More perfect than we imagined: A physicist's view of life

Science on Saturday
Princeton Plasma Physics Laboratory
Saturday 5 March, 2005

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http://www.princeton.edu/~wbialek/wbialek.html

Seeing the world through sound

image from Ohio Department of Natural Resources, Division of Wildlife
http://www.dnr.state.oh.us/wildlife/resources/wildnotes/pub372.htm

Discrimination of jittered sonar echoes by the echolocating bat, Eptesicus fuscus: The shape of target images in echolocation. JA Simmons, M Ferragamo, CF Moss, SB Stevenson & RA Altes, Journal of Comparative Physiology A 167, 589-616 (1990)

Bats navigate by making pulses of (ultra)sound, and listening for the echoes

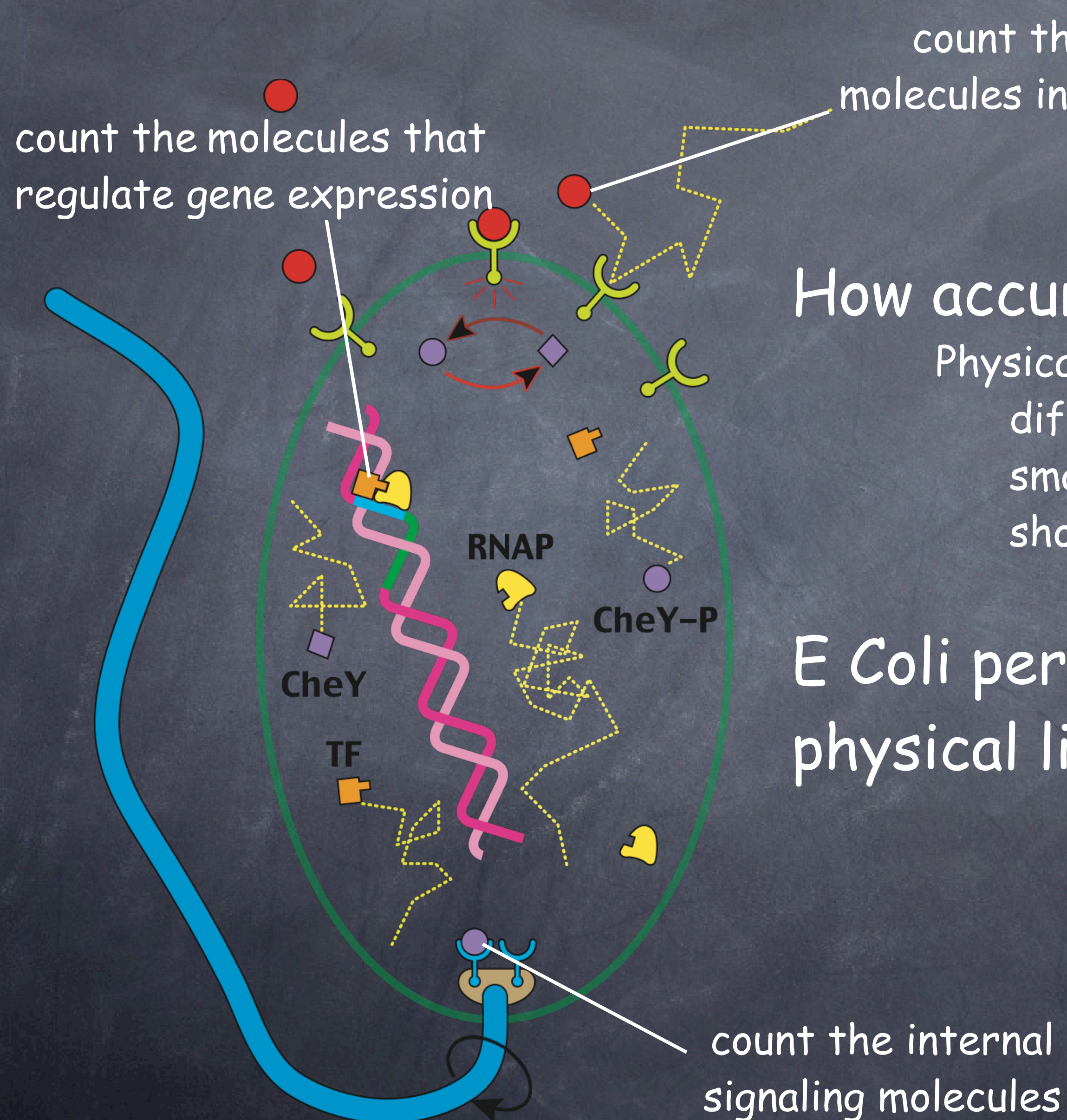
Successful navigation (and finding bugs!) depends on measuring the time at which echoes return

