NEPR 208 Lecture 3 Sensory Encoding
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How does the nervous system represent sensory information?
What stimuli drive neurons, let's call them sensory 'features'?

How are mechanisms used to construct a sensory representation?
How can a neural code be decoded?
How do properties of sensory neurons influence behavior?

Why is a particular neural code advantageous (or optimal)?
Why are particular mechanisms advantageous?
What design principles influence sensory systems, can they be used for artificial systems?

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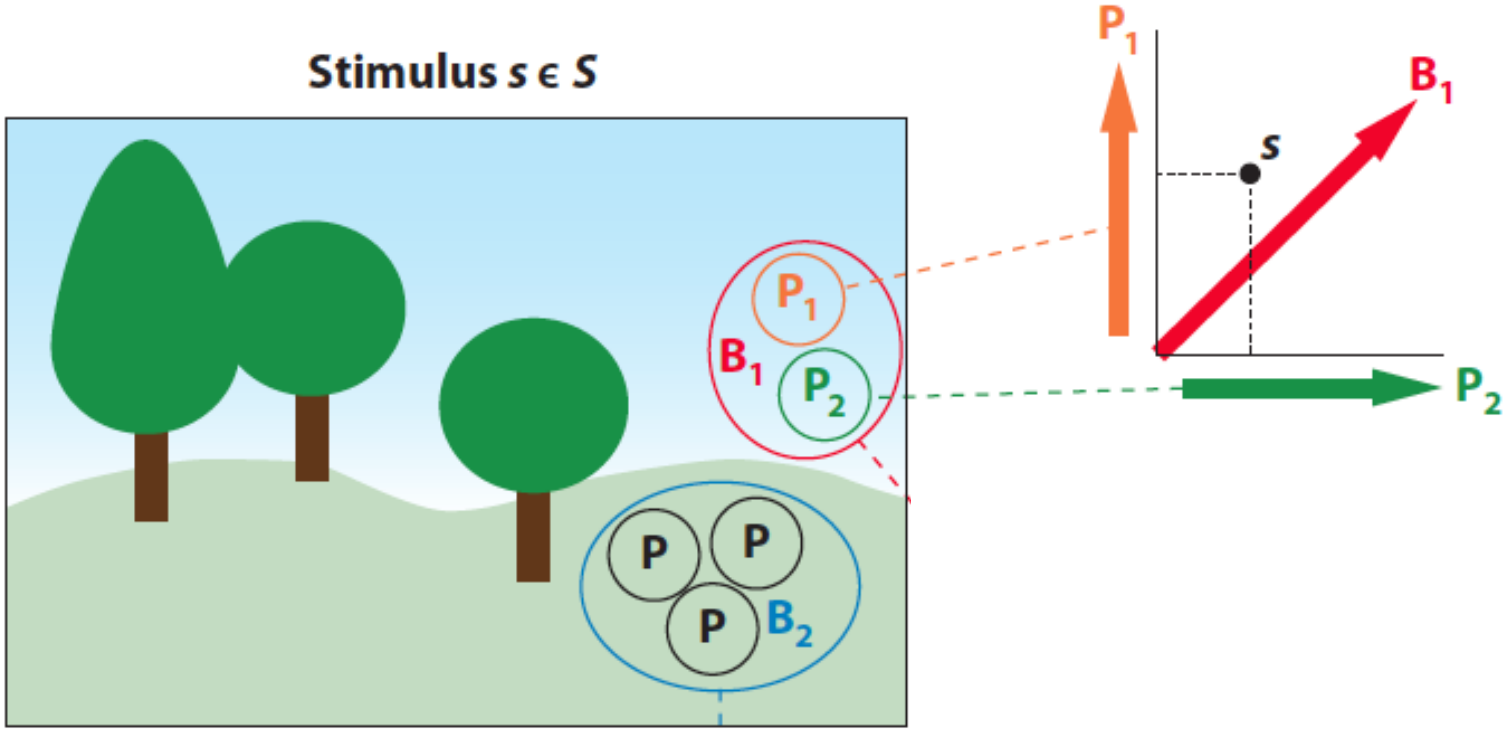
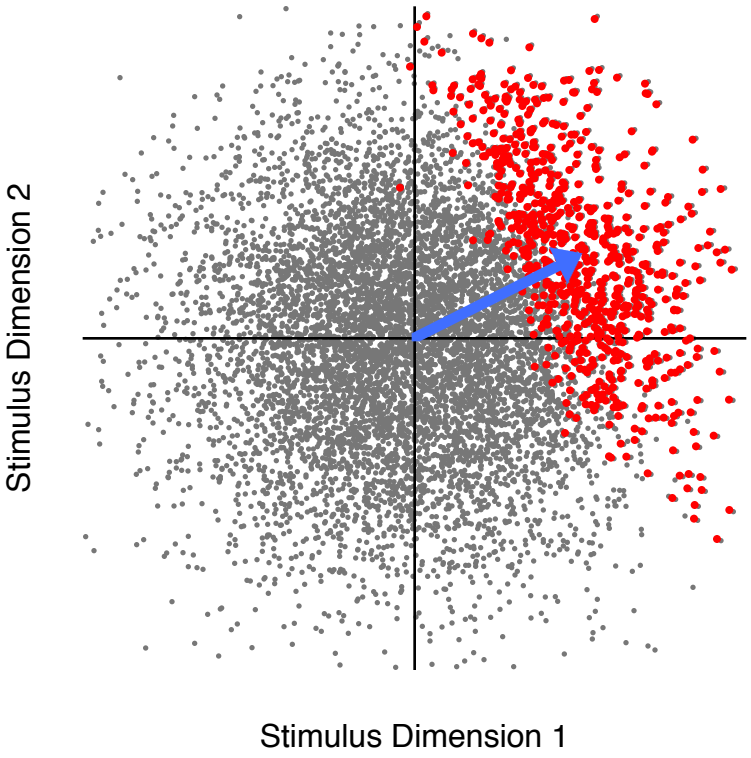
Stimulus space: A geometrical representation of input



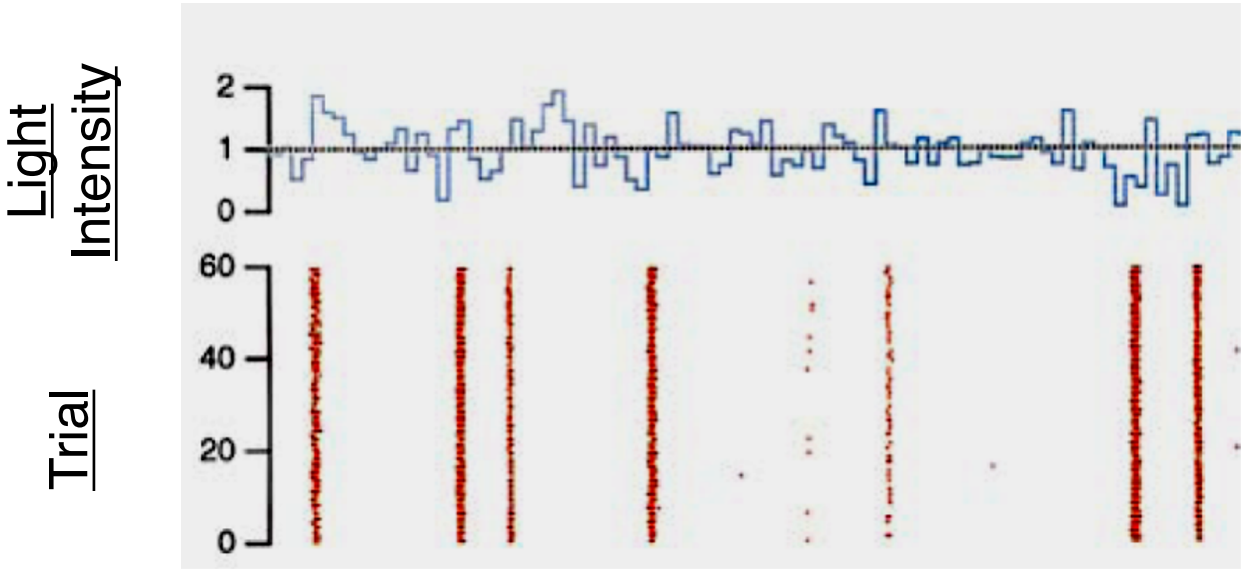
Not the same as “visual space”:
receptors are *dimensions*, not points

Stimulus space: A geometrical representation of input
Receptive field: a direction of sensitivity



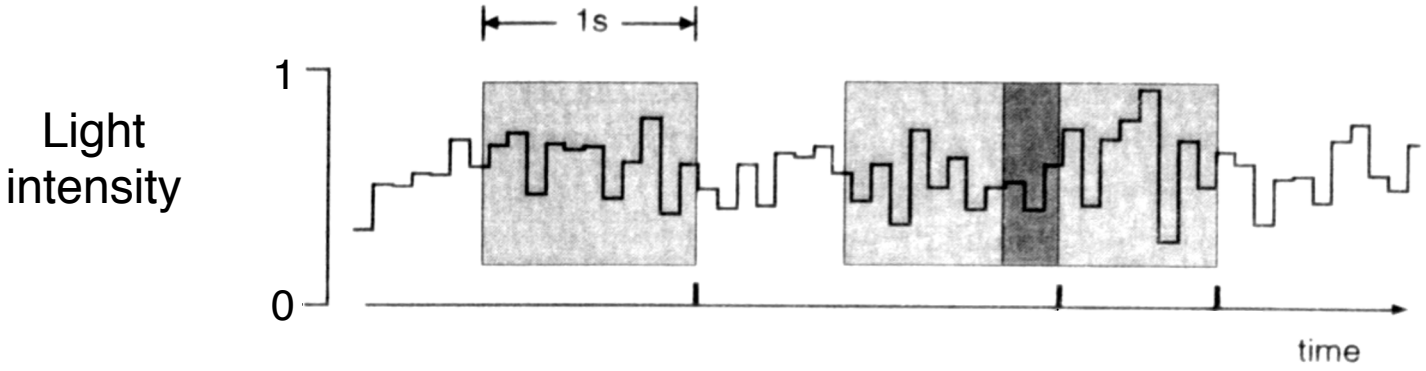
All stimuli
Stimuli producing spikes
Preferred direction in stimulus space

Receptive field: What stimuli makes the neuron respond?

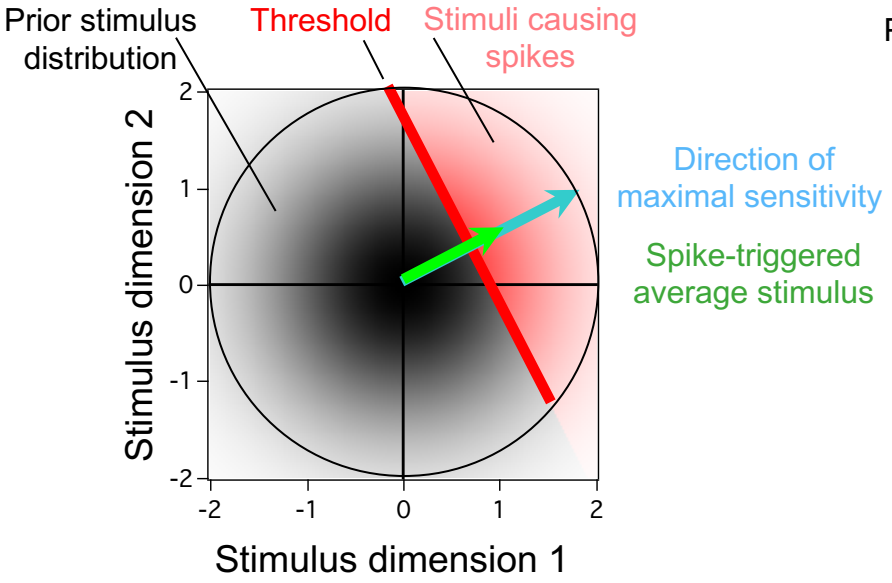


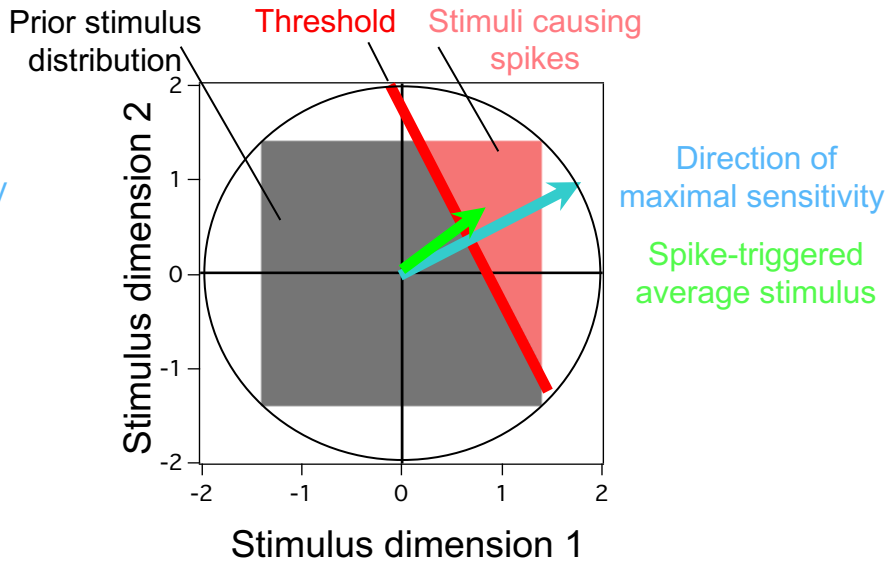
Receptive field: What stimuli makes the neuron respond?

