How has Computational Neuroscience been useful?

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ANALYSIS

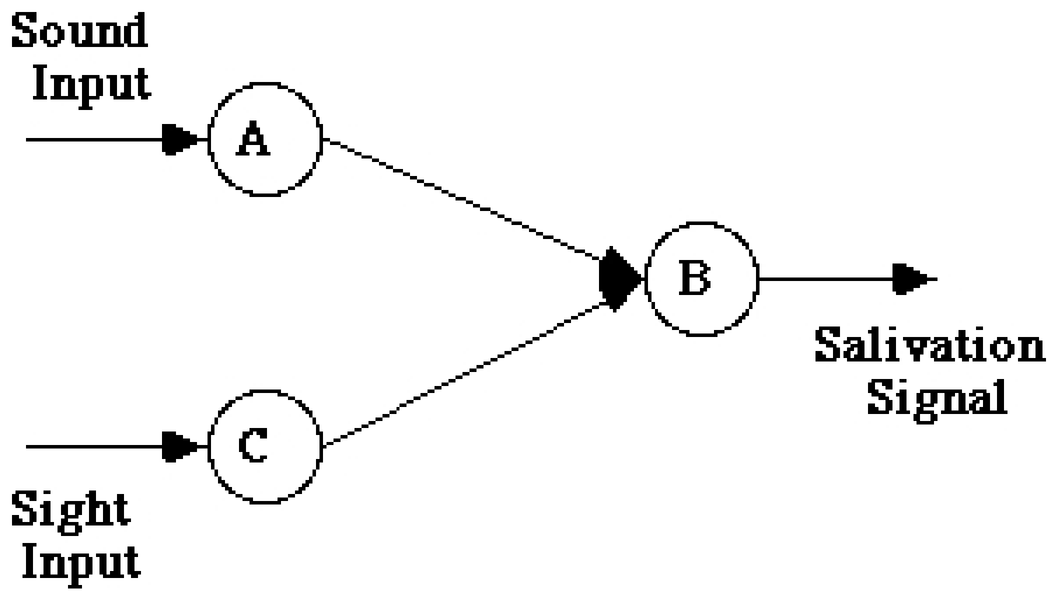
- Designing new theoretically based analysis techniques

Hebb: Explanatory Theory

In his 1949 book "The Organization of Behavior" **Canadian** Donald Hebb specified the following proposed rule

When an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased (Hebb 1949)(figure below from http://www.qub.ac.uk/mgt/intsys/nnbiol.html)

Hebb: Explanatory Theory



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Hebb: Explanatory Theory

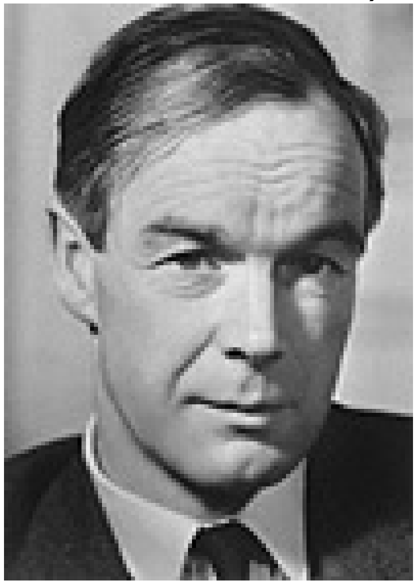
This theory was largely found to be true when [Bliss & Lomo 1973] discovered long term potentiation (LTP). Many experiments that followed have investigated the form of this "growth process".

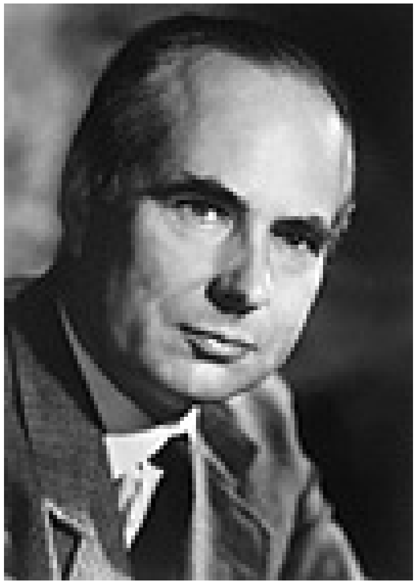
Hebb's Theory is useful not only because it turned out to be correct, but because it influenced the thinking and experiments of many people in a fruitful way.

> "His book, "The Organization of Behavior: A Neuropsychological Theory," wielded a kind of magic in the years after its appearance (Hebb, 1949). It attracted many brilliant scientists into psychology, made McGill University a North American mecca for scientists interested in brain mechanisms of behavior, led to many important discoveries, and steered contemporary psychology onto a more fruitful path." Ray Klein (The Hebb Legacy)

Hodgkin & Huxley: Mechanistic, explanatory model

(Hodgkin, A. L. and Huxley, A. F. (1952) "A Quantitative Description of Membrane Current and its Application to Conduction and Excitation in Nerve" Journal of Physiology 117: 500-544)

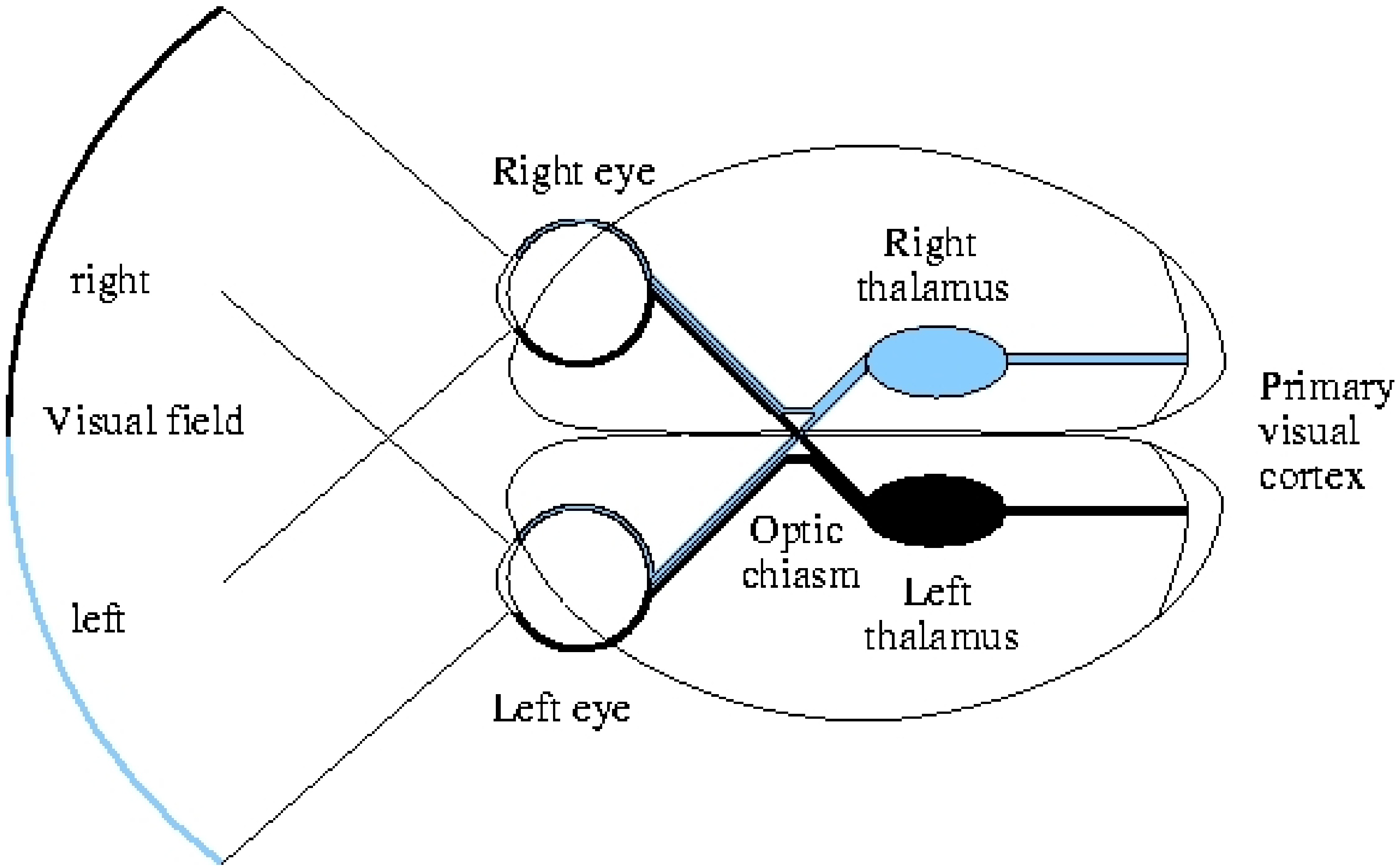




Hodgkin and Huxley won the Nobel prize in Physiology/Medicine in 1963 "for their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane"