In fact bats can detect timing differences of 10 nanoseconds: 0.00000001 seconds(!)

[compare with Galileo's attempt at measuring the speed of light]

Timing resolution tracks the limit set by background noise ...

Bacteria as molecule counters



How accurately can they count?

Physical limits from:

- diffusion
- small size of receptor sites
- short time to average

E Coli perform close to these physical limits

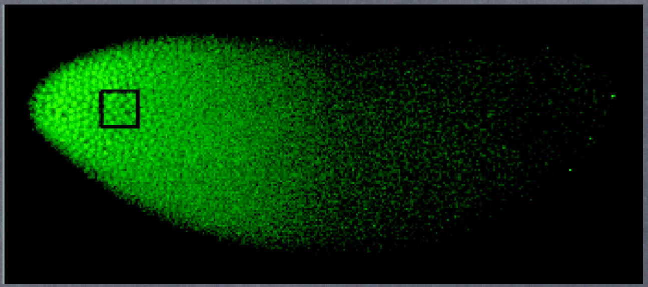
Physics of chemoreception.
HC Berg & EM Purcell,
Biophysical Journal 20, 193-219 (1977).

Physical limits to biochemical signaling.
WB & S Setayeshgar, preprint.
http://arXiv.org/abs/physics/0301001

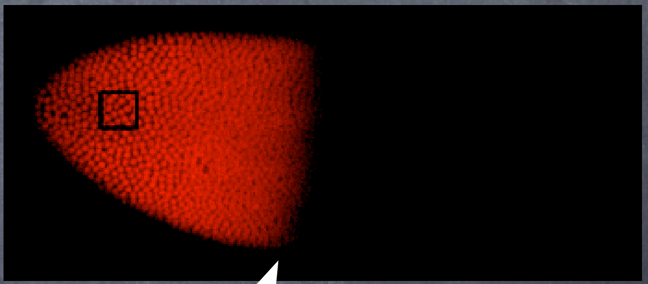
Molecule counting in the first stages of fruit fly development

spatial structure in the adult organism results from spatial patterns of gene expression

mother puts messenger RNA for bicoid at (future) head of the embryo
stain for bicoid protein



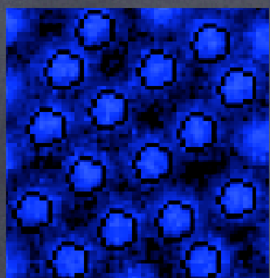
bicoid acts as a transcription factor to activate expression of hunchback
stain for hunchback protein

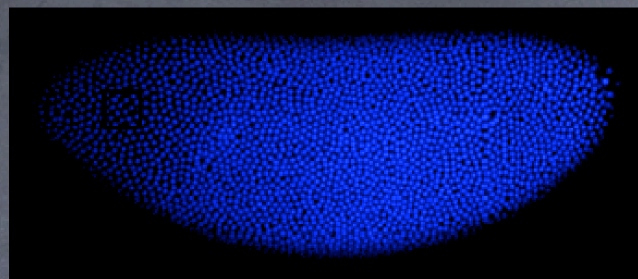


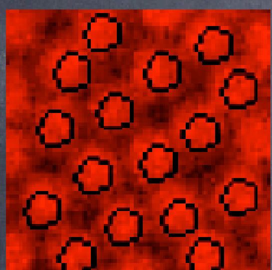
this boundary is the first step in making the "segments" of the fly's body

how accurately can the boundaries be drawn?
or, how precisely can the system measure bicoid concentration?
what are the physical limits to counting bicoid molecules?