Spike-triggered average for a spiking neuron



Computing the most effective stimulus (Bussgang's theorem)





If an input is Gaussian white noise, correlation of the input with the output yields the most effective input , even if there is a distortion of the signal's amplitude such as a threshold or saturation.

Bussgang (1952)

What stimulus makes the neuron respond?

Reverse correlation

Continuous

$$C(\tau) = \int_0^T r(t)\, s(t-\tau)\, dt$$

Discrete

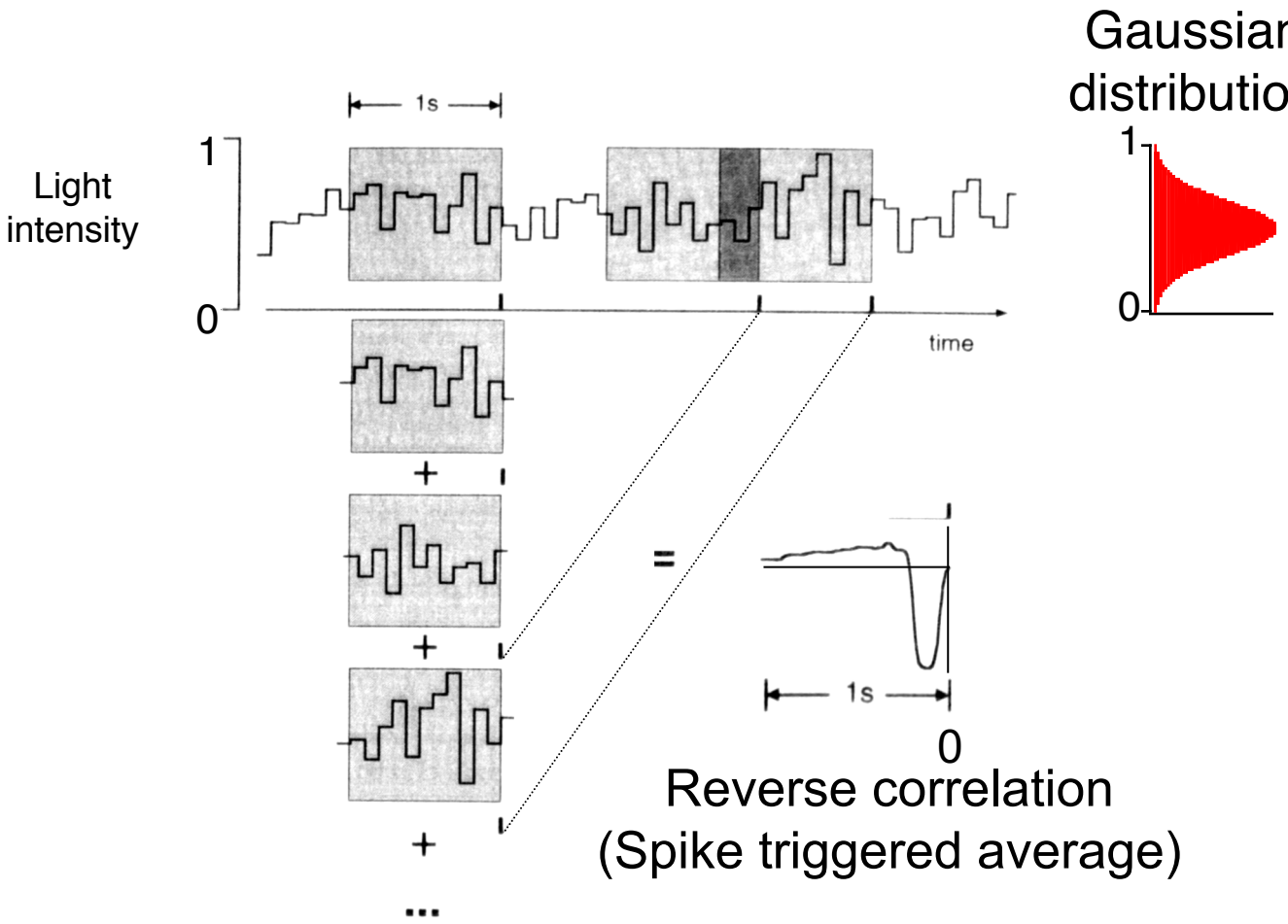
$$C(\tau) = \sum_{t=0}^{T} r(t)\, s(t-\tau)\, \Delta t$$

For spikes, this is proportional to the spike-triggered average

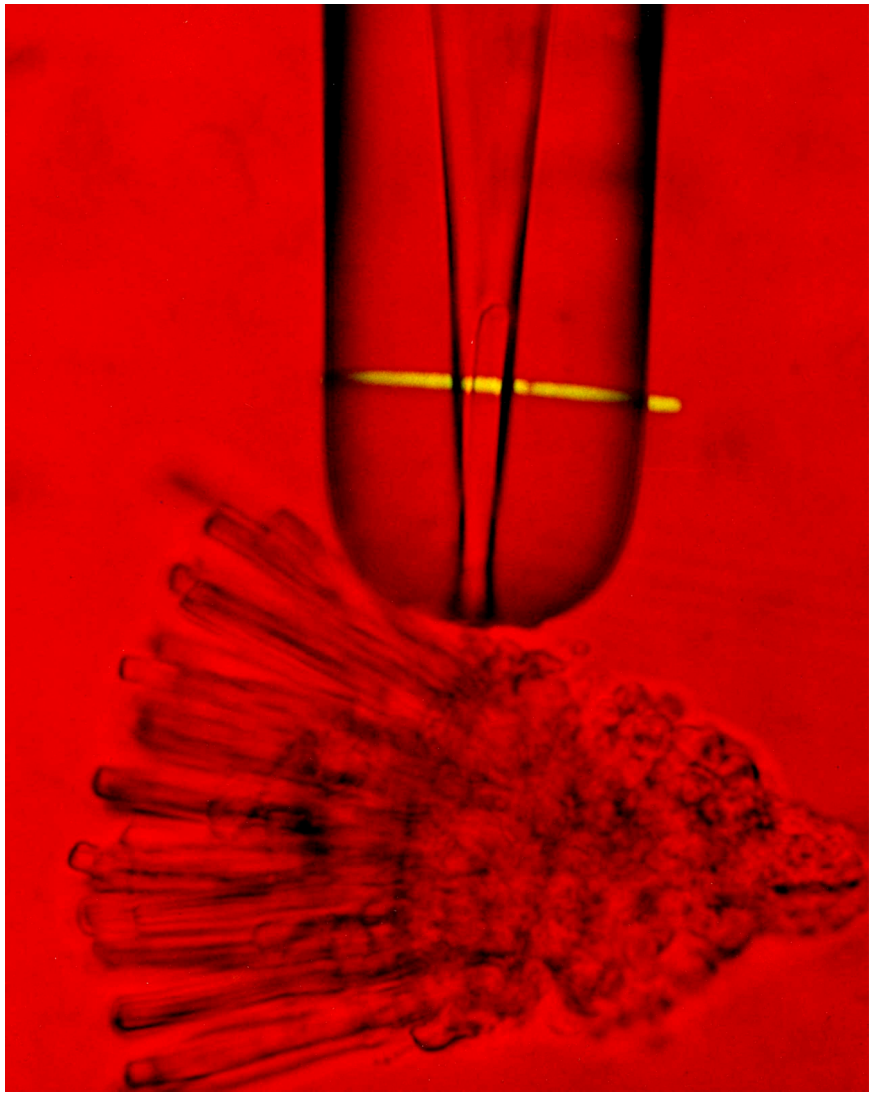
What stimulus makes the neuron respond?

White noise analysis

For a Gaussian white-noise stimulus, the reverse correlation gives the input that is transmitted with greatest sensitivity



How will a neuron respond to a stimulus?

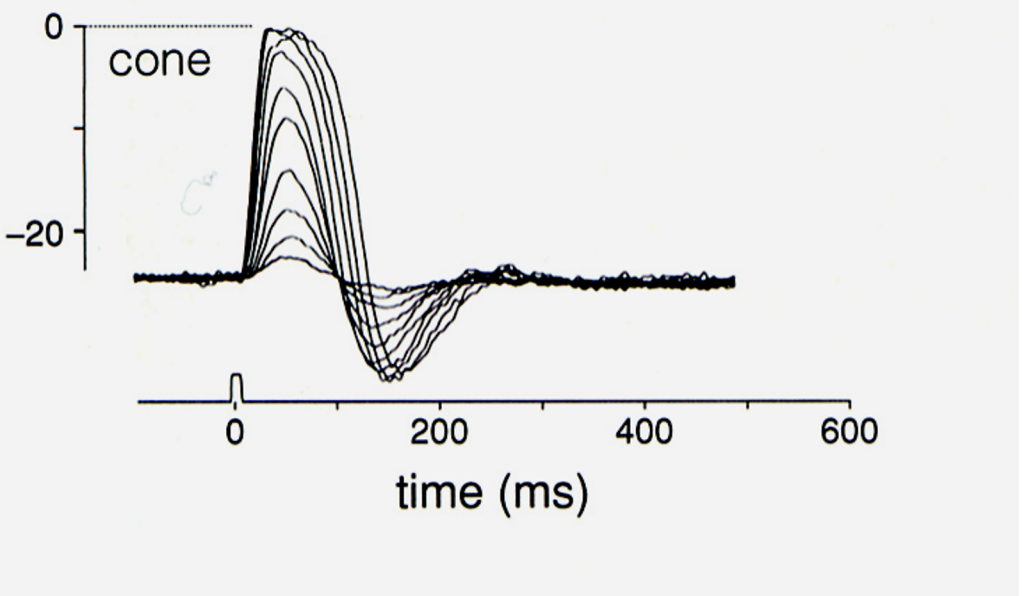


Baylor, Lamb and Yau (1979)

How will a neuron respond to a stimulus?

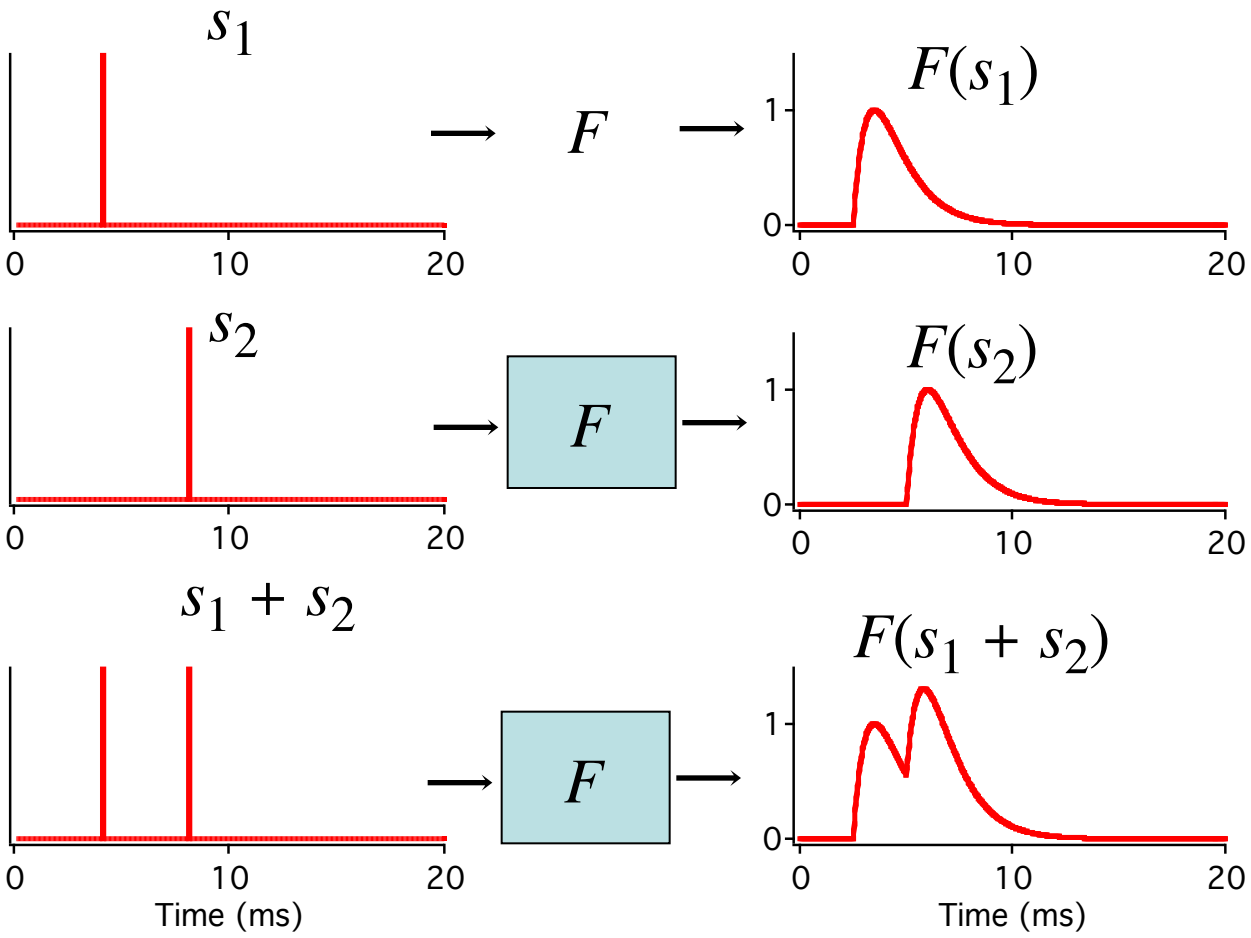
Single photoreceptor responses to a flash of light