Their physiology discovered the rules, but their model explained them.
http://arrhythmia.hofstra.edu/java/hheq.html

Aside: Background on Visual Cortex



(http://www.cs.utexas.edu/users/jbednar/papers/bednar.thesis/node6.html)

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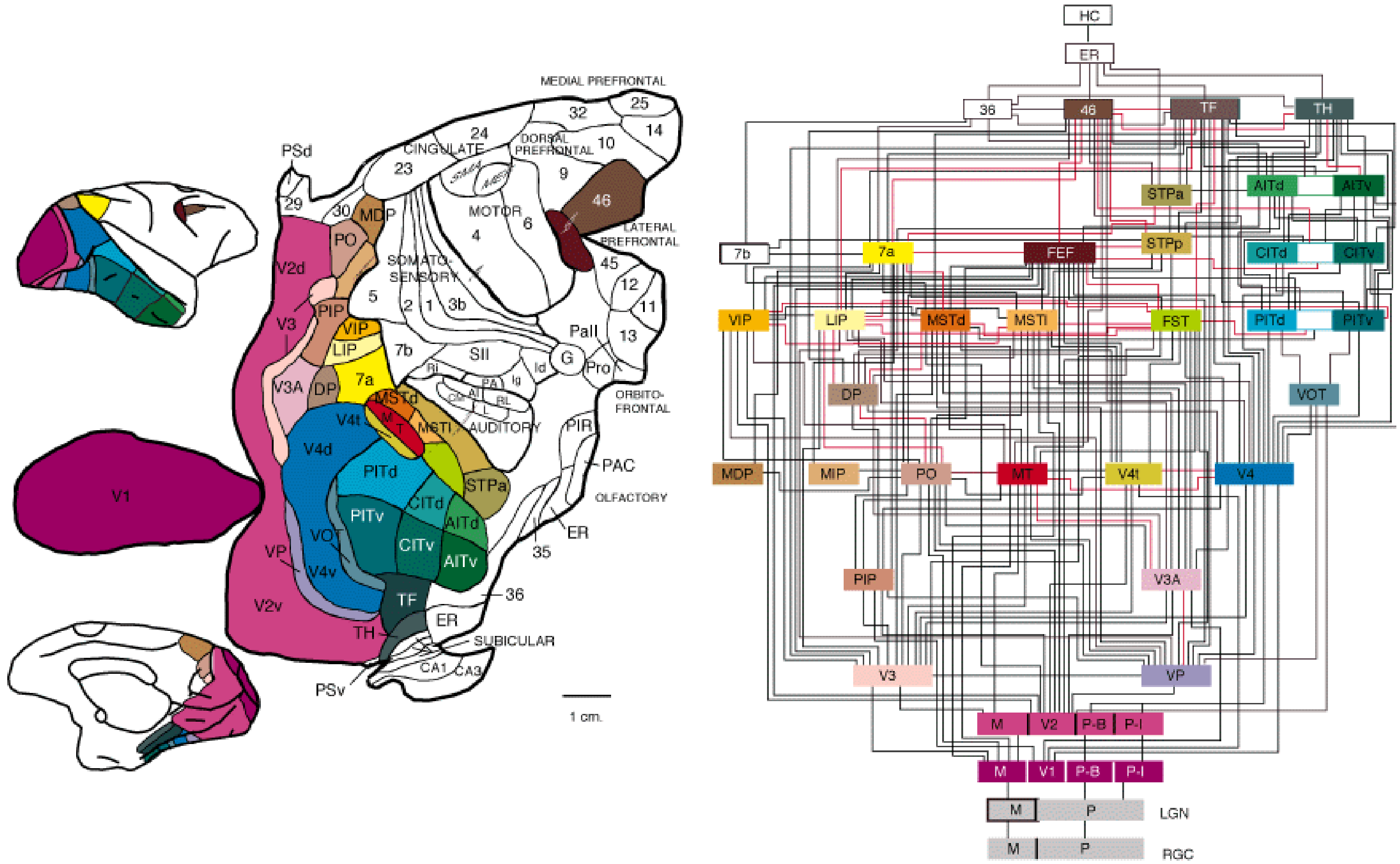


from Felleman, D.J. and Van Essen, D.C. (1991) *Cerebral Cortex* 1:1-47.

