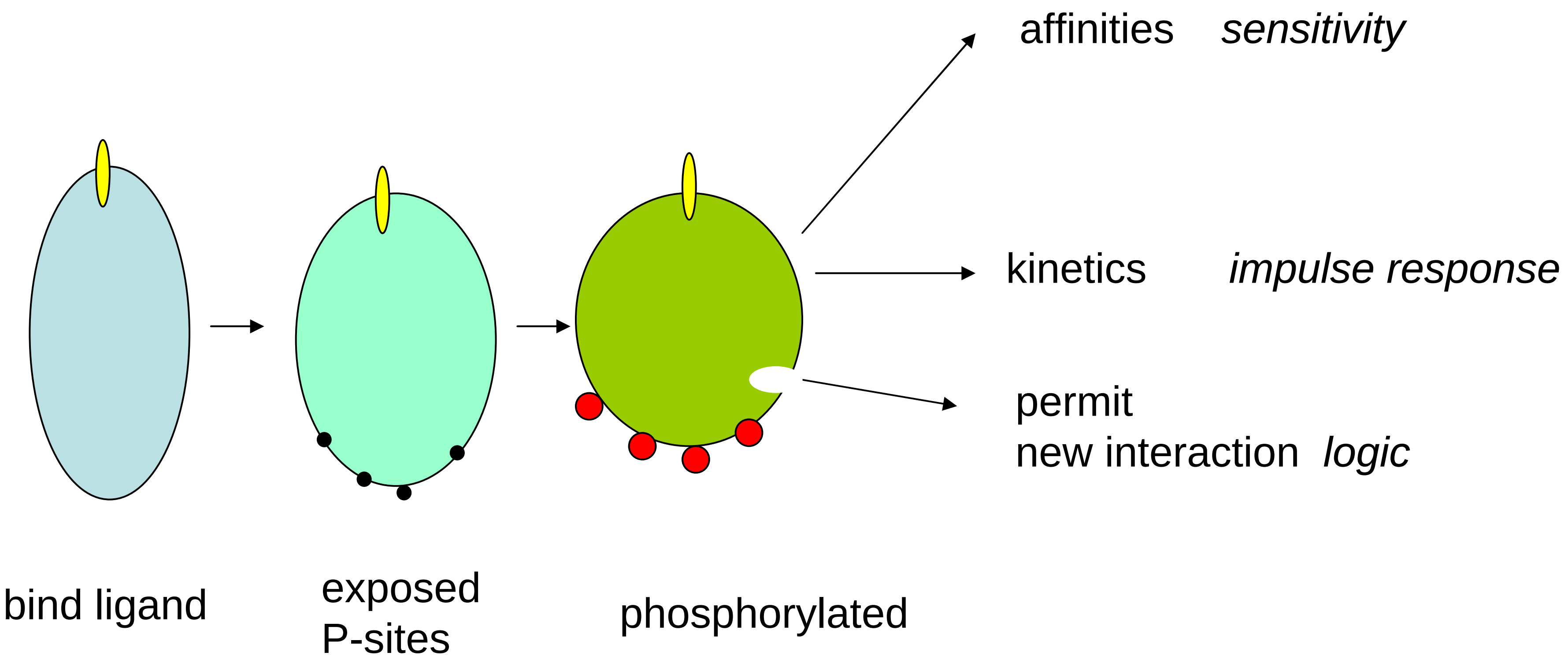
Receptor-G protein interactions.