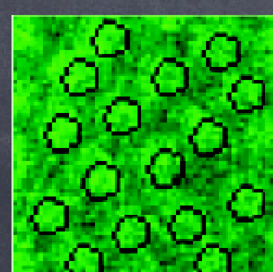
stain the DNA so we can find every nucleus ...







and then in each nucleus we can measure the bicoid (bcd) and hunchback (hb) concentrations



The hunchback level in each nucleus gives a "readout" of the bicoid concentration with a precision of better than 10%

this is enough that boundaries can be drawn with an accuracy of one nucleus (!)

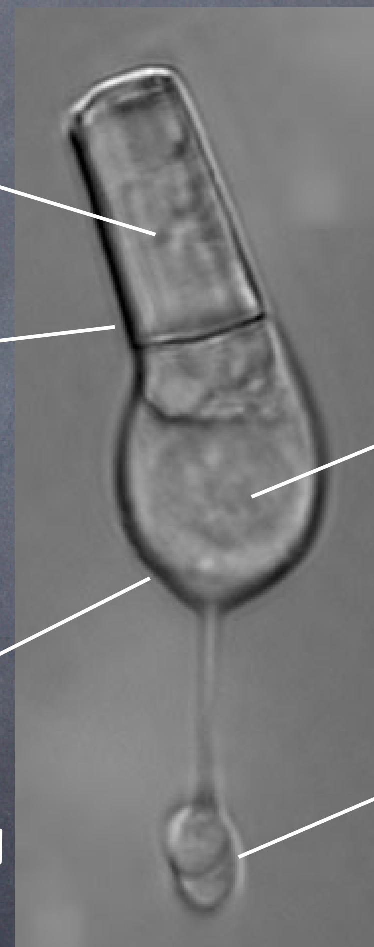
but the physical limits predict that this would take hours ...

But if nuclei communicate to "agree" about the bicoid level, the observed precision requires only ~1 minute (can we detect this communication?)

Biophysics problems in early embryonic development: Precision and dynamics in the bicoid morphogen gradient.
T Gregor (PhD thesis, 2005)
advisors: WB, DW Tank & EF Wieschaus

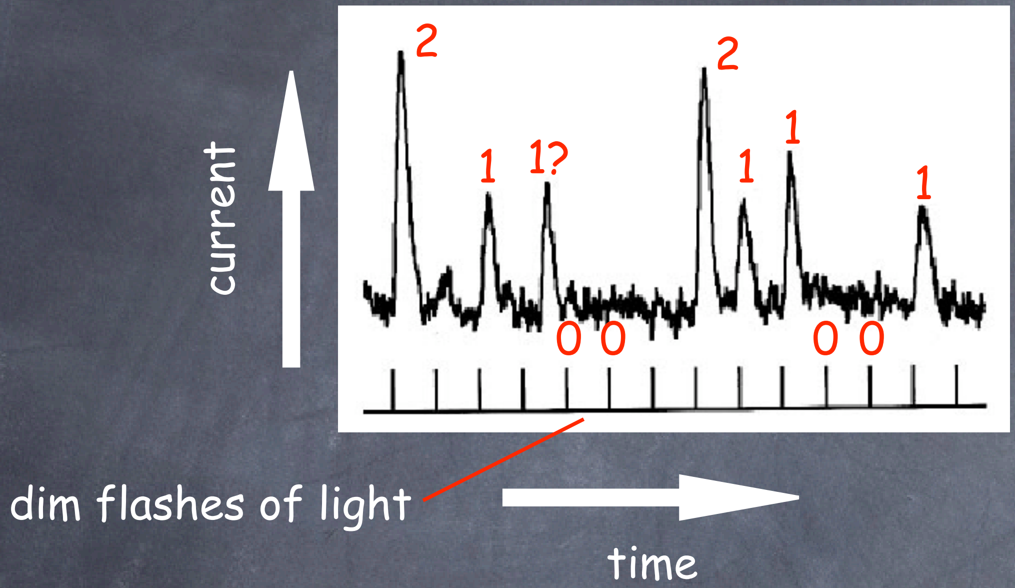
Where vision begins (at night) ...