Aside: Simple cells in V1

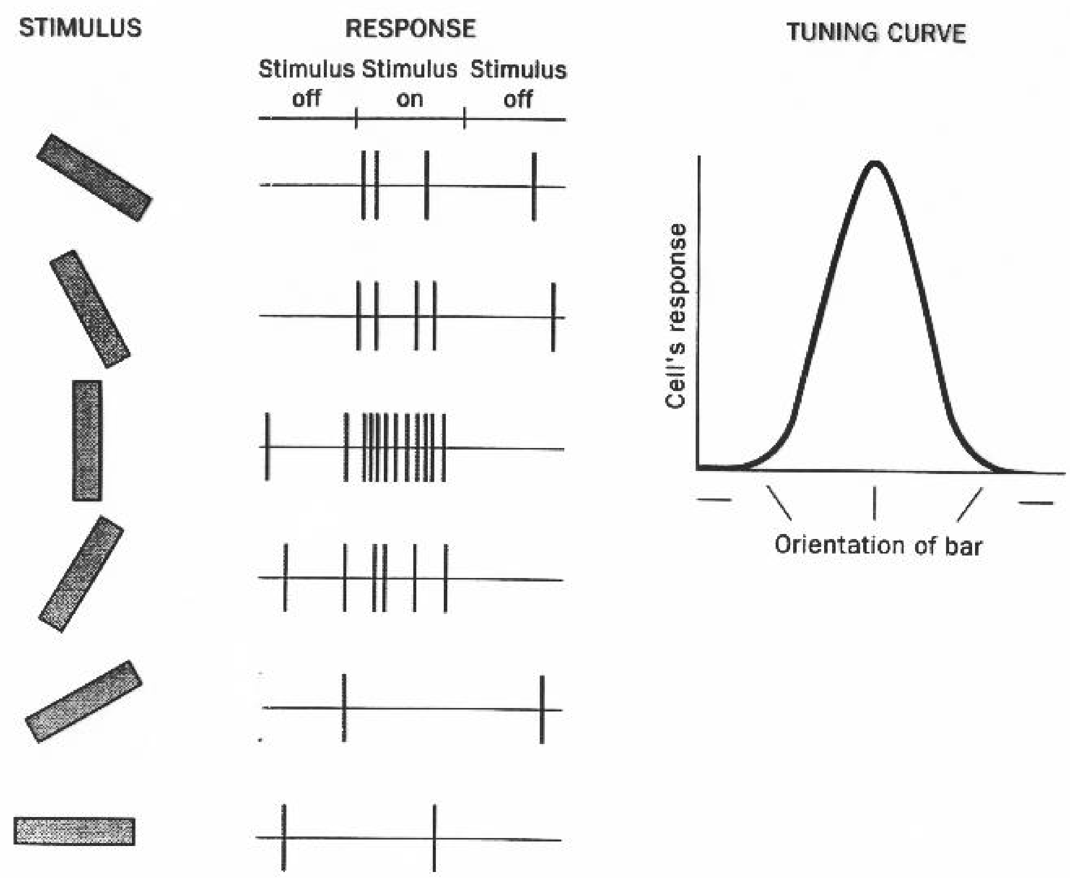
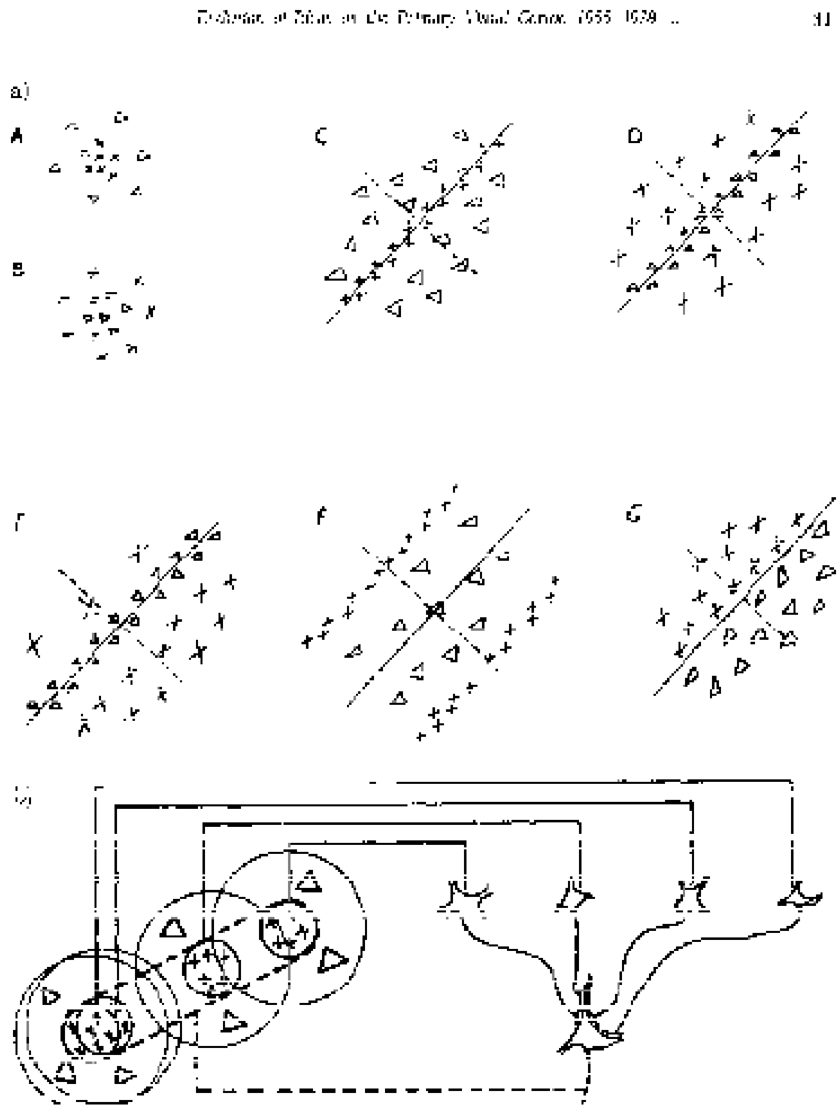


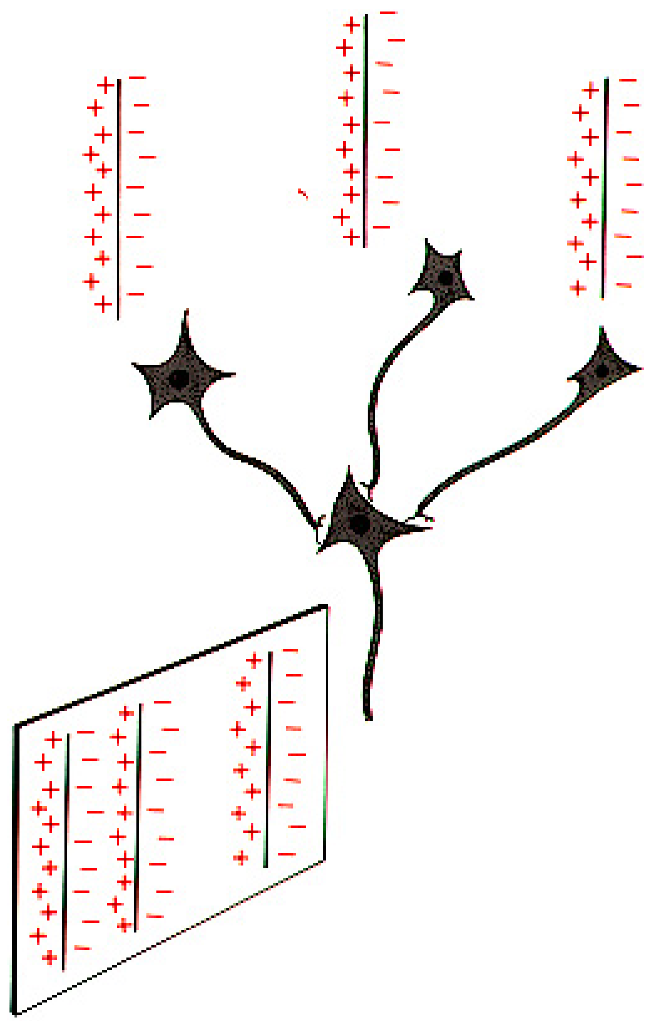
FIGURE 4.8 Response of a single cortical cell to bars presented at various orientations.