SGF Rasmussen *et al. Nature* **000**, 1-7 (2011) doi:10.1038/nature10361

Note: This figure is from a near-final version AOP and may change prior to final publication in print/online

Changing protein nano machine states by changing their energy landscape

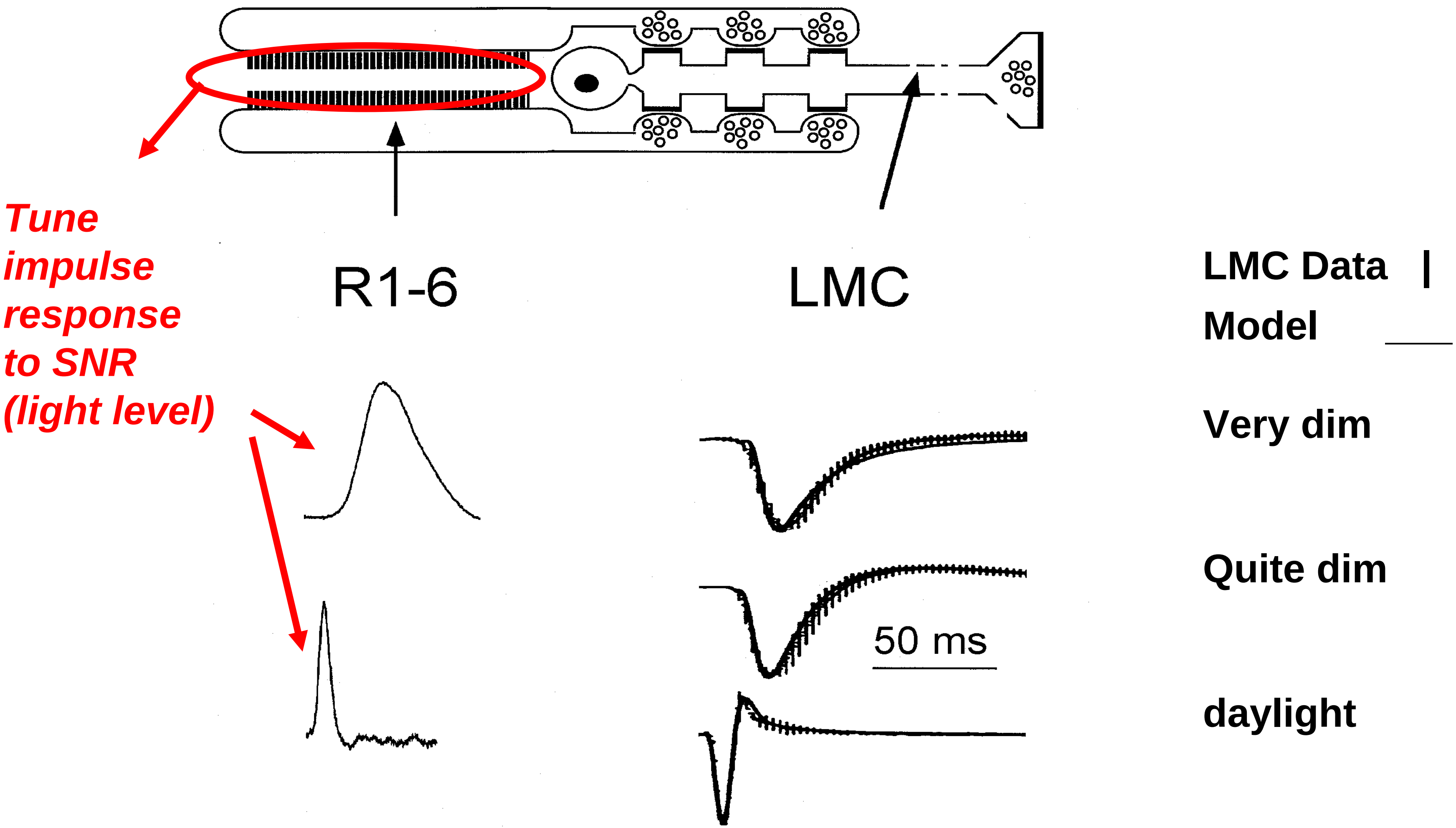