Rod photoreceptor cell in the retina



images from MJ Berry & FM Rieke

"suck" the rod cell into a pipette and collect the electrical current flowing across the membrane ....



responses to 0, 1, 2 quanta of light (photons)!

small background "rumbling" noise

spontaneous events (1?)

[a few words about history]

Single photon detection by the rod cells of the retina.
FM Rieke & DA Baylor,
Reviews of Modern Physics 70, 1027-1036 (1998).

Single photon counting involves optimization at many levels:

The rhodopsin molecule itself

The biochemical network for amplification of single molecular events

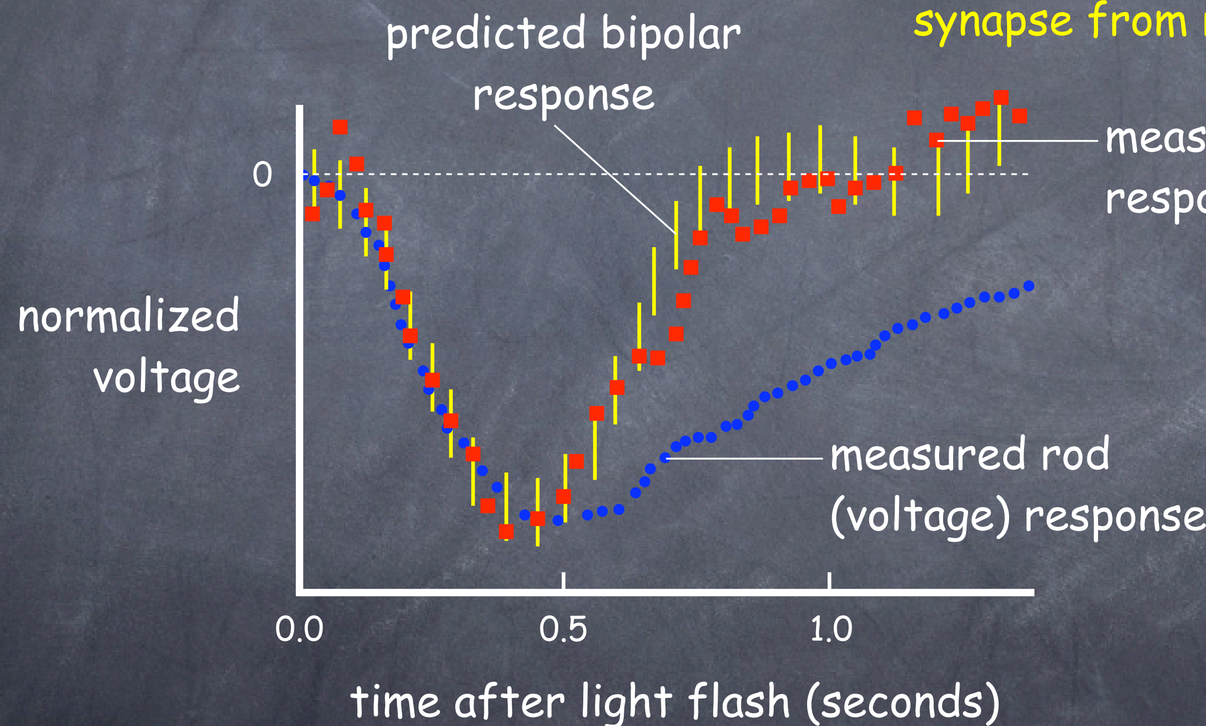
Filtering and nonlinearity in the synaptic network of the retina

Learning

How can the synaptic network of the retina separate single photon signals from background noise?

just the right amount of averaging over time:
smooth out the noise, don't smear the signal