http://zeus.rutgers.edu/~ikovacs/SandP/prepI_3_1.html

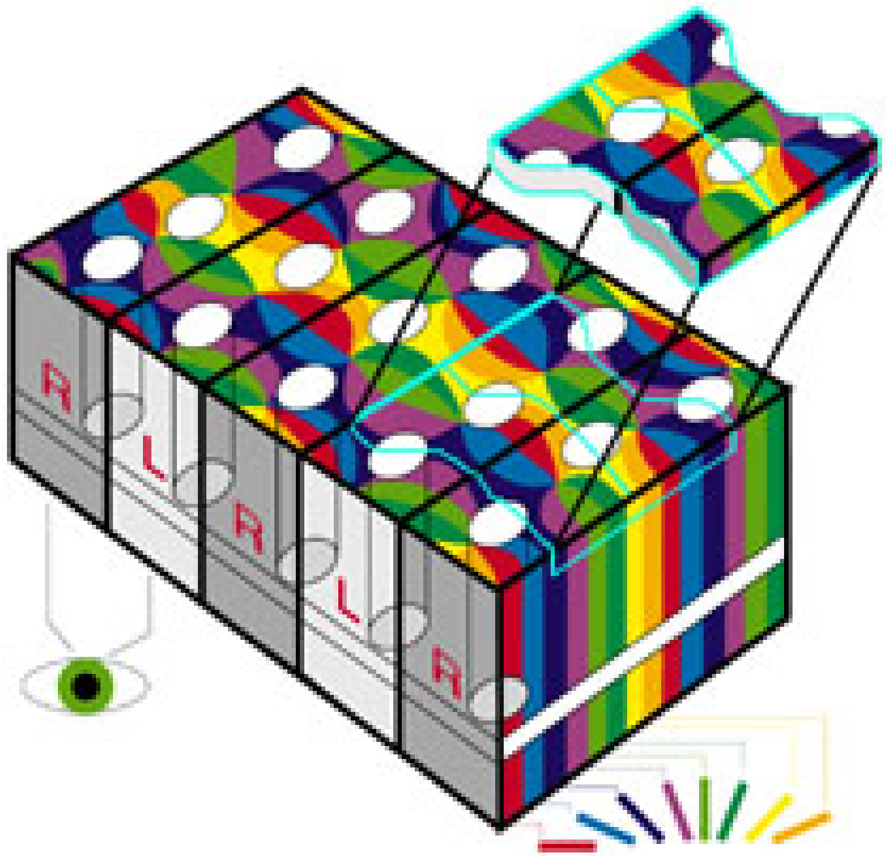
Aside: Simple cells in V1



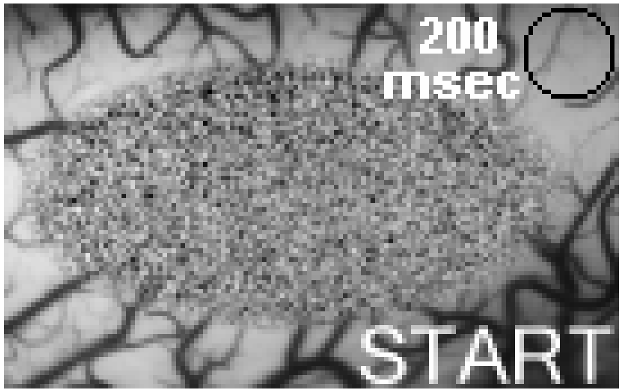
Aside: Complex cells in V1



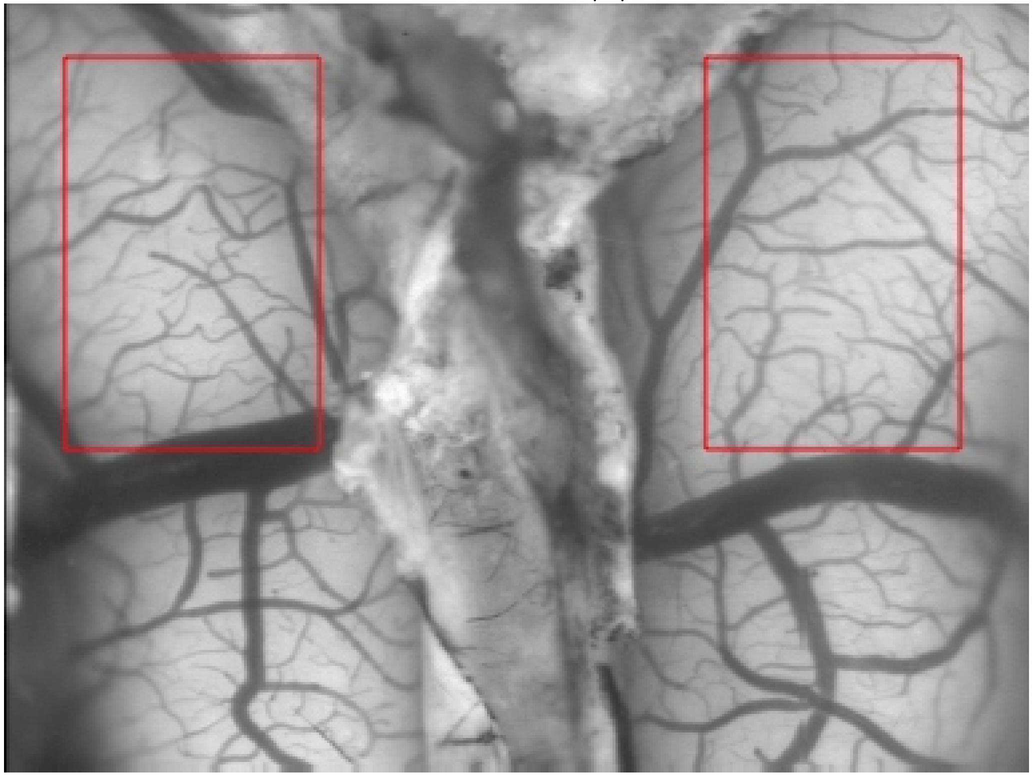
Aside: Ocular dominance and orientation columns



Aside: Orientation columns



http://www.opt-imaging.com/



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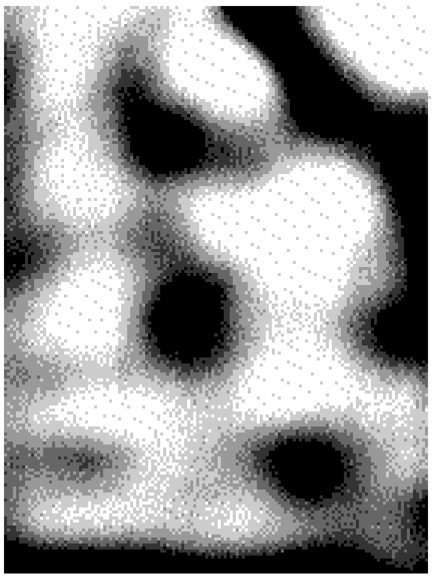