Protein molecules are flexible and versatile

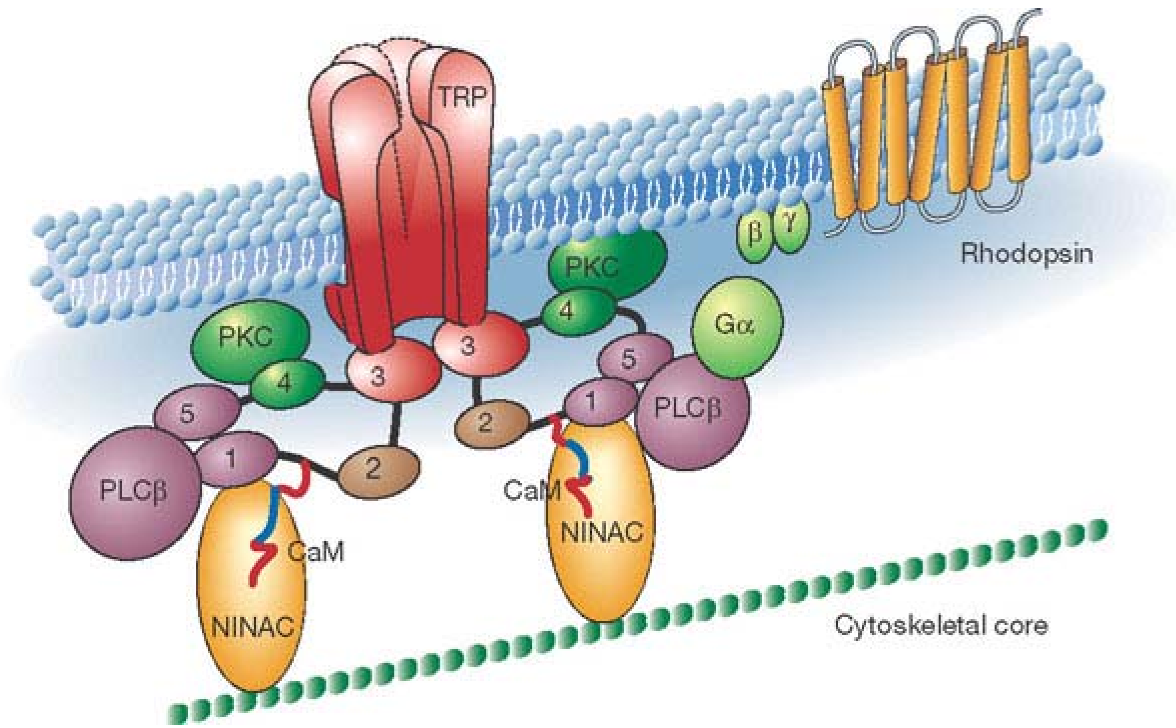
- Easily fine tuned
  - variable gain amplifiers
  - temporal filters
- Process information
  - coincidence detectors (AND gates)
  - NAND gates
- Assembled into information processing complexes and networks