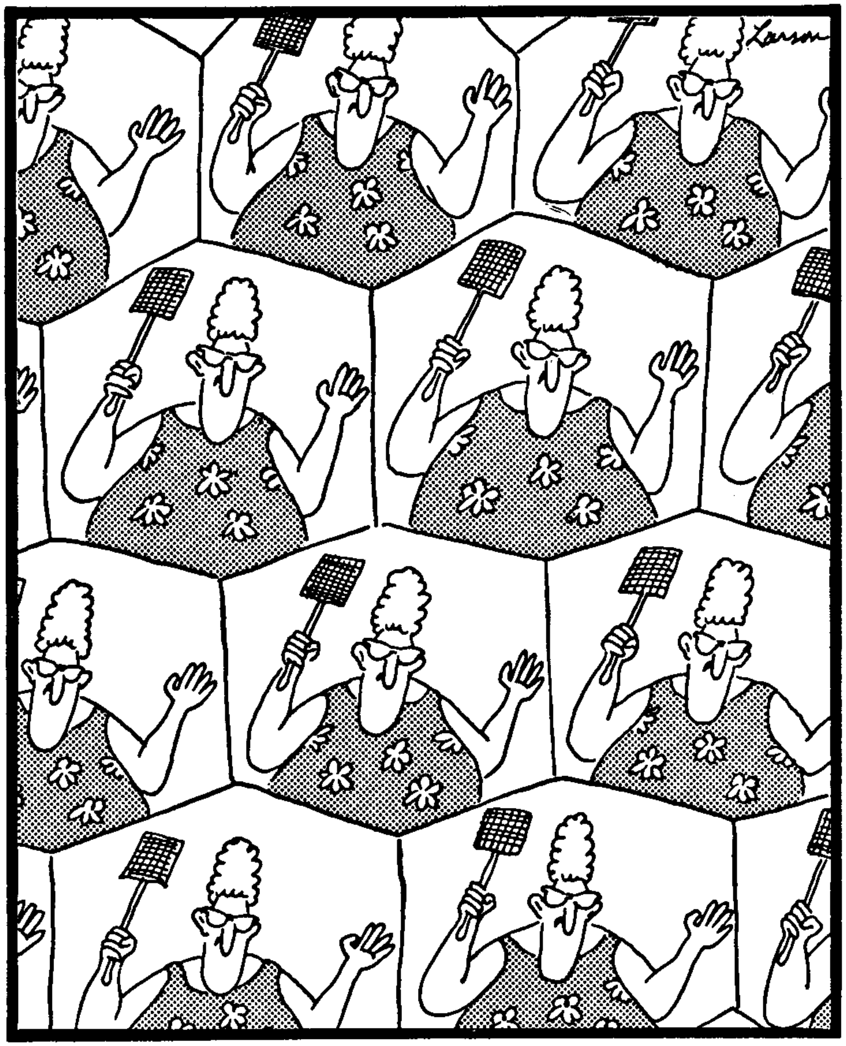
first chance for averaging:
synapse from rod to bipolar cell



Optimal filtering in the salamander retina.
F Rieke, WG Owen & W Bialek,
in Advances in Neural Information Processing 3,
R Lippman, J Moody & D Touretzky, eds, pp 377-383
(Morgan Kaufmann, San Mateo CA, 1991).

more to say about this synapse ...
Nonlinear signal transfer from mouse rods to bipolar cells
and implications for visual sensitivity.
GD Field & F Rieke, Neuron 34, 773-785 (2002).