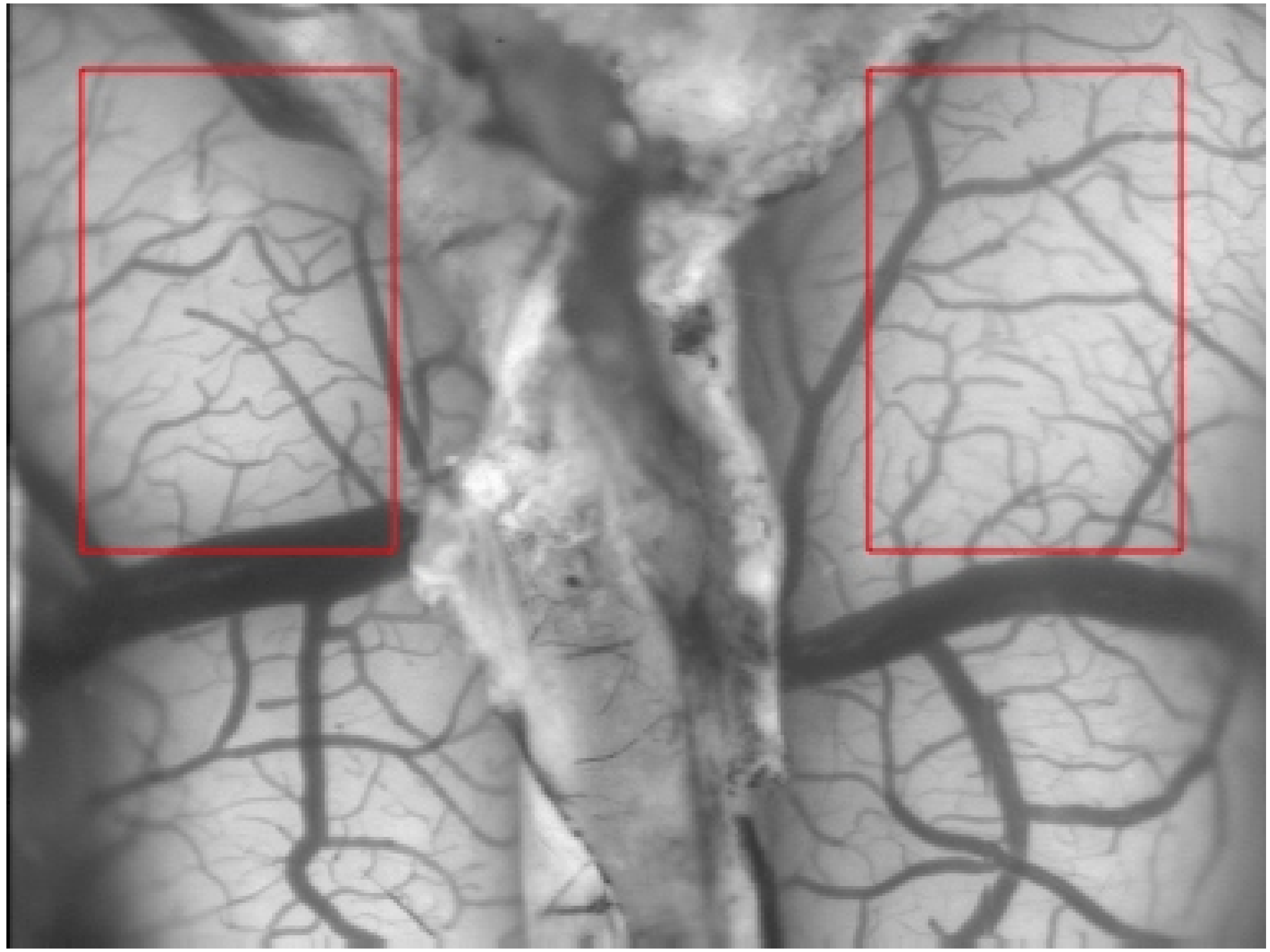

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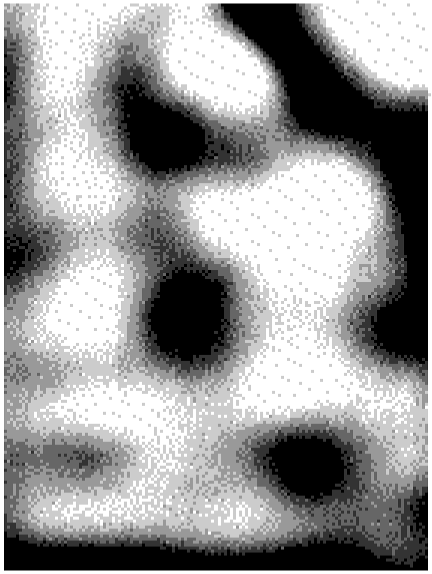
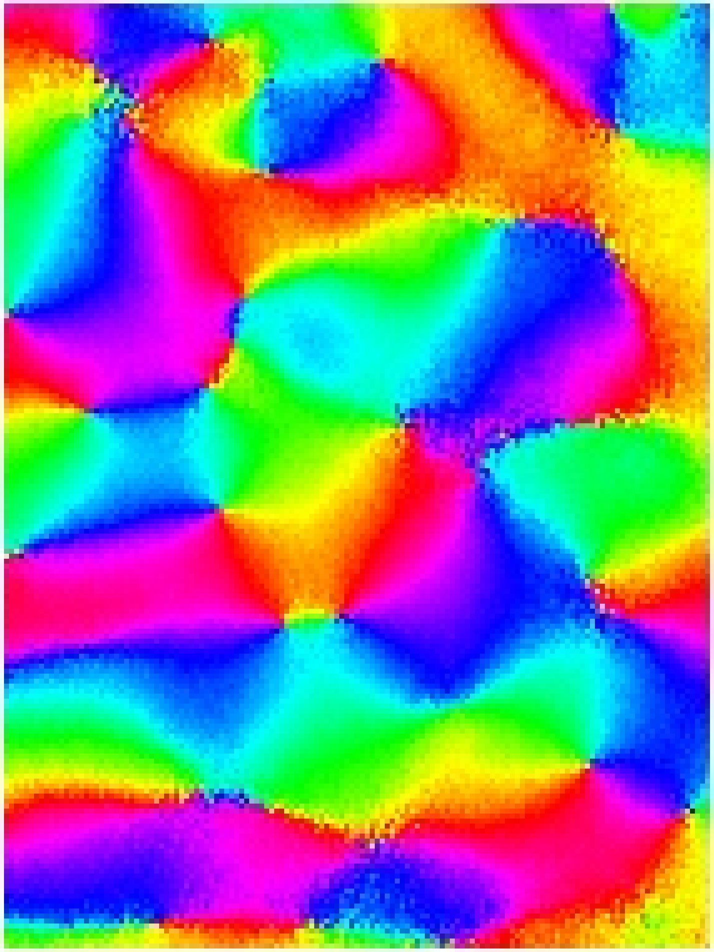
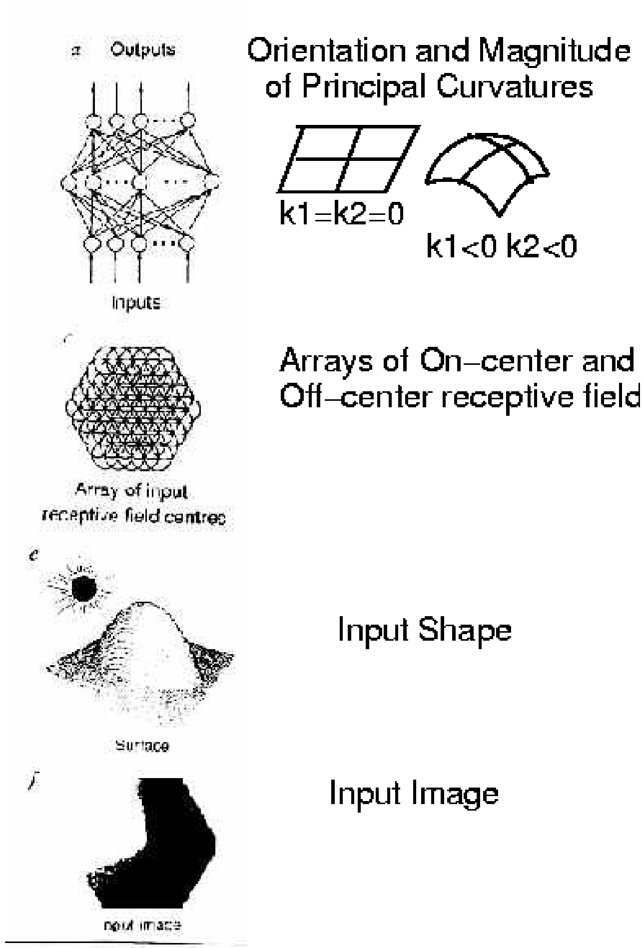
  from Josh Trachtenberg (http://phy.ucsf.edu/ joshua/postdoctoral.html)

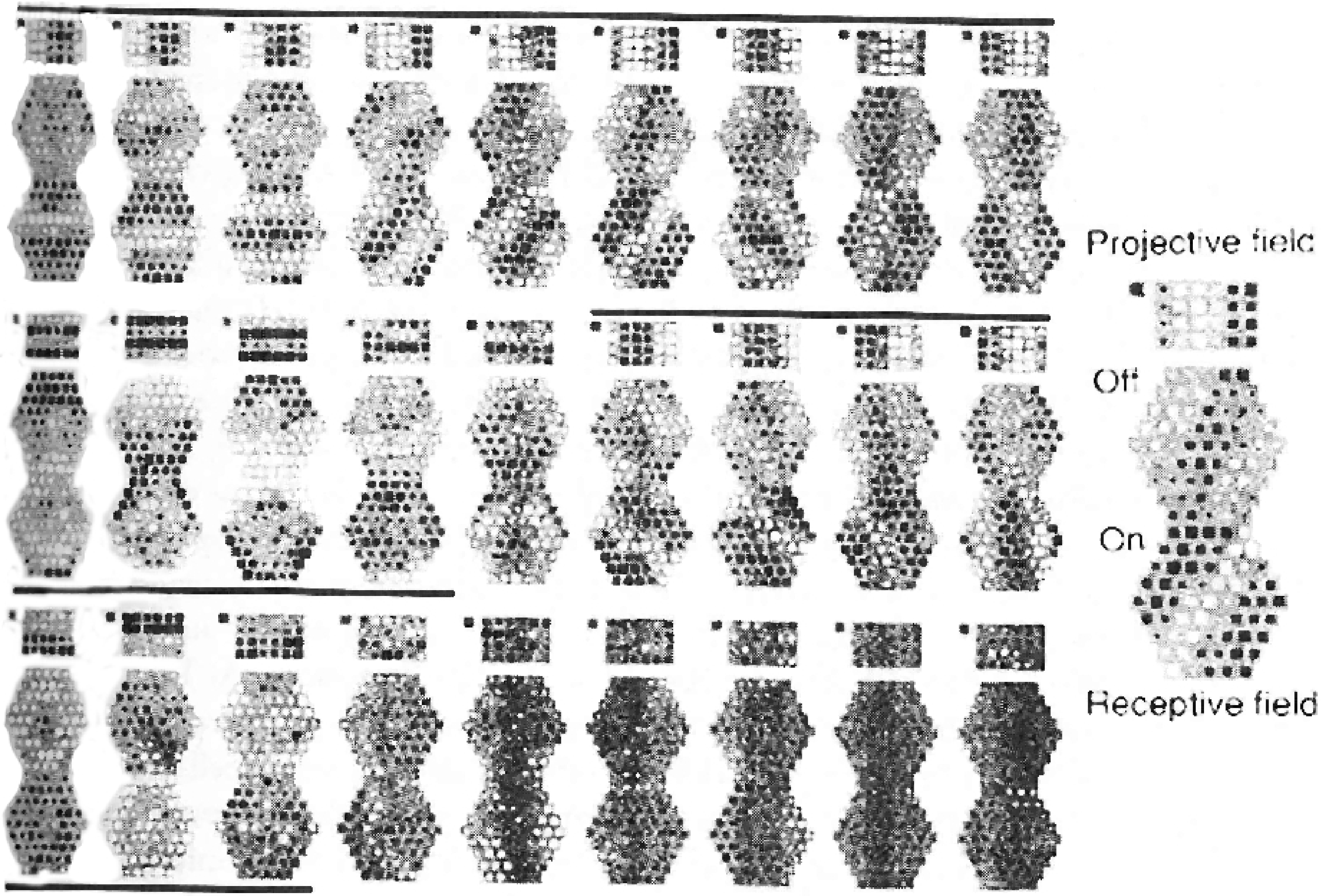
Lehky & Sejnowski: Modeling addressing function

Lehky and Sejnowski trained a back-propagation network to determine information about 3-D shape from a 2-D grayscale picture [Lehky & Sejnowski 1988]



Lehky & Sejnowski: Modeling addressing function

and developed oriented receptive fields

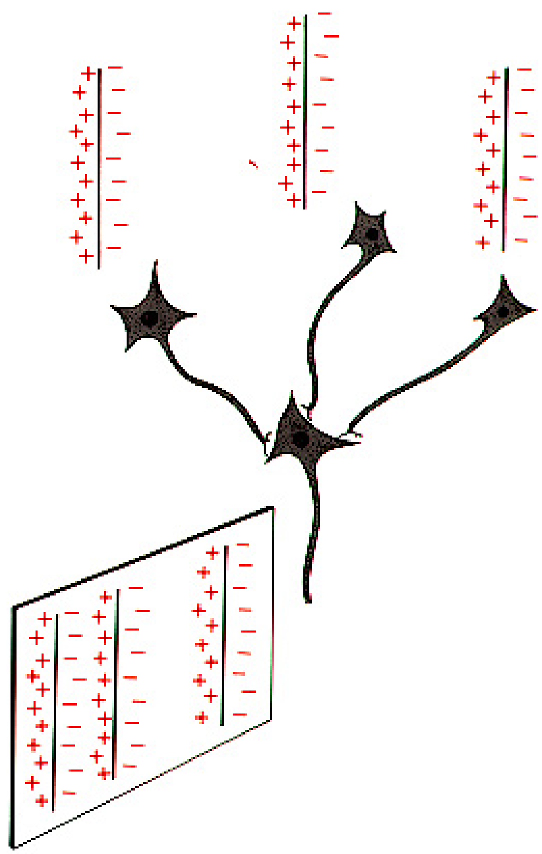


Lehky & Sejnowski: Modeling addressing function

Lehky & Sejnowski's simulations are interesting because they introduced a new view of V1 edge detectors — maybe the V1 edge detectors aren't just edge detectors but are important in the computation of "shape from shading".

Chance, Nelson & Abbott: Modeling addressing architecture

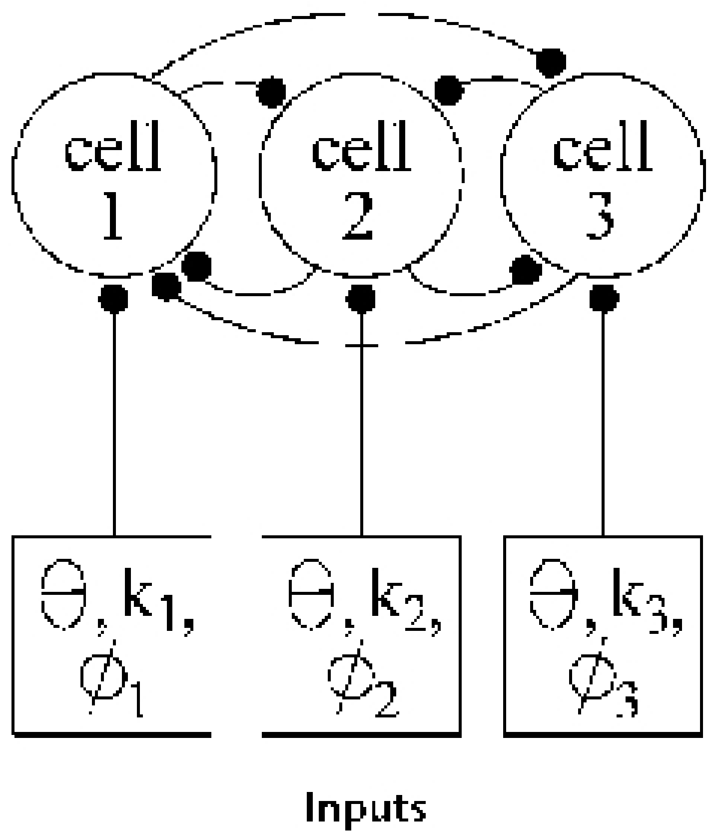
Hubel and Wiesel's original model of complex cells was that they receive input from several simple cells with the same orientation preference but different spatial offsets.



This is a reasonable model but Chance et. al. explored another option....

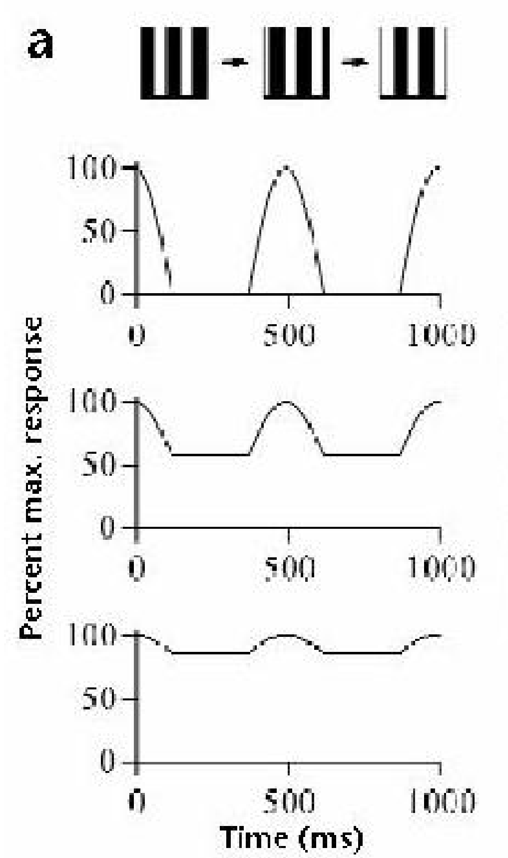
Simple and Complex Cells: Modeling addressing architecture

Chance, Nelson and Abbott proposed that complex cells may be simply simple cells with strong recurrent connections (excitatory between cells with similar spatial frequency and inhibitory between cells with different spatial frequency and no connections to cells with different orientation preference)



Chance, Nelson & Abbott: Modeling addressing architecture

Chance, Nelson and Abbott found they could move a neuron's properties from "simple-cell-like" to "complex-cell-like" simply by increasing the strength of the lateral connections.



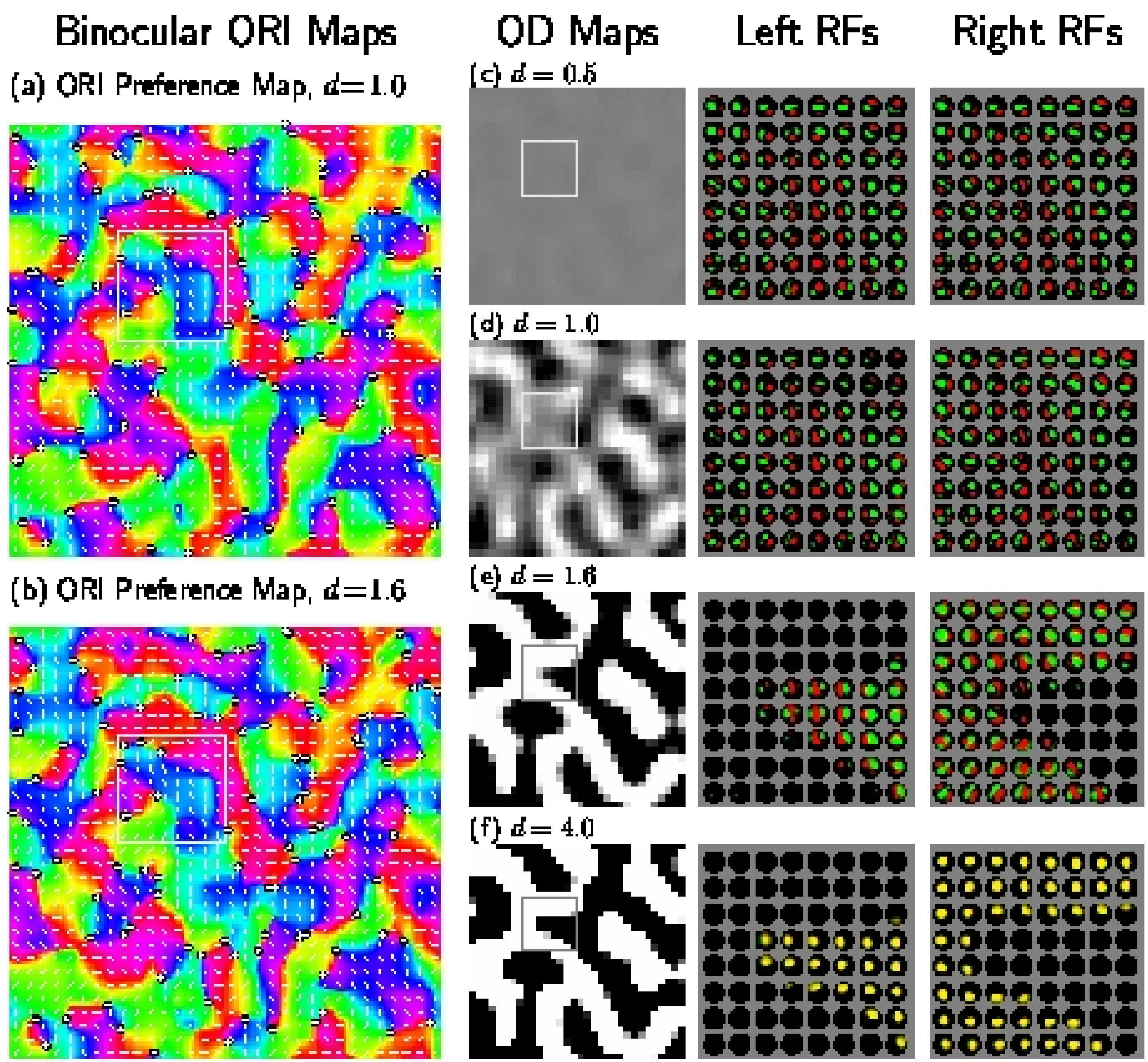
This model may or may not be true, but it is useful because it has people thinking about another possible wiring of complex cells.

Linsker, Miller et al: Modeling addressing learning and development

Many groups have taken the idea of Hebbian learning and competition and showed how you can get the pattern of ocular dominance columns and orientation columns of V1.

Erwin and Miller took realistic rules for initial connecivity and a plausible (Hebbian) learning rule and determined the conditions under which they could develop a V1 map of responses similar to that observed in cat.

Ocular dominance arose from competition between the two eyes and orientation columns arose from competition between on-center and off-center receptive fields. It was tricky to find a parameter regime that enabled both ocular dominance columns to develop and orientation columns.


Binocular ORI Maps
OD Maps
Left RFs
Right RFs
(a) ORI Preference Map, $d = 1.0$
(b) ORI Preference Map, $d = 1.6$
(c) $d = 0.5$
(d) $d = 1.0$
(e) $d = 1.6$
(f) $d = 4.0$

Linsker, Miller et al: Modeling addressing learning and development

Miller showed that ON/OFF competition could explain development of simple cell receptive fields, through the same mechanism by which left/right competition yields ocular dominance columns but in a different parameter regime. He introduced a new idea to those thinking about these issues.

The model made the prediction that disrupting ON/OFF correlations would prevent development of orientation selectivity. This result was confirmed in experiments by Chapman and Godecke (2000), "Cortical Cell Orientation Selectivity Fails to Develop in the Absence of ON-Center Retinal Ganglion Cell Activity", J Neurosci 13:5251-5262,

Computational Models can Address Different Questions

1) Address what kinds of units may be useful for computations— Learn a task and look at the hidden unit representations e.g. [Lehky & Sejnowski 1988],[Zipser & Andersen 1988]

2) Address how a particular computation may occur with neural circuitry e.g. [Chance, Nelson & Abbott]

3) Address how learning occurs (and over what parameter range)— Need a biologically plausible learning algorithm e.g. [Erwin & Miller 1998]

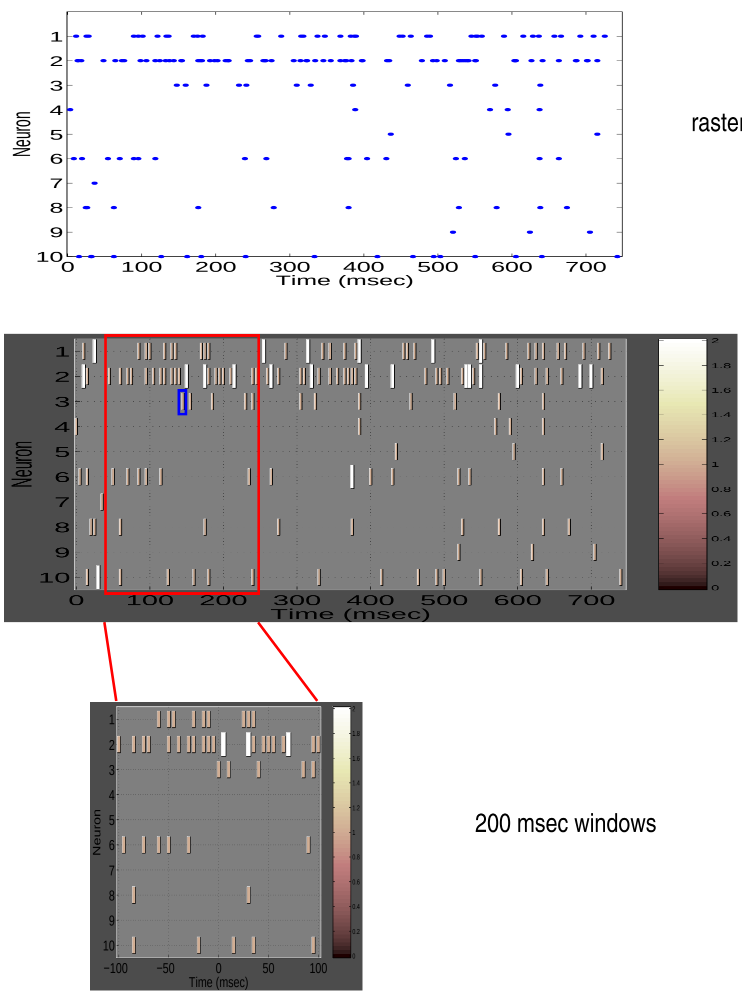
How can Computational Models help Neuroscience

- Help us understand problems the brain is solving
- Force us to be specific in our theories
- Can suggest future experiments and make predictions about their results
- Can show new “possible solutions”

Bialek et. al.: New theoretically motivated analysis techniques

Say you are observing the firing patterns of several neurons

Data Collection



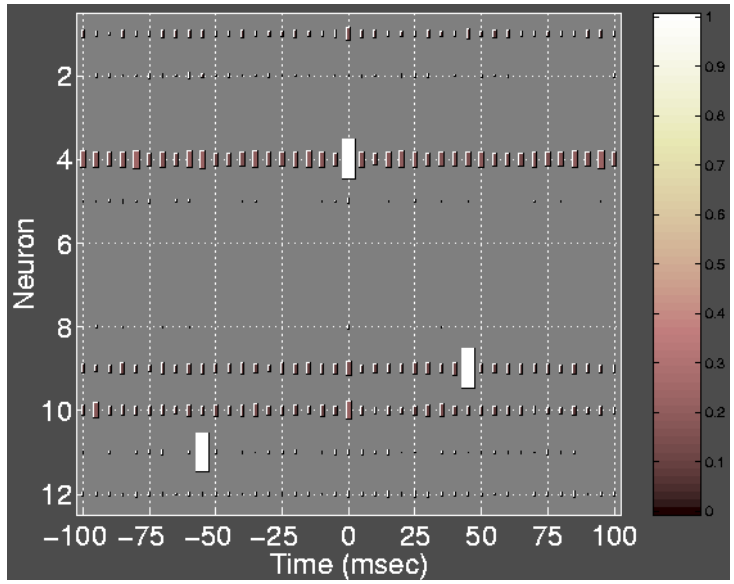
rastergrams

5msec

bins

200 msec windows

Bialek et. al.: New theoretically motivated analysis techniques



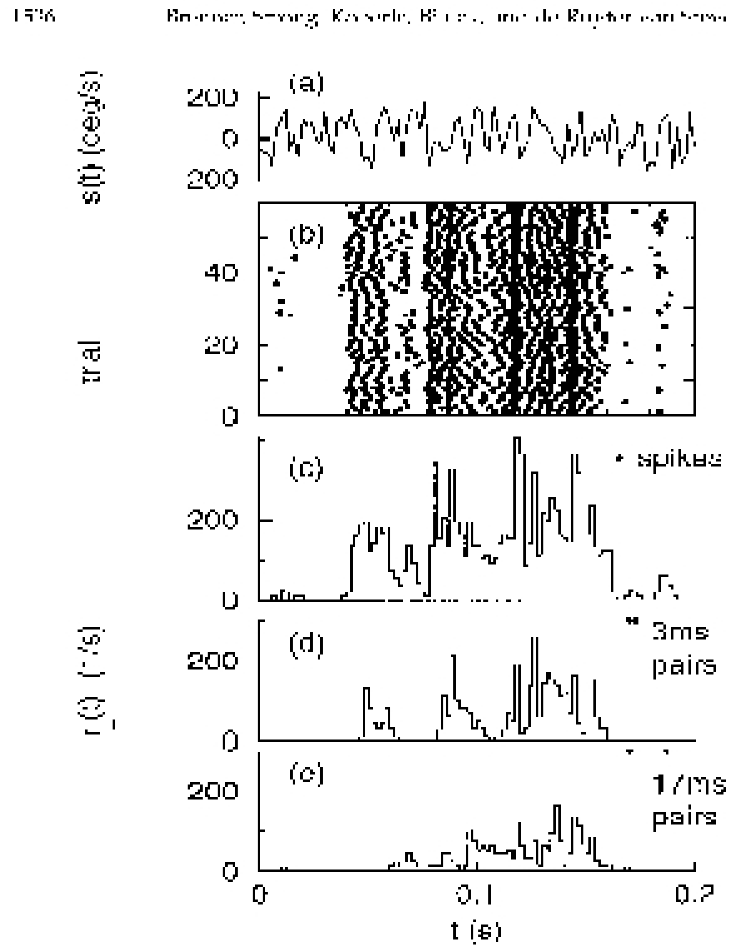
in five minutes of recording, you see that there are several times when neuron 11 fires 55 milliseconds before neuron 4 that fires 45 msecs before neuron C.

How do you determine if this pattern is occuring “more often than chance”, and more importantly that it has a “special meaning”?

You can compute the probability that you would expect this given the firing rates of the neurons, but this probability will depend crucially on the assumptions you make about the firing model.

Bialek and colleagues have developed a method that allows them to compute the information content of any such event (with sufficient data)

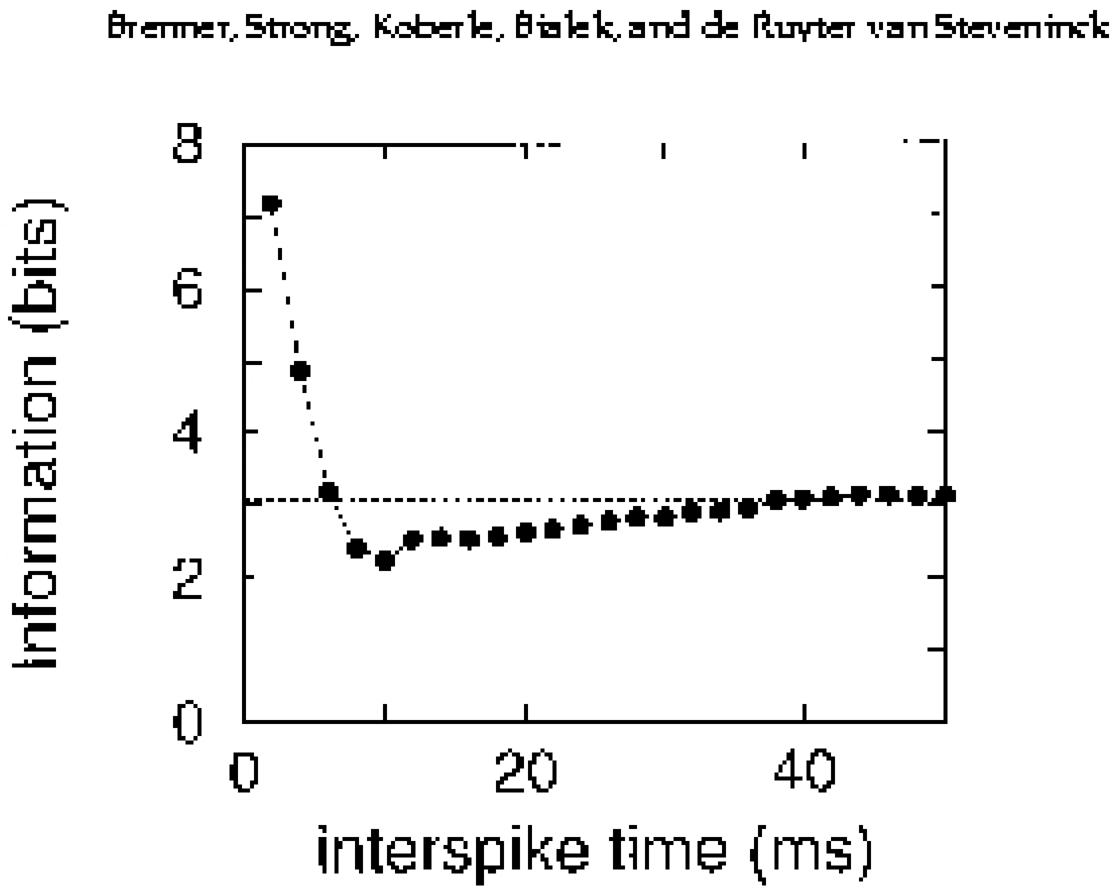
Bialek et. al.: New theoretically motivated analysis techniques



Information (Event;s) = Entropy(P(Event)) - Entropy(P(Event|stimulus history))

$$I(E;s) = \langle \left(\frac{r_E(t)}{\bar{r}_E} \right) \log_2 \left(\frac{r_E(t)}{\bar{r}_E} \right) \rangle_s$$

Bialek et. al.: New theoretically motivated analysis techniques



In the fly visual system, Bialek and colleagues found that two spikes occuring within a few milliseconds of each other contain more than twice the information carried by a single spike.

Bialek et. al.: New theoretically motivated analysis techniques

They concluded that burst spiking is $synergistic$ and with more calculation, they computed that the fly gained "almost a factor of two in resolving power for distinguishing different trajectories of motion across the visual field"

Most importantly, though they introduced a new analysis technique that can be used for any spiking system.

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  - ⋆ Introduce a new way of thinking about something (e.g. Hebb, Lehky&Sejnowski,Chance&Abbott)
  - ⋆ Introduce a new analysis technique (e.g. Bialek)

see also the Nature Neuroscience special issue on Computational Neuroscience (November 2000 Volume 3 Supplement)