Fine tuning

photoreceptor protein network implements van Hateren's optimum filter



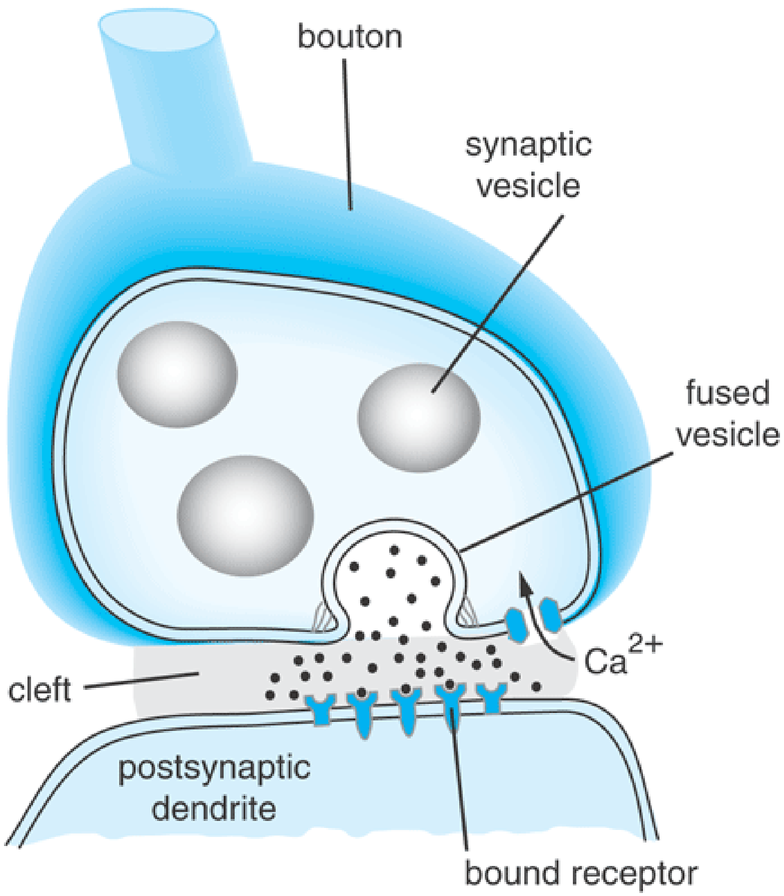
Molecular machinery for phototransduction in the fly photoreceptor