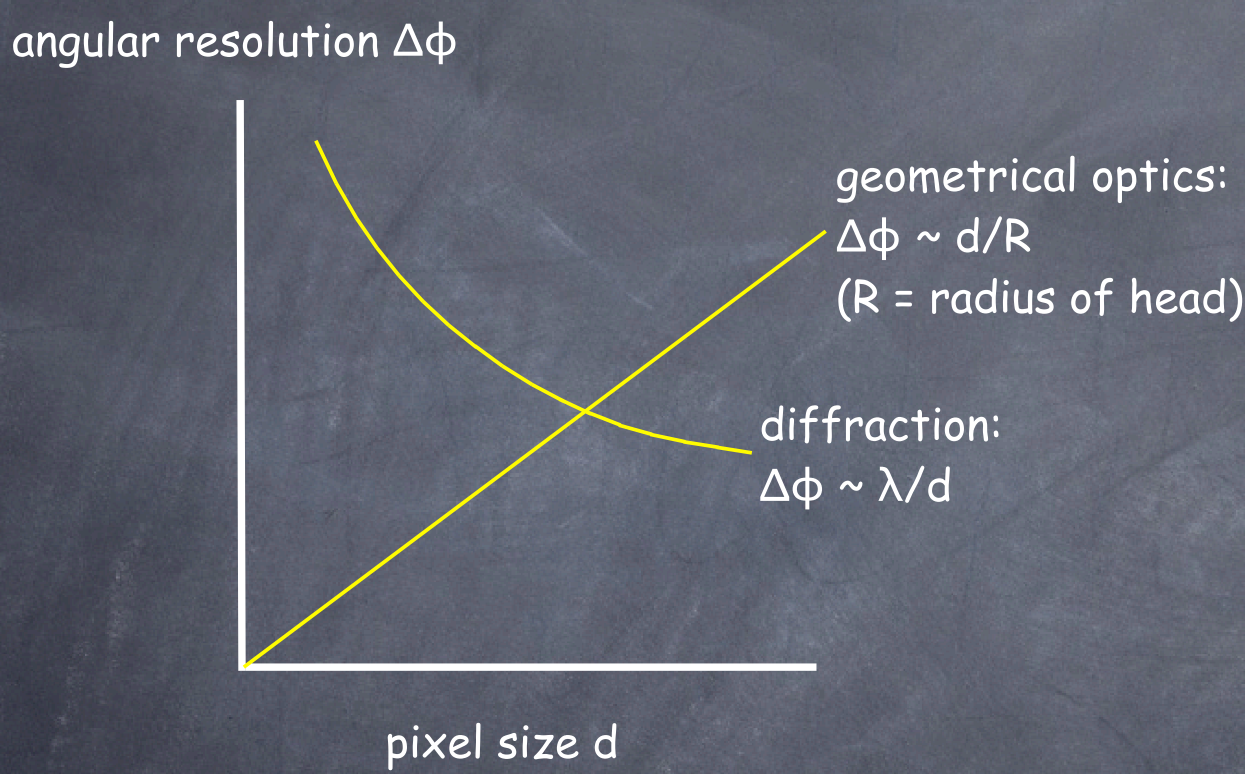
Vision, but in a different animal ...



The last thing a fly ever sees

not as different as Mr Larson thinks

how big should we make the pixels of the compound eye?



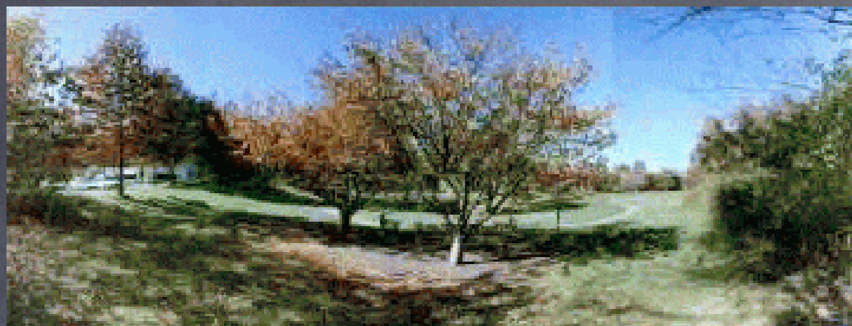
optimum: min $\Delta\phi$ at $d \sim (\lambda R)^{1/2}$