Photocurrent
pA



Baylor (1987)

A linear system

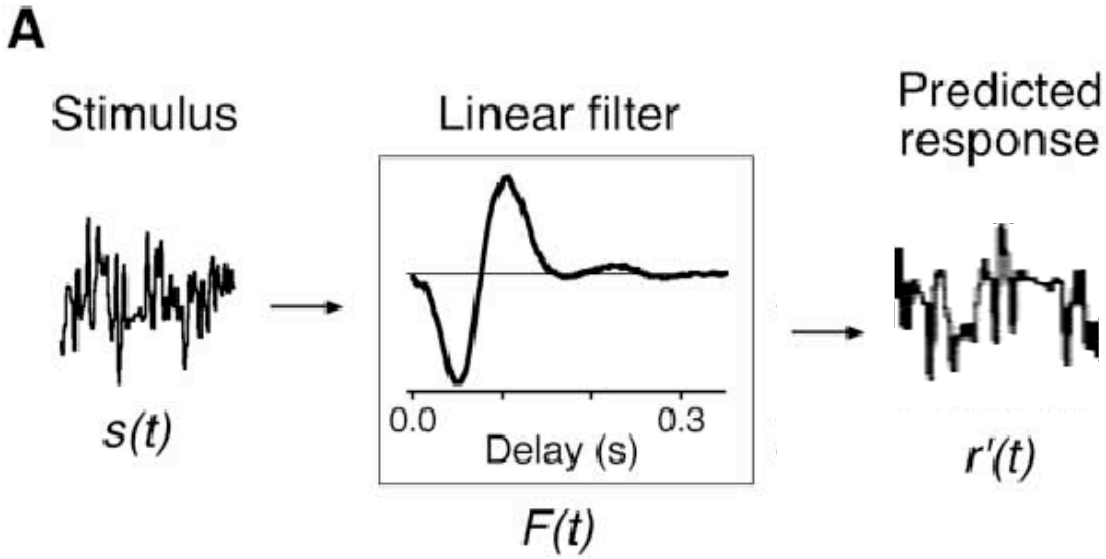


The Superposition Principle

When two inputs are presented to a linear system, their effects sum.

$$F(s_1 + s_2) = F(s_1) + F(s_2)$$

A linear model of the cell's response



Convolution

$$r'(t) = \int s(\tau)F(t-\tau)d\tau \qquad r'(t) = \sum s(\tau)F(t-\tau)\Delta\tau$$

$$= F * s$$

$F(t)$ is called:

Impulse response function
Linear kernel
First-order kernel
First-order Wiener kernel

Filters and step responses

- Monophasic
- Biphasic

Two different concepts for convolution

- Dot product with time-reverse of filter
- Impulse response

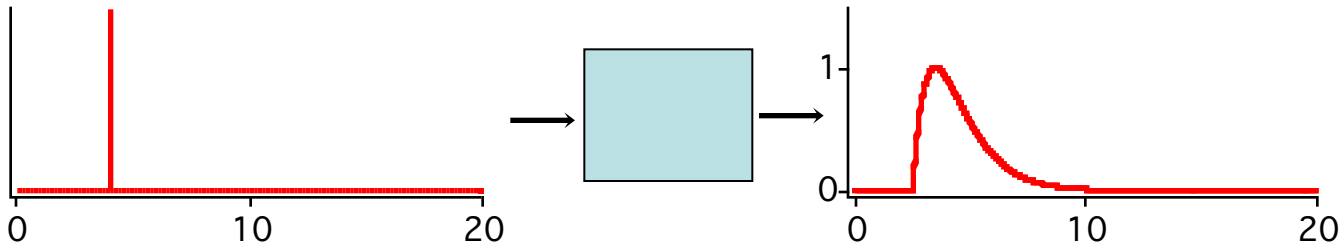
How do you find the filter?

What stimulus produces the largest response?

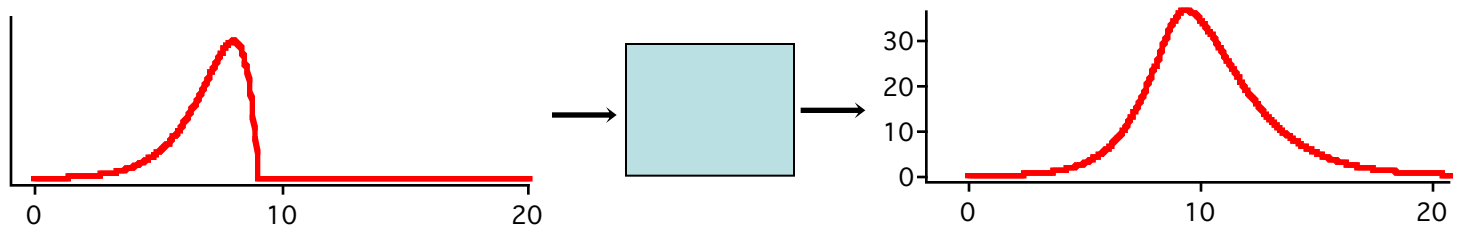
- geometrical interpretation

Summary of relationship between the response to an impulse and the most effective input.

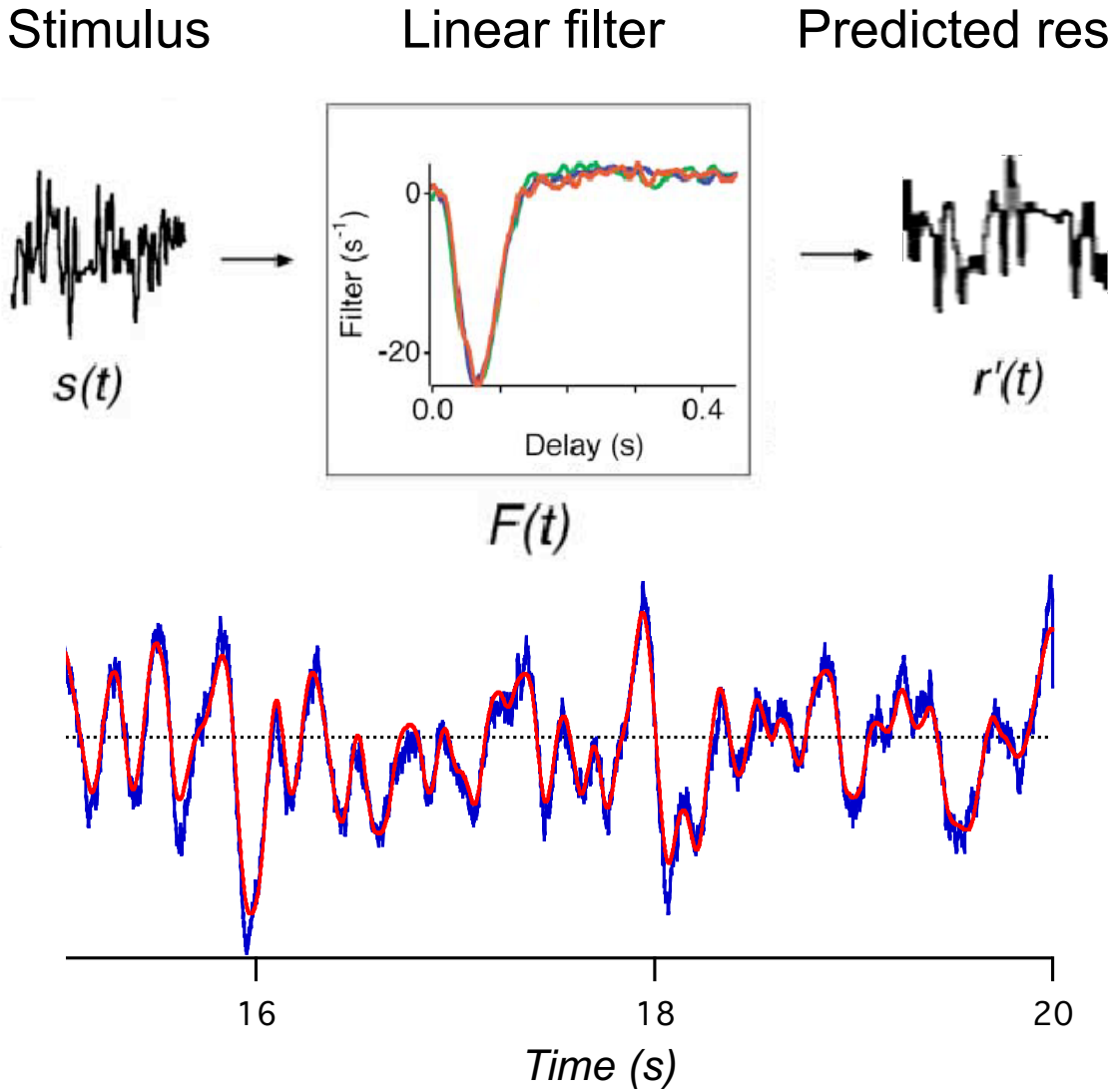
For a cell (or any system) responding in the linear range, the response to a brief input (an impulse):



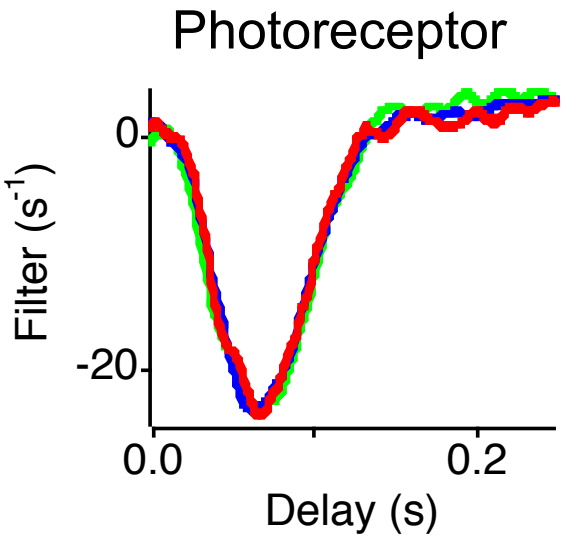
yields the time-reverse of the input that the cell is most sensitive to:

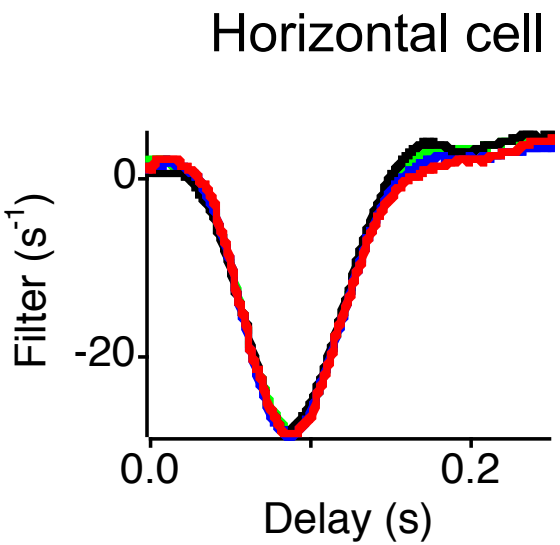


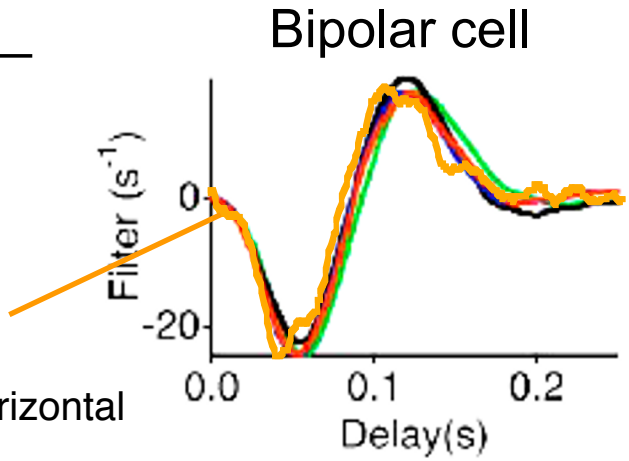
A linear model of the cell's response



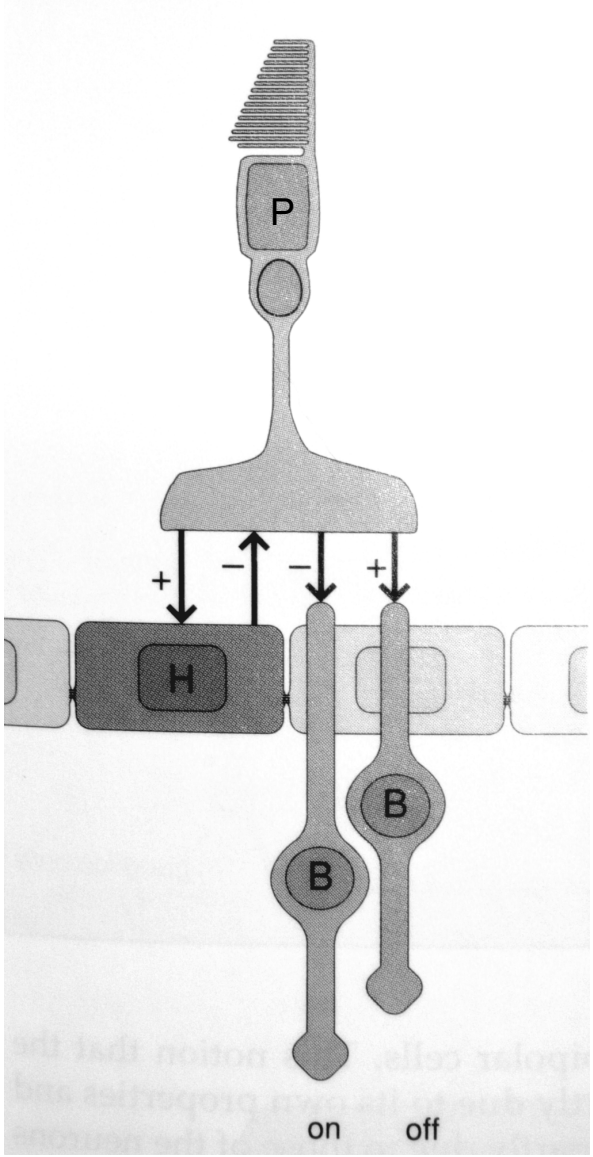
Linear filters in the early visual system



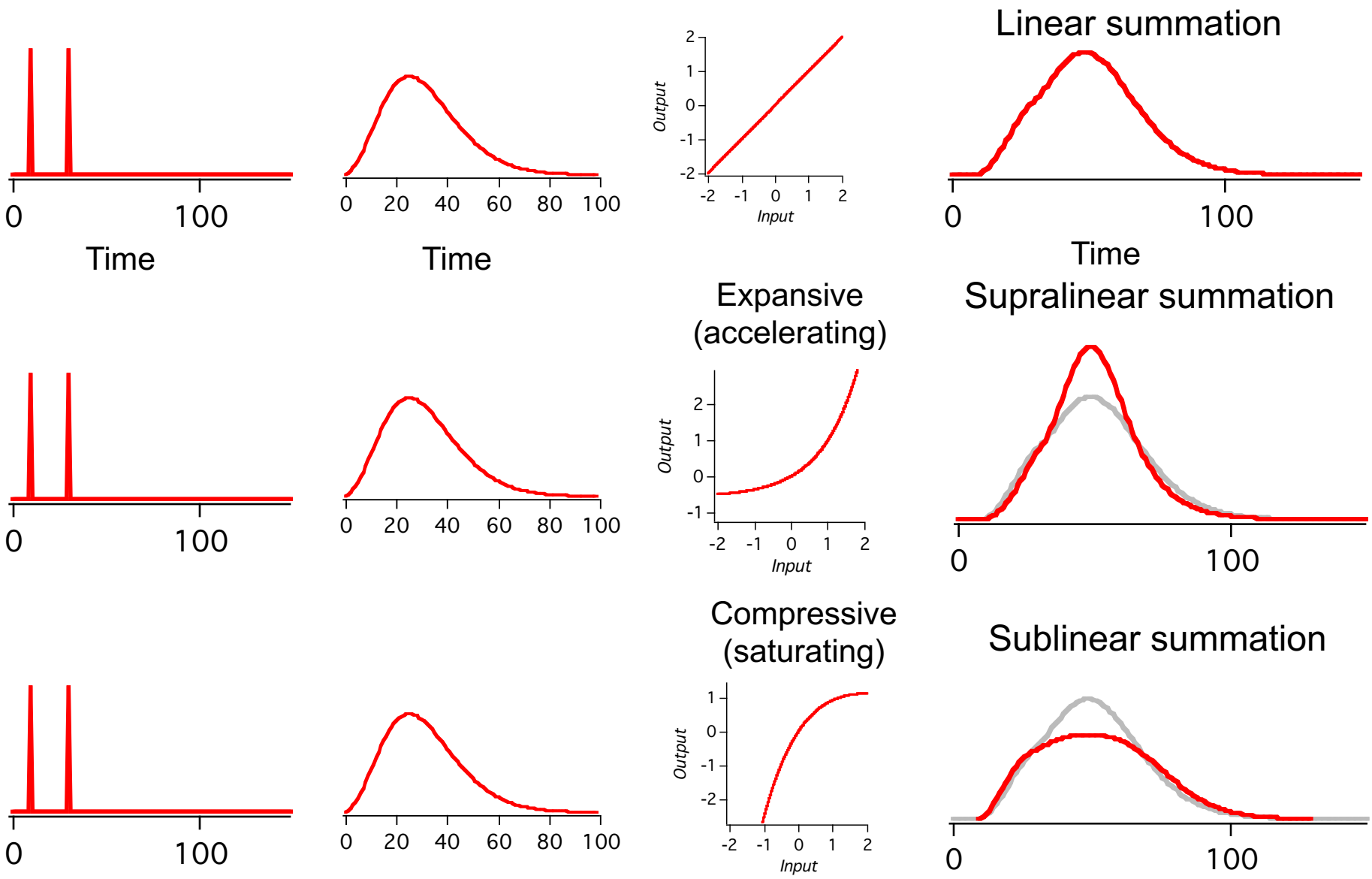




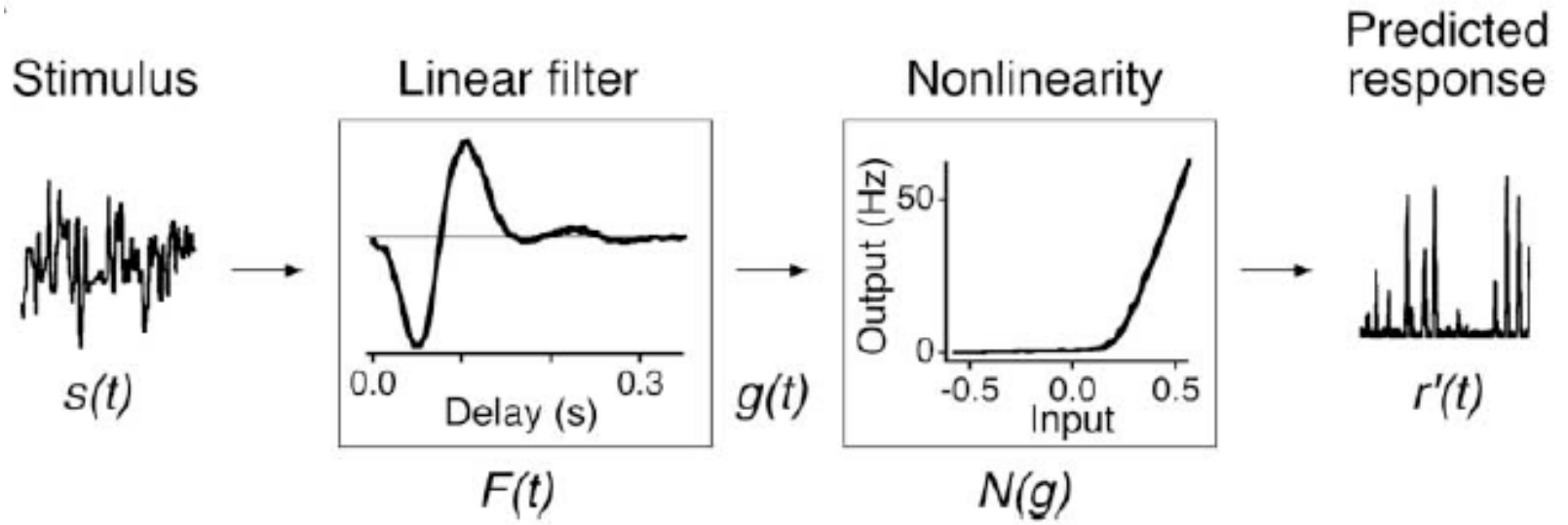
Weighted sum of Photoreceptor and Horizontal Cell filters



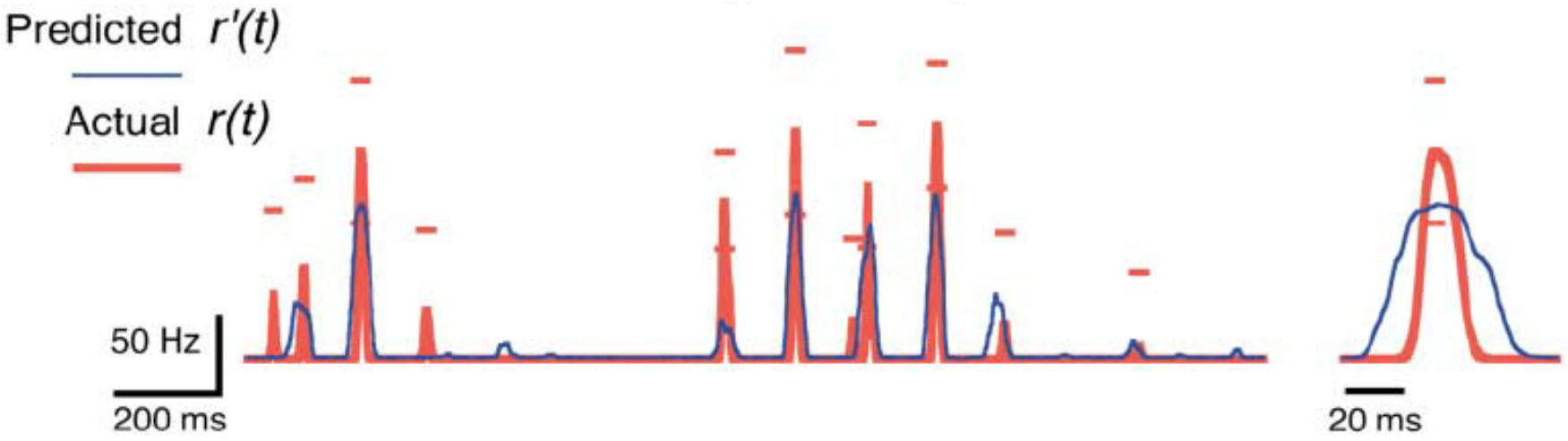
Nonlinear summation of inputs by a static nonlinearity



Linear - Nonlinear “LN” model of a “Feature Selective Neuron”



Retinal ganglion cell firing rate and LN model



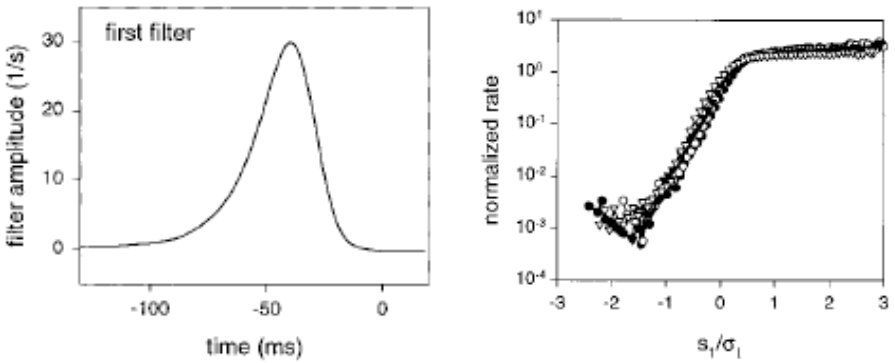
LN models in the nervous system

"Filter"

Nonlinearity

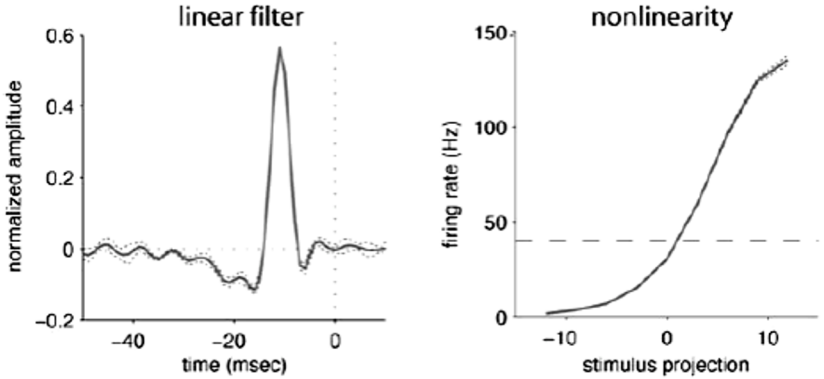
Fly H1 Motion sensitive neuron

Brenner et al.,, *Neuron* (2000)



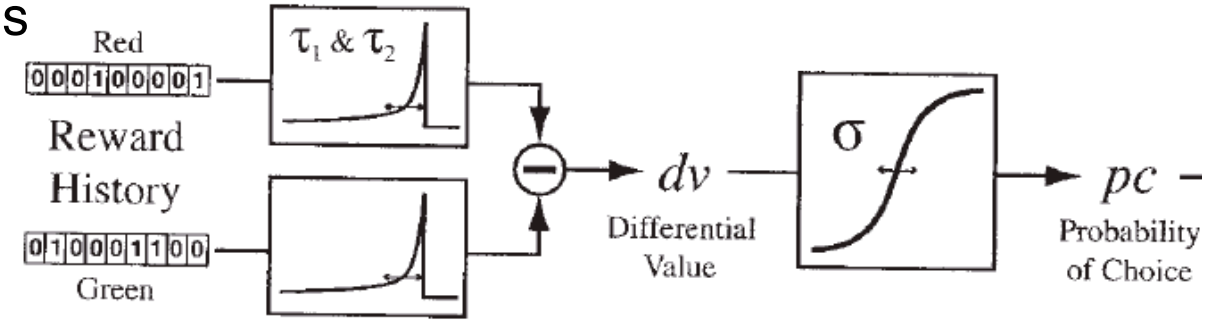
Songbird auditory forebrain neuron

Nagel & Doupe, *Neuron* (2007)



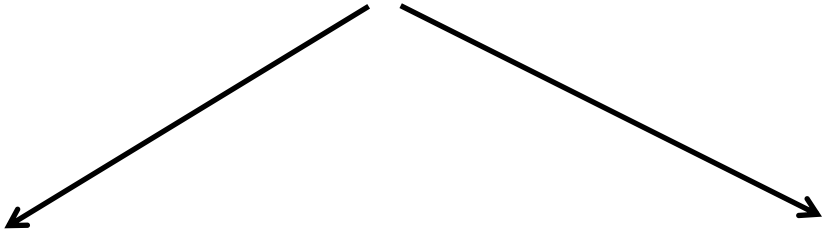
Whole monkey making decisions

Corrado, Sugrue, Seung & Newsome, *J. Exp. Anal. Behav.* (2005)

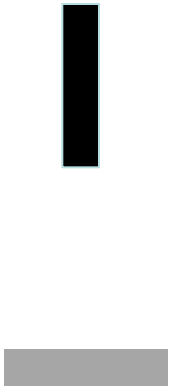


How do we study more complex responses to sensory input?

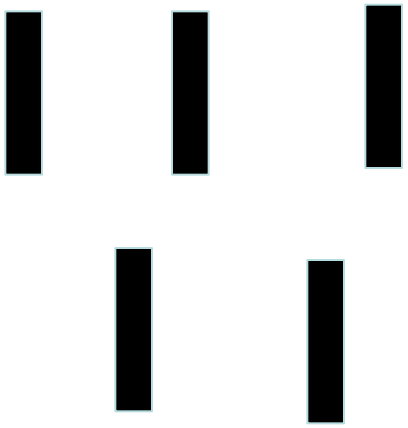
Properties of feature detection



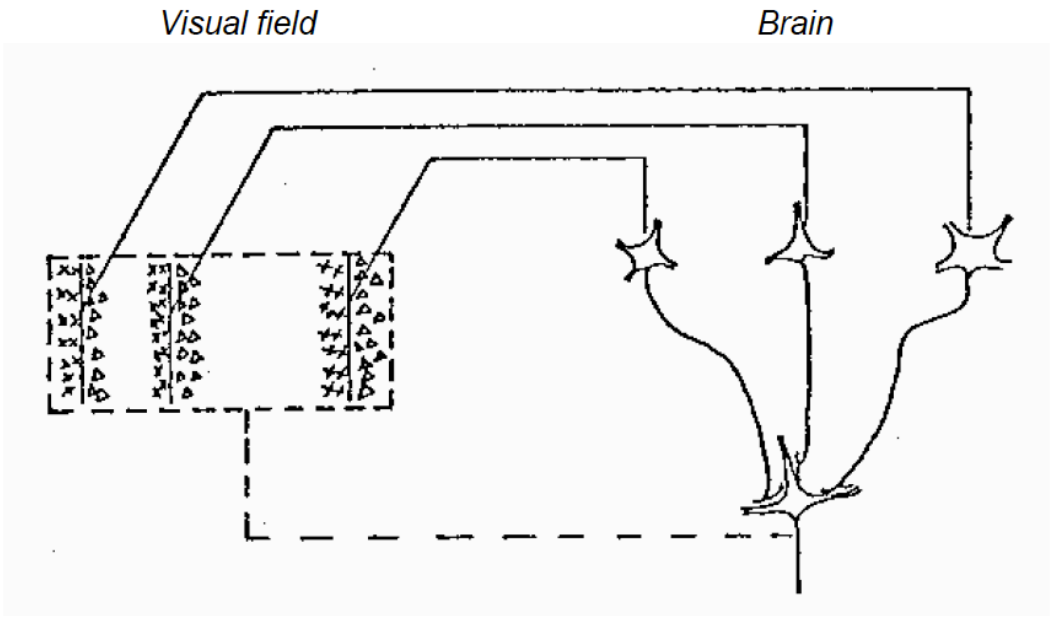
Selectivity



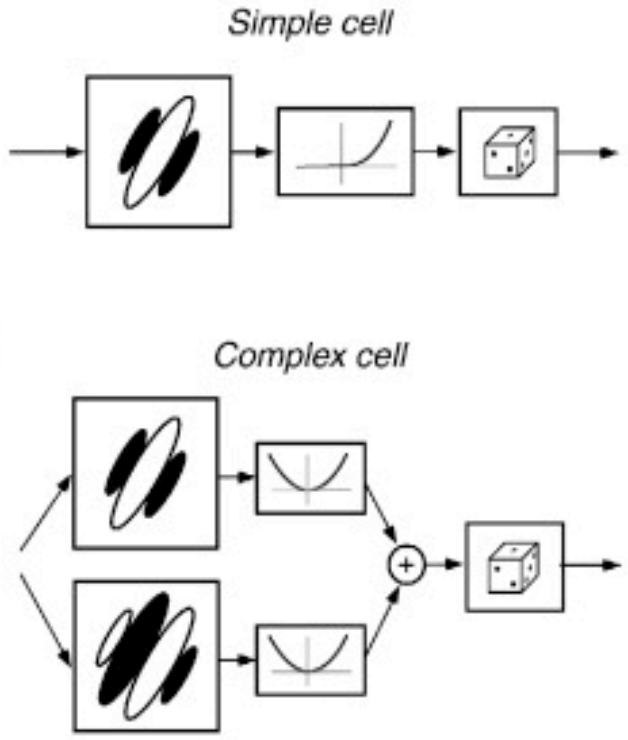
Invariance



Models of selectivity and invariance in primary visual cortex

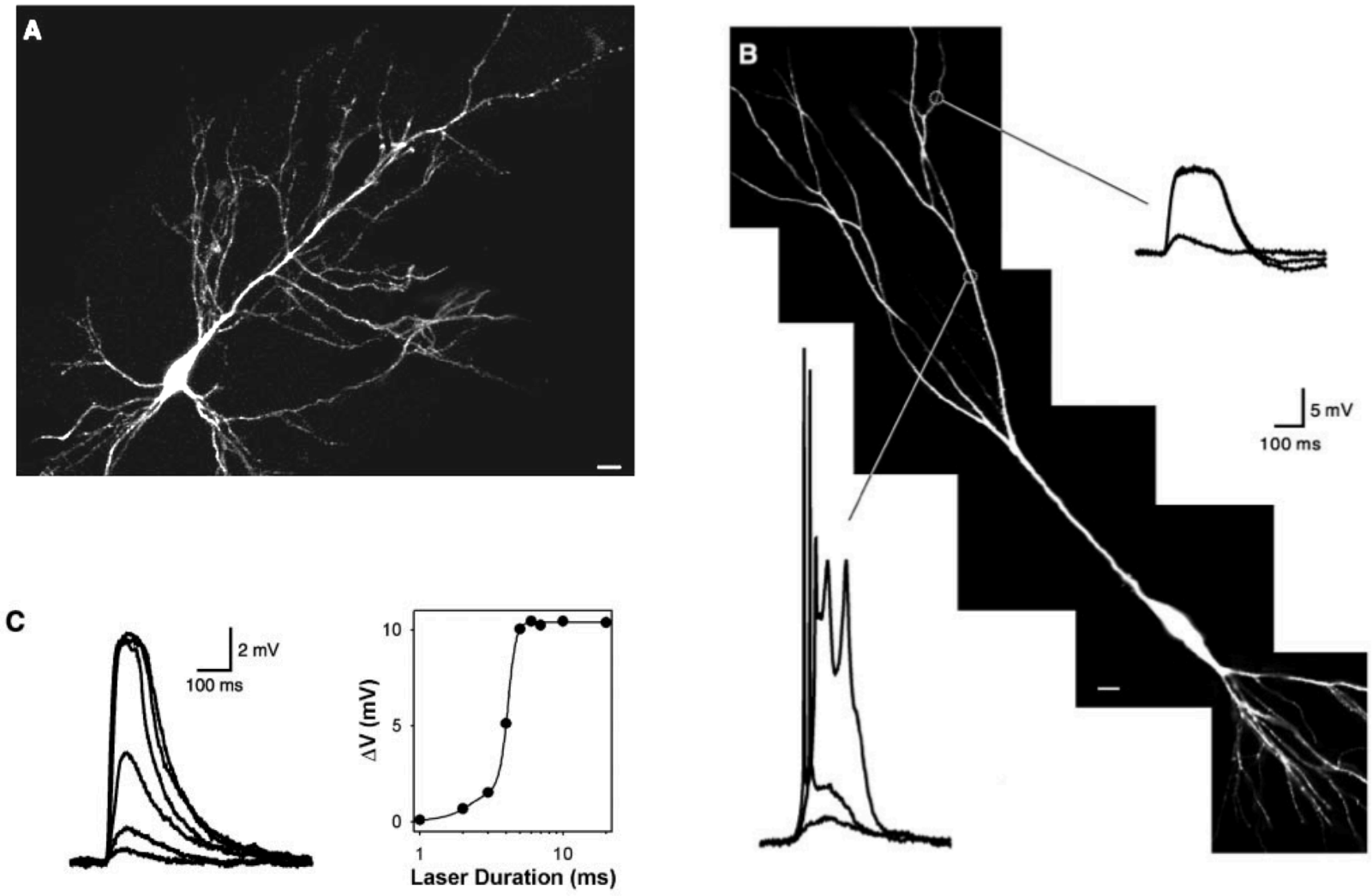


Hubel & Wiesel, 1963



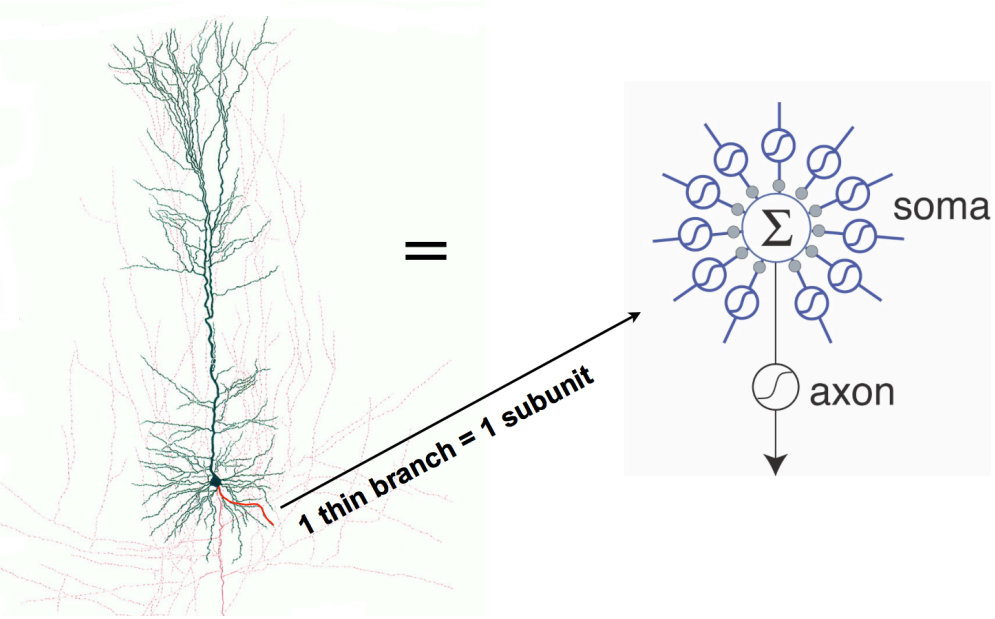
Rust et al., 2005

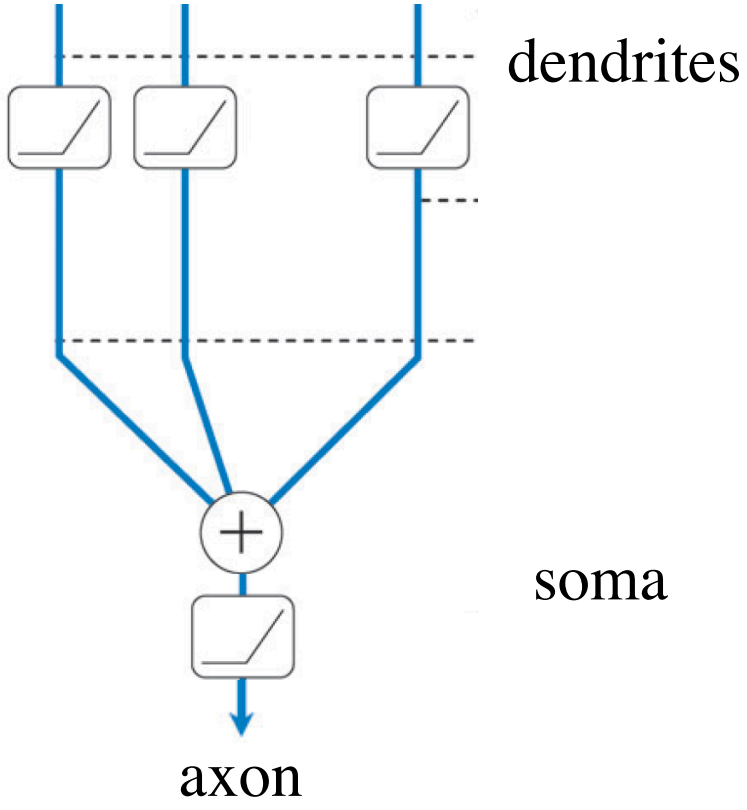
All or none calcium action potentials in pyramidal cell dendrites



Wei et al., 2001. Compartmentalized and Binary Behavior of Terminal Dendrites in Hippocampal Pyramidal Neurons

“Two layer” model of active dendrites

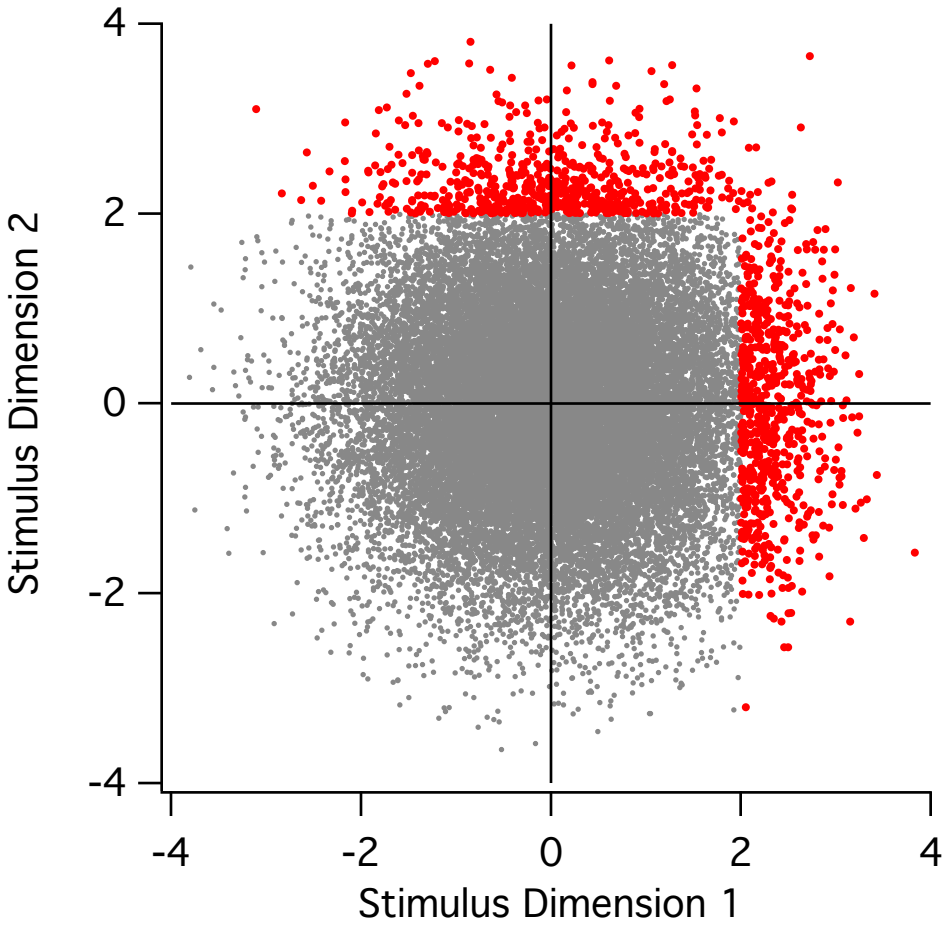




Poirazi, Brannon & Mel, 2003

Bartlett Mel

Sensitivity to multiple stimulus dimensions



All stimuli

Stimuli producing spikes

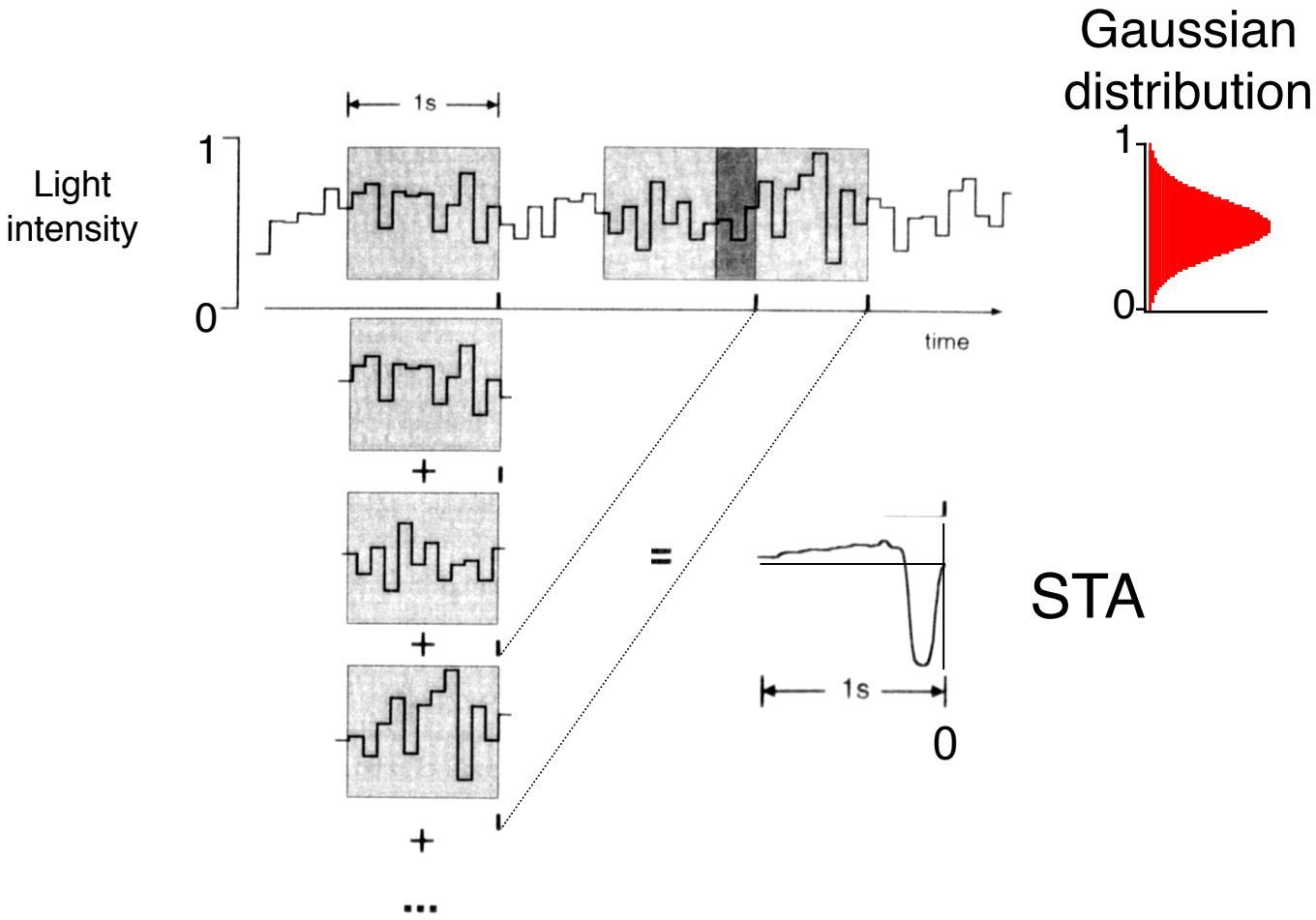
Spike-triggered Covariance

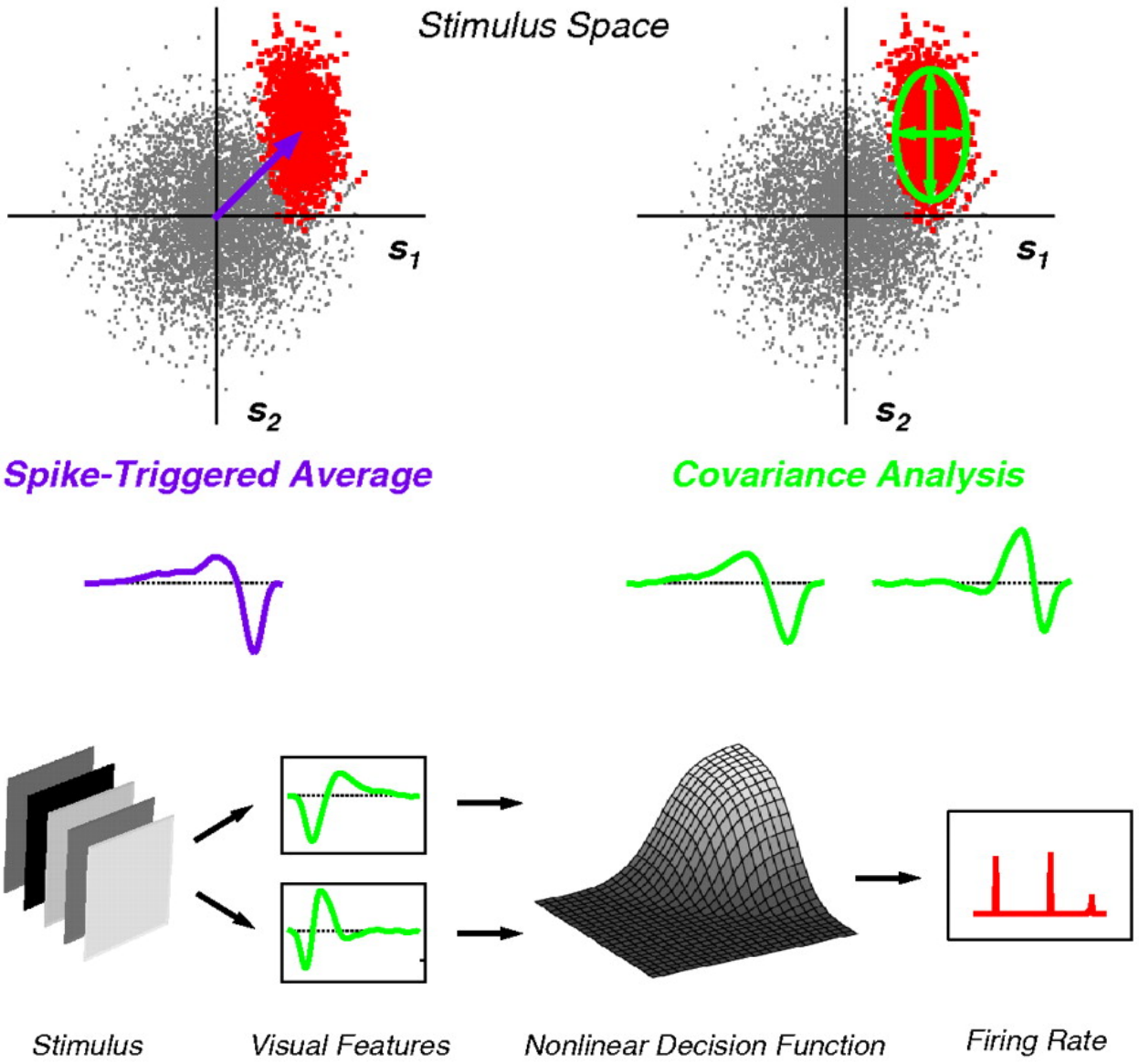
What are special directions in stimulus space that influence the response?

What are the stimulus directions where the spike triggered ensemble “differs” from the original stimulus distribution?

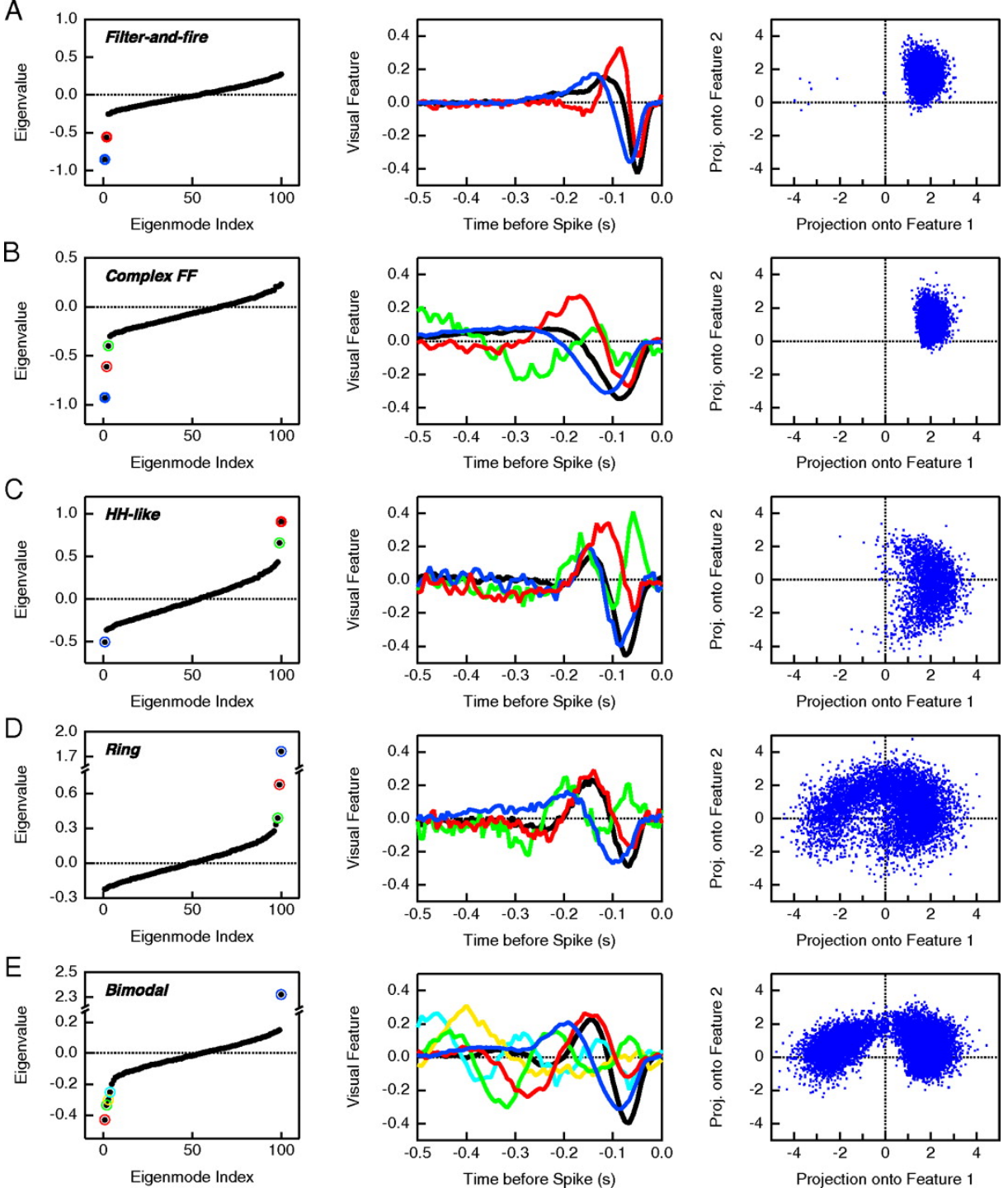
What are the stimulus directions where the spike triggered ensemble *has a different covariance* from the original stimulus distribution?

Analyzing the spike-triggered stimulus ensemble

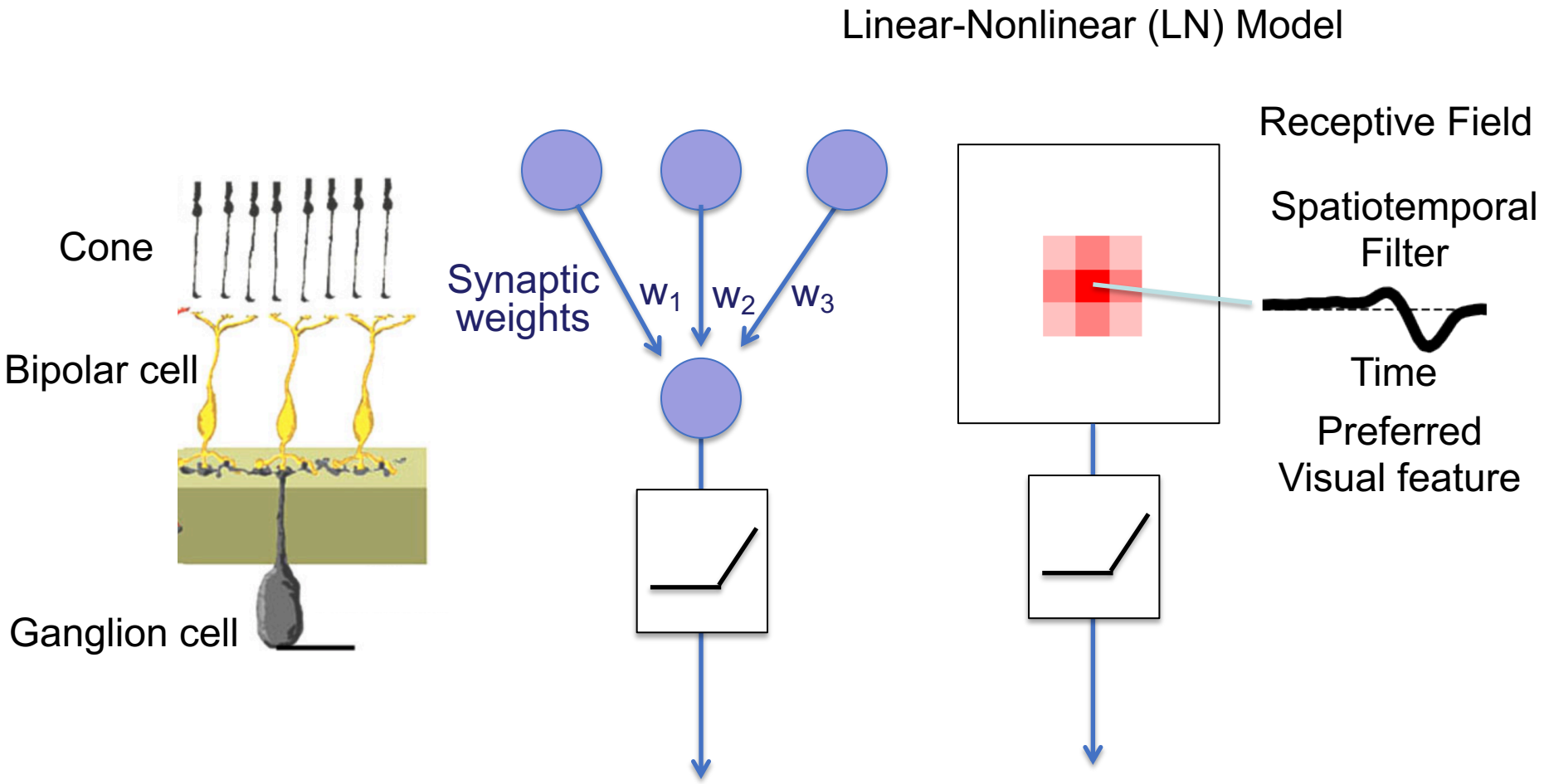




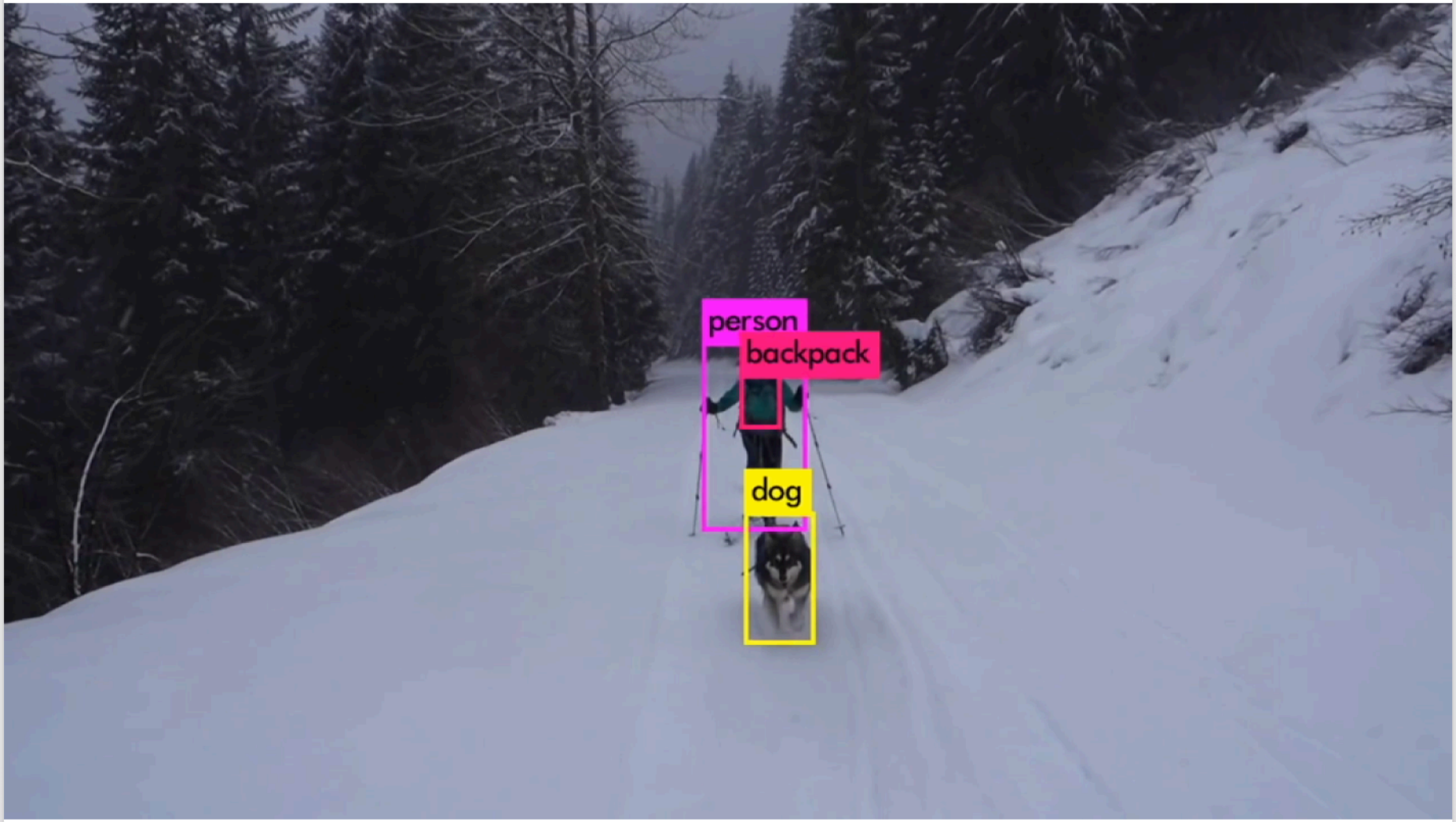
Fairhall et al, 2006


A
Filter-and-fire
Eigenvalue
Eigenmode Index
Visual Feature
Time before Spike (s)
Proj. onto Feature 2
Projection onto Feature 1
B
Complex FF
C
HH-like
D
Ring
E
Bimodal

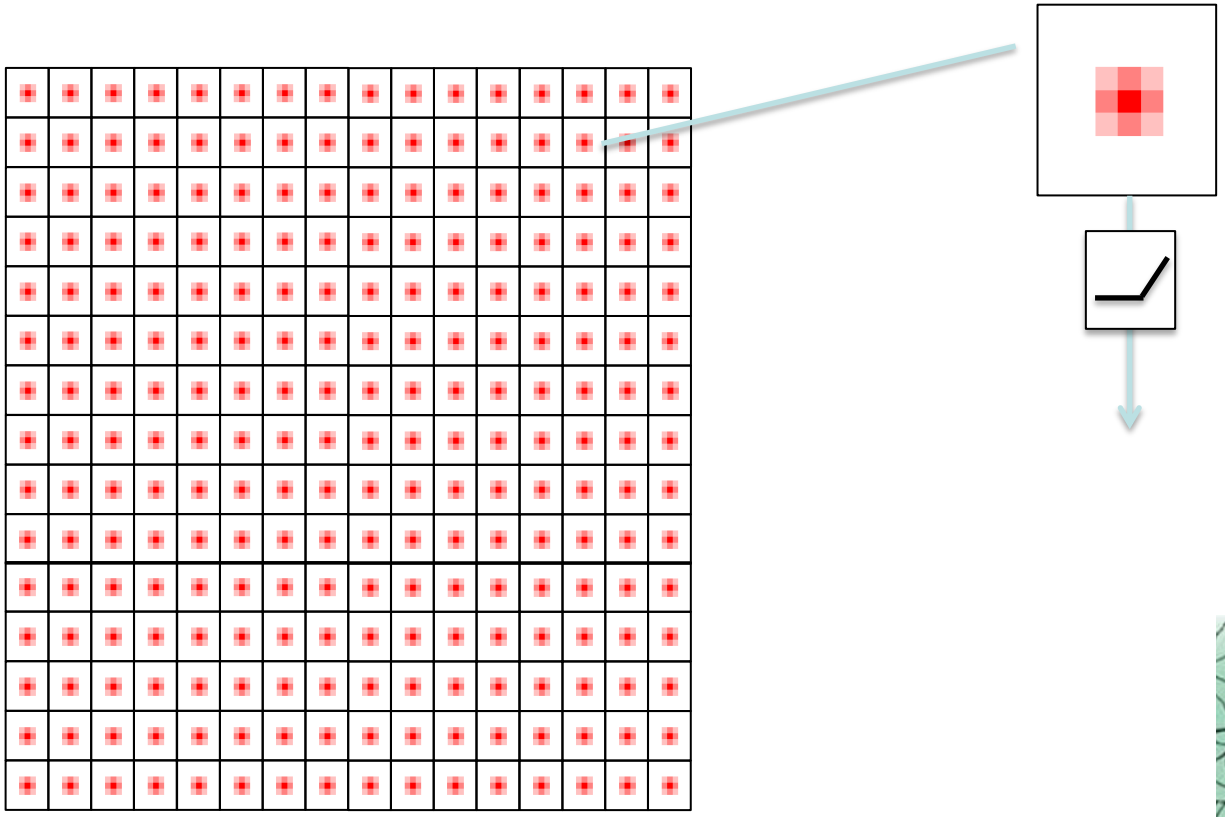
A Simple Model of Visual Responses



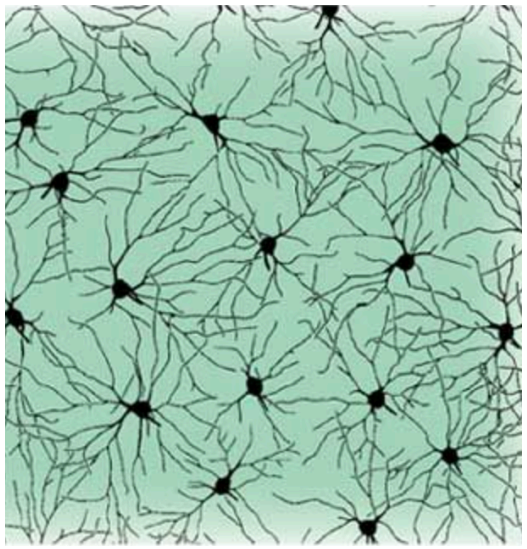
Deep Learning Object Recognition



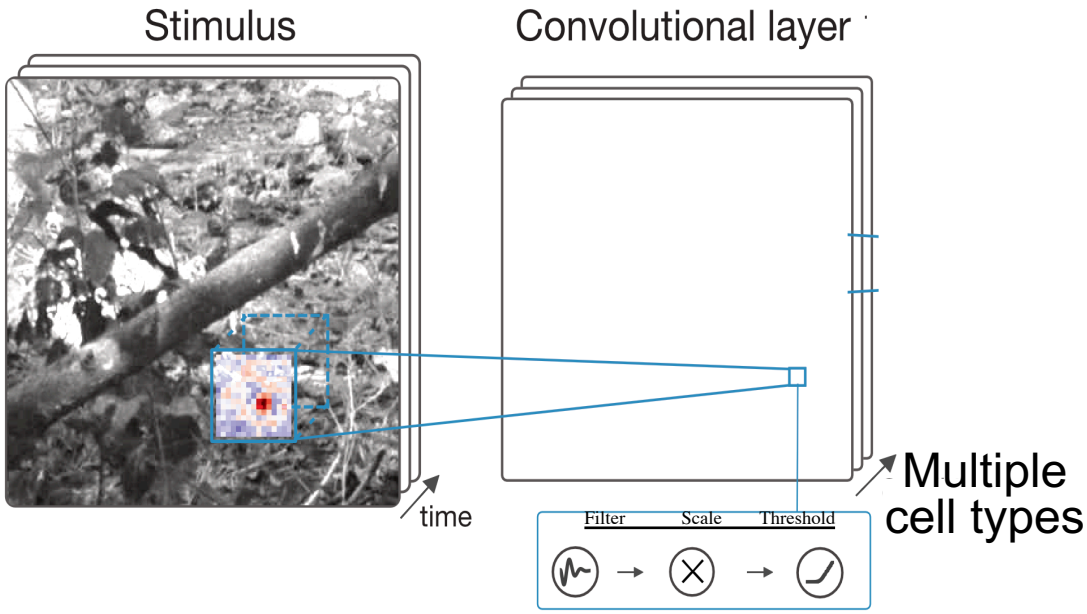
“Convolutional” layer



Like a mosaic
of retinal neurons

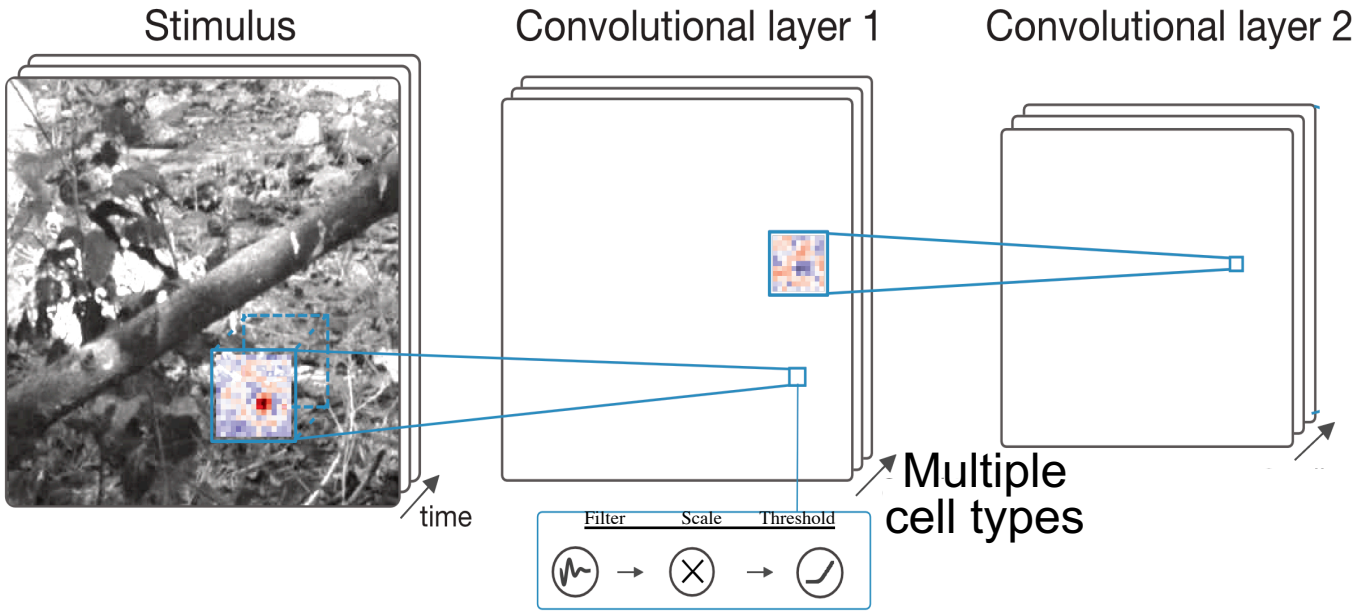


Multiple cell types

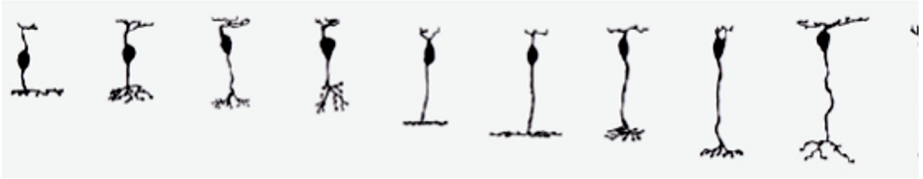


Like the multiple cell types in the retina

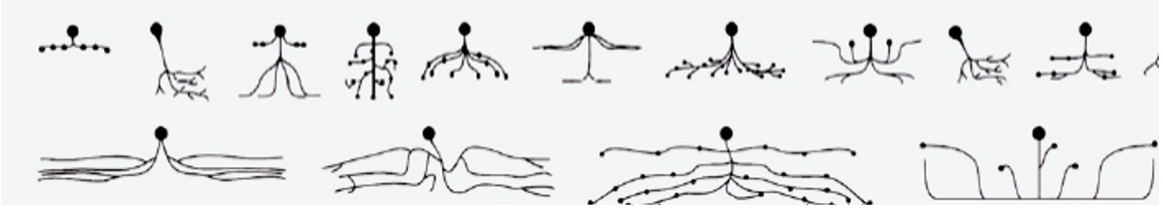
Multiple Layers



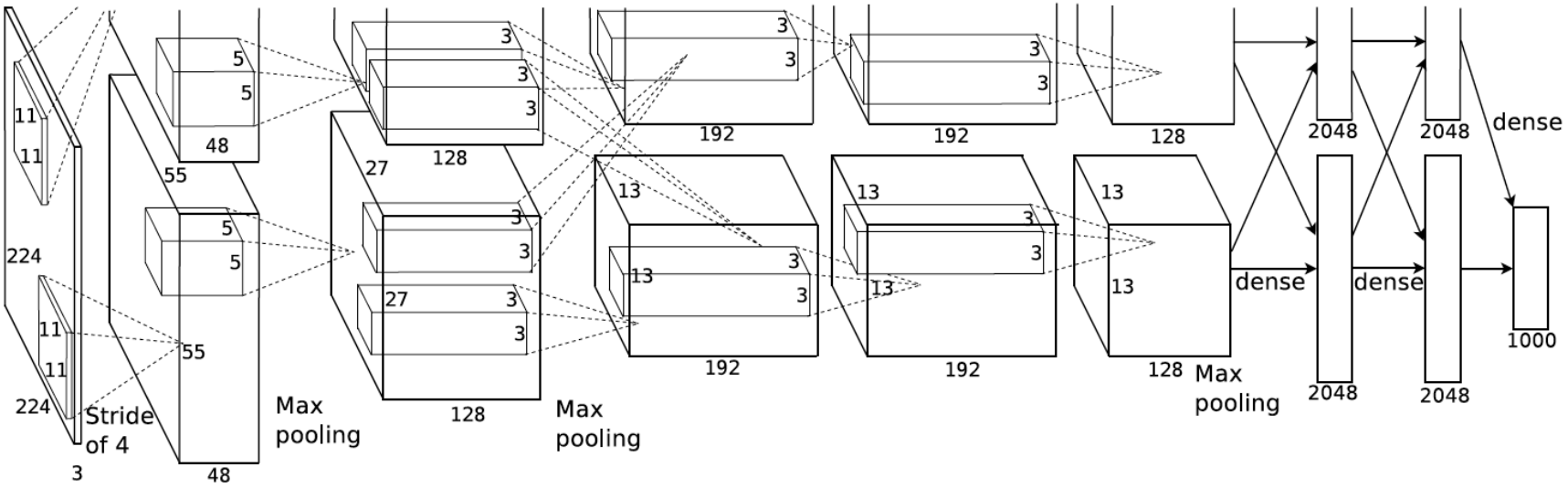
Like the multiple cell types in the retina



Like the hierarchy of retinal circuitry



Object Recognition Deep Network



Different sensory models for different questions

More Computationally Interpretable

More Mechanistically Interpretable

More Expressive

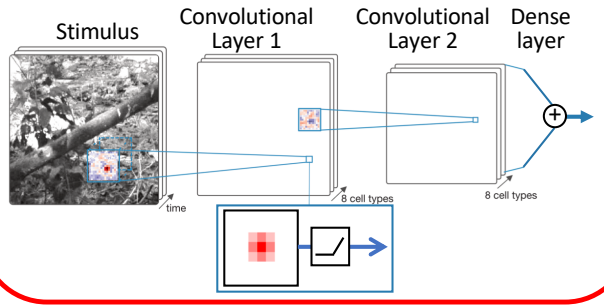
LN Model

Spatiotemporal Filter

Time

LN-LN Model

Minimal Convolutional Neural Network



Deep CNN