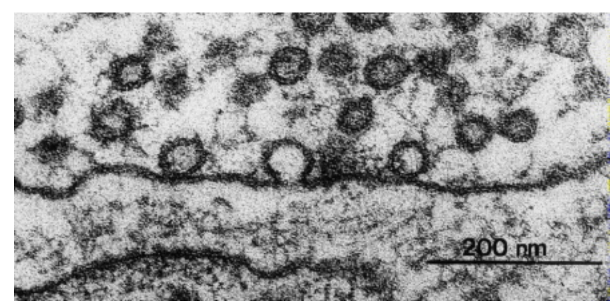


Hardie & Raghu, 2001

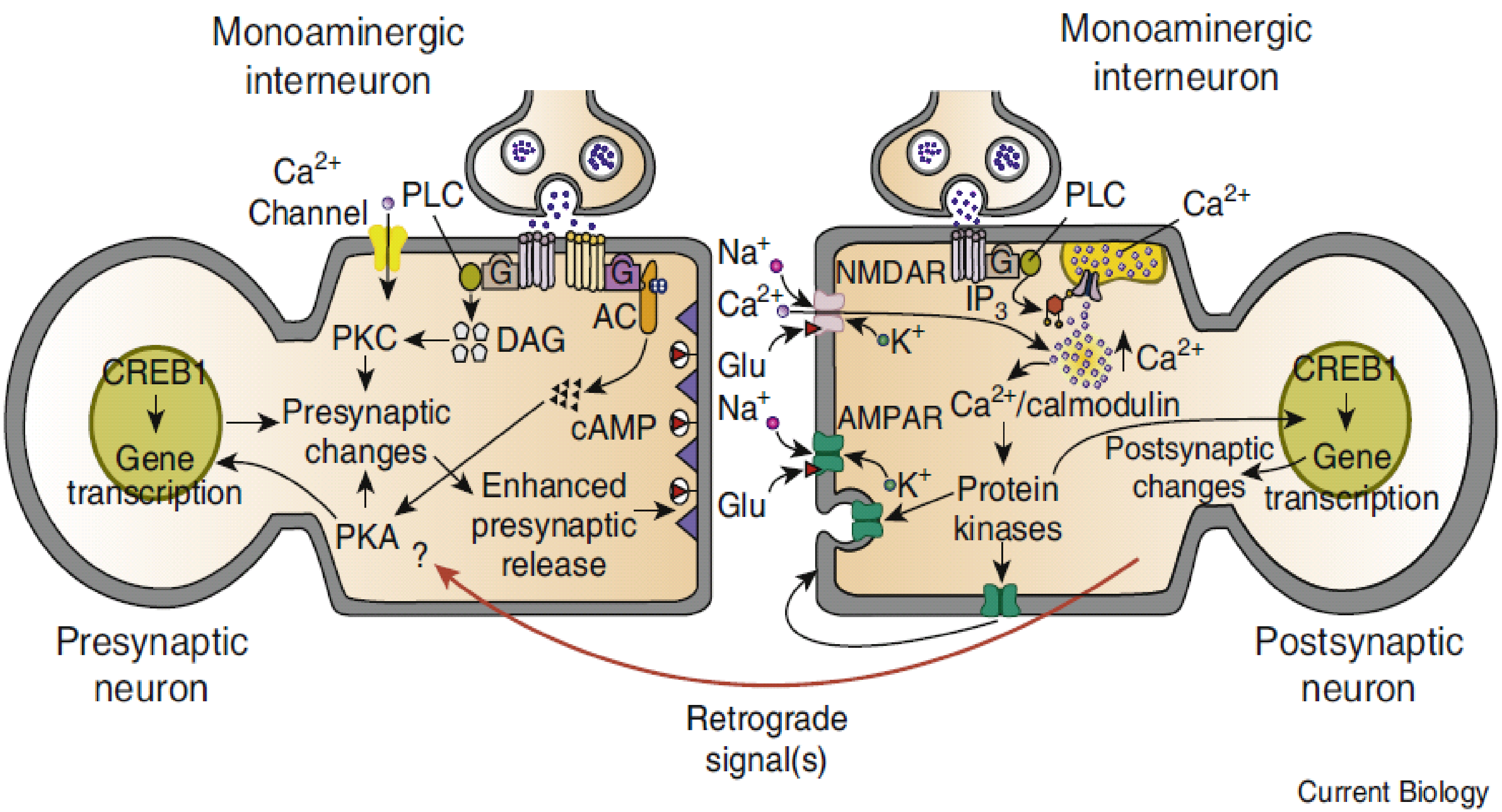
Networks revealed

The chemical synapse before the molecular neurobiology revolution





The outcome of revolution - promiscuity



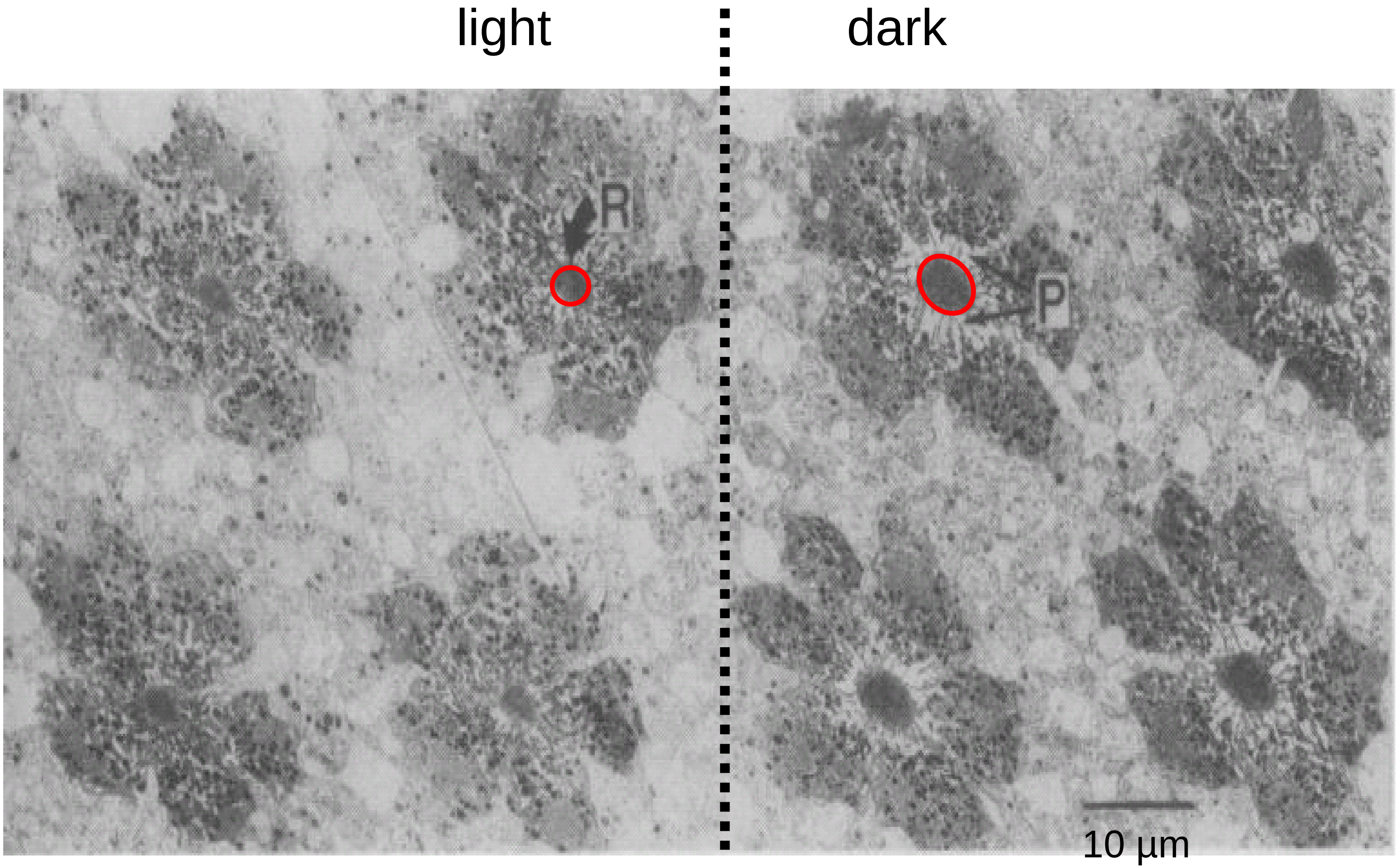
Glanzman Curr Biol 2010

Protein potential

- Nano-scale devices
- Receive transduce and transmit signals
- Select, amplify and filter signals
- Rich repertoire of analogue and logic operations
- Form networks that integrate and process signals, *therefore*
- *Control and drive all cellular processes*
- *Reconfigure networks – demand, history*
- *Allocate resources – demand, history*