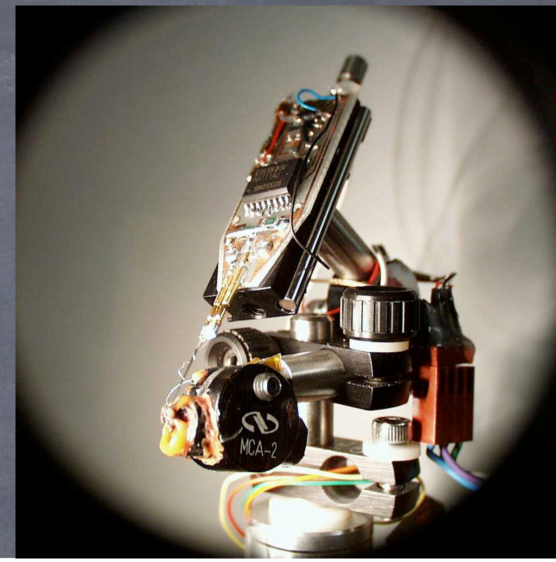
agrees with exp't on many insects with different R
not right when SNR is low ...
need to optimize information not resolution

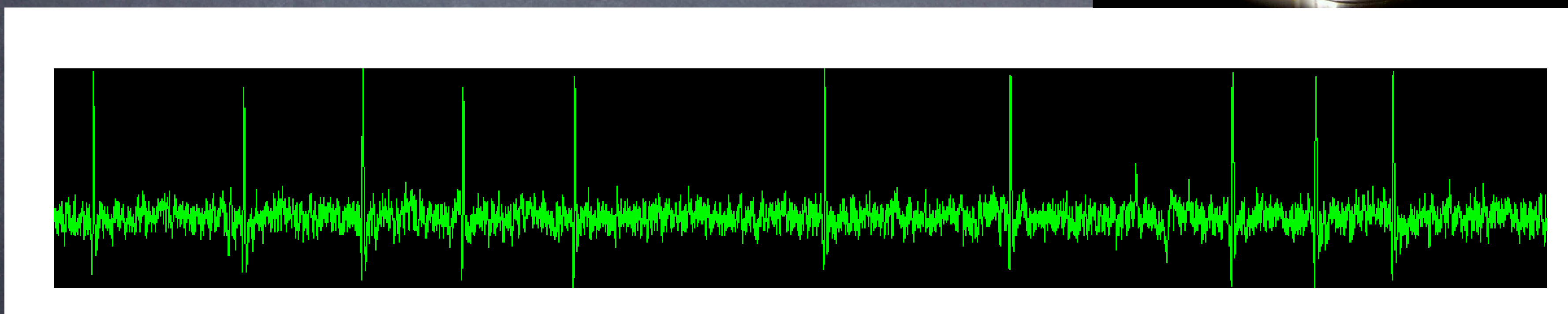
The size of ommatidia in compound eyes.
HB Barlow,
Journal of Experimental Biology <u>29</u>, 667-674 (1952).

see also the Feynman lectures!

place a small wire in the back of the fly's head
to "listen in" on the electrical signals from nerve cells
that respond to movement







Neural coding of naturalistic motion stimuli
GD Lewen, WB & RR de Ruyter van Steveninck,
Network 12, 319-329 (2001).

The fly has to solve (at least) two problems:

estimate motion from the "movie" on the retina, and

represent or encode the result in the sequence of spikes

Optimization principles:

estimates as accurate as possible

coding in spikes should be matched to input signals

To make optimal estimates of motion, the fly has to compute a very specific function ...

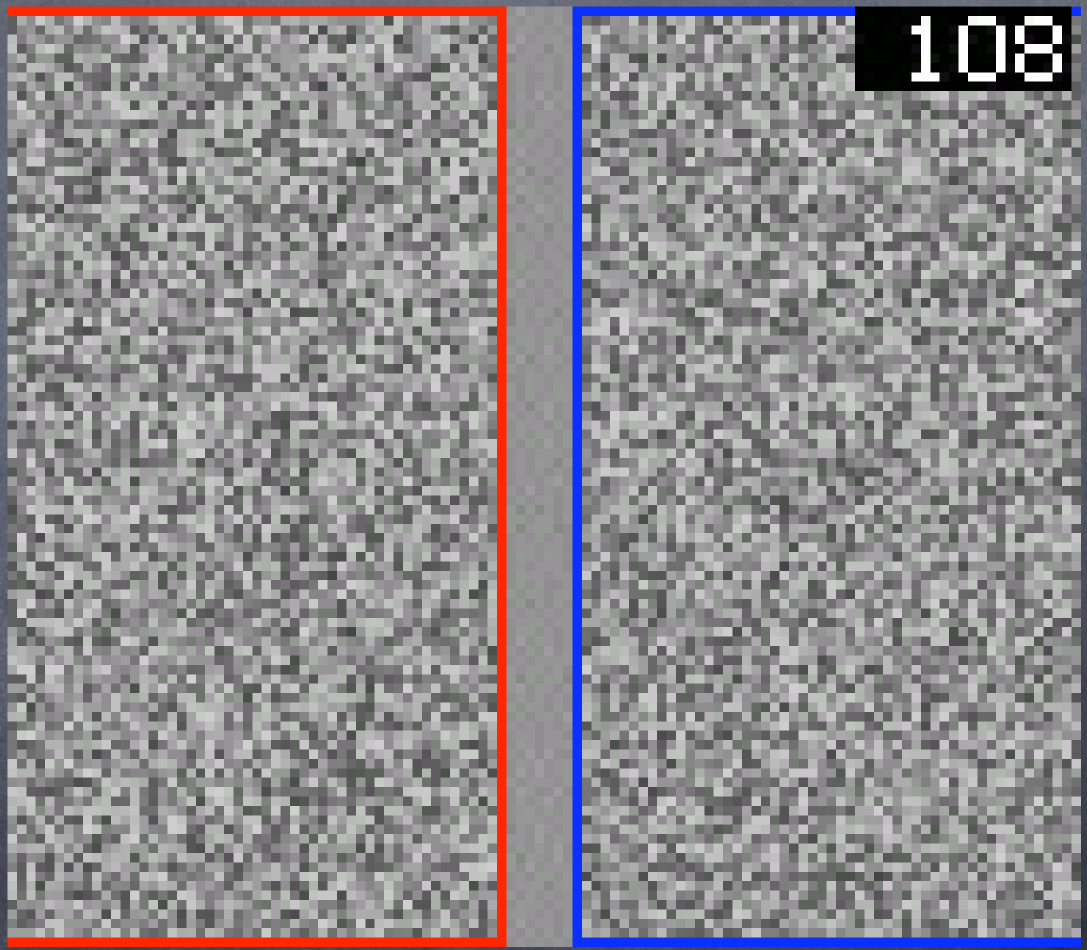
how do we test this prediction?

crucially, even the "best" estimate is a compromise, and so can give the wrong answer ...

seeing motion when nothing is moving

(flies see it too)

we can dissect the whole structure of the fly's strategy for computing motion ...



visual stimuli from R de Ruyter van Steveninck

Even if you're perfect you can still be fooled

Imagine watching someone toss a coin: Heads = H Tails = T

HHTHTTTHTHT	are these sequences "random"?
HHHHHTTTTT	is the coin fair?
HTHTHTHTHT	could there be an underlying pattern?

Suppose that the patterns are changing and you try to track them ...
- there are limits to how reliably you can do this!
- average over time - more when certain something changes,
  - but you might miss something
- what's the best compromise?: averaging time can be surprisingly short
- very hard to convince yourself that things truly are random

These are classic problems, but a new generation of experiments is looking at how close animals come to the limits, and whether they use the optimal time

The rat approximates an ideal detector of change in the rates of reward: Implications for the law of effect.
CR Gallistel, TA Mark, AP King & PE Latham,
Journal of Experimental Psychology: Animal Behavior Processes 27, 354-372 (2001).

So ... we have seen several examples of optimal performance -- performance close to limits set by basic physical principles:

- Nanosecond echo timing in bats
- Molecule counting in bacteria and fruit fly embryos
- Photon counting in vision (humans and others)
- Motion estimation in fly vision
- Learning in a probabilistic environment

Other notions of optimization:

is optimality a general principle?
can we construct a unified theory?

- Efficient coding of signals in spikes
- Optimal model estimation in learning
- Minimum wire length in the brain
- Energy efficiency

Theory: optimality ➡ predictions about how things must work
predictions ➡ new experimental discoveries