Neurons

pictures taken from: Natural Image Statistics (Hyvarinen, Hurri, Hoyer; 2009)

Visual processing
Visual processing

▶ **Photo receptors.** Mainly:
  ▶ Rods ($> 10^8$)
  ▶ Cones ($\approx 6 \cdot 10^6$, most in fovea)
▶ **Retinal ganglion cells**
  ▶ Multiple different types ($\approx 1.5 \cdot 10^6$ in total)
▶ **Optic nerve**
▶ **Lateral geniculate nucleus (LGN)**
▶ **Visual Cortex**
  ▶ Ventral stream ($V_1 \rightarrow V_2 \rightarrow V_4$)
  ▶ Dorsal stream ($V_1 \rightarrow V_2 \rightarrow MT$)

Spikes and firing rate

▶ Neurons communicate information via series of *action potentials* travelling along the axon.
▶ The *firing rate* depends on the total input collected from other neurons via its dendrites.
▶ Action potentials and firing rates are complex chemical processes.
▶ They can be modeled with differential equations whose solutions yield highly idealized models of the dependency of firing rate on total input.

Spikes and firing rate

▶ This makes it possible to abstract away the spikes and think of real numbers being sent along wires.
▶ Because of phenomena like *refractory periods* firing rates saturate at a maximum value.
▶ Some neurons have non-zero minimum firing rate called *spontaneous firing rate*.
▶ The input collected from other neurons depends on synaptic efficacies, which can be modeled as a weighted sum.

Idealized input-output behaviour

▶ Together this yields the common idealized input-output model

\[
output = \frac{1}{1 + \exp(-w^T x)}
\]
Idealized input-output behaviour

- The use of an element-wise nonlinearity which is applied to a linear combination of inputs is sometimes referred to as linear/nonlinear model.
- It is the building block of all practical neural network models.
- In practice, completely different non-linearities than the sigmoid are now used. The (currently) most common one is ReLU($w^Tx$) = $w^Tx \cdot (w^Tx > 0)$

Roland Memisevic

Hebbian learning

- The fact that synaptic efficacies can change is the basis for learning.
- The most famous learning rule is Hebbian learning, introduced by Donald Hebb in 1949: 
  "When an axon of cell A is near enough to excite 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."
- "Fire together, wire together".

Roland Memisevic

Receptive fields

- The firing rate of a neuron can be highly selective wrt. the input.
- The set of stimuli parameters that make a neuron fire is called receptive field.
Receptive fields

- a: Typical receptive fields of retinal ganglion cells and of cells in LGN.
- b: Typical receptive fields of cells in V1. These are also known as simple cells.

Retinotopy

- The receptive fields of neighboring neurons in LGN and V1 tend to cover neighboring areas of the visual field.
- This is known as retinotopic organization.
- It means that their joint responses yield a kind of “2-D STFT”.
- A convolution layer could be used to simulate this (But this is not the only organizing principle that can be found in visual cortex.)
Gabor filter response

- (a) input image, (b,c) filters, (d,e) the two response maps, (e) amplitude response.

Introspective evidence for frequency channels

- To compute local Fourier amplitudes (the spectrogram, (f)) it is necessary to sum over the squares of two filter responses.
- In practice, this requires “convolving” the image with a non-linear function, in other words computing non-linear combinations of multiple feature maps.

Complex cells

- There do seem to be cells in V1 whose responses are phase independent. They are called complex cells (also proposed by Hubel and Wiesel).
- A simple mathematical model for these (called “energy mechanism”) is to sum over squared simple-cell responses.
- A Fourier feature