Changing sensor sensitivity – day to night

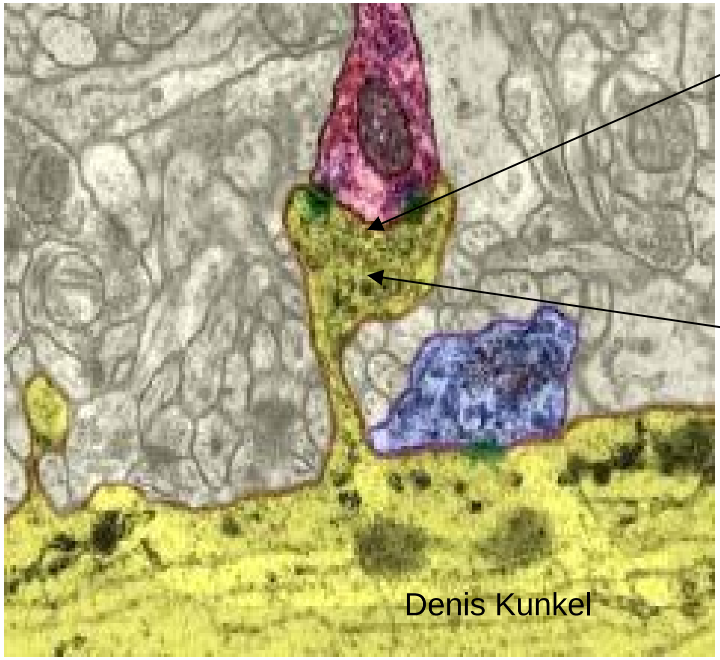
Locust



David Williams, Science 1982

Chemistry is cheaper than Electronics

Cost of signalling at single cortical spine



Synaptic current flowing through receptor ion channels

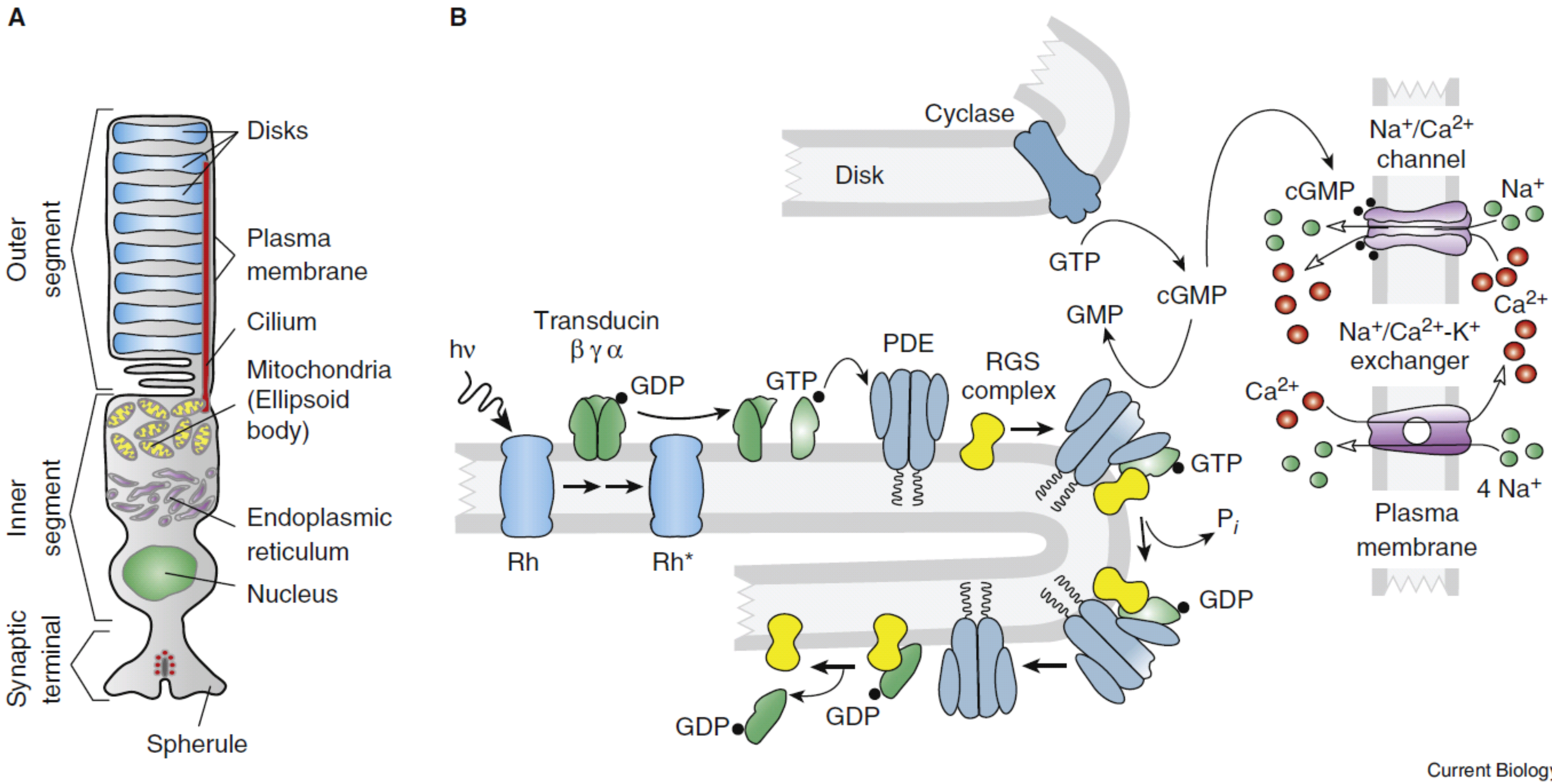
200,000 ions, 67,000 ATPs

Post-synaptic Ca transient triggered by G-protein coupled receptors

1000 ions   1000 ATP

Attwell & Laughlin, 2001

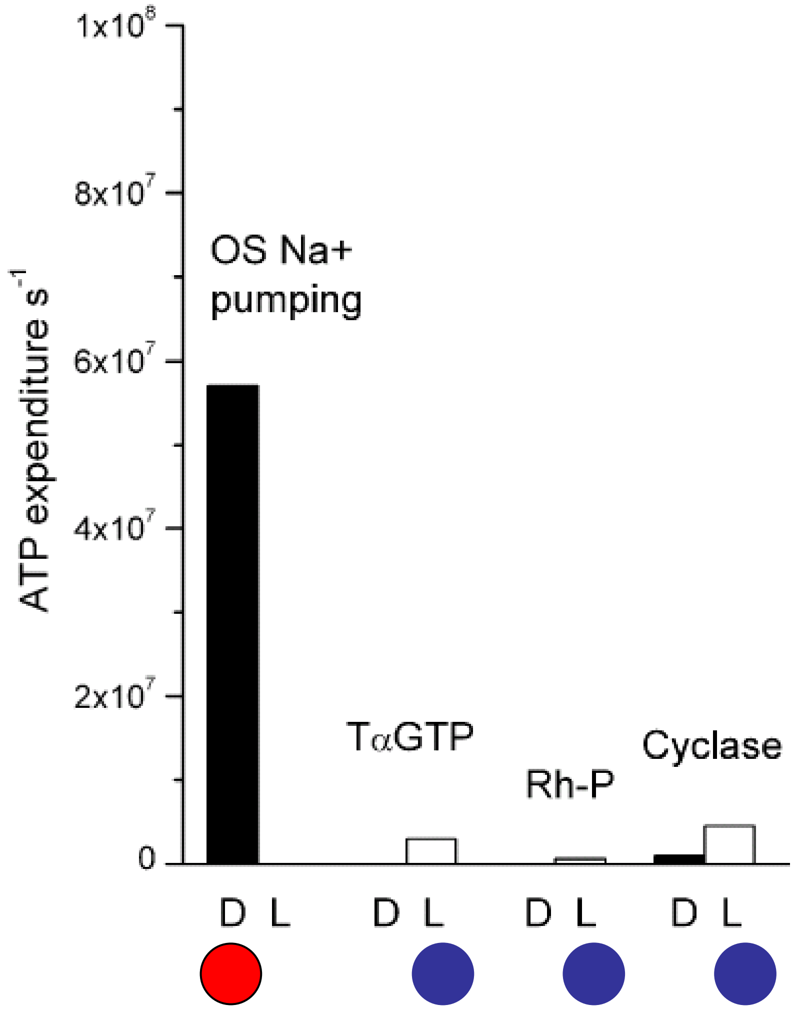
A heavy weight chemical signalling network rod photoreceptors



Fain, Hardie & Laughlin, Current Biology 2010

Energy costs of
electrical and **chemical**
signalling in a mouse rod
photoreceptor

Okawa, Sampath, Laughlin & Fain, 2008



Secret 11

Mix electronics and chemistry

Getting the mix balance pro and cons

- **Chemistry**
- versatile
- computationally powerful
- economical
- links all levels
- slow
- no universal currency at a node

- **Electricity**
- less versatile
- computationally weak
- expensive
- isolated (uses chem)
- fast
- universal currency, "instantaneous" integration of many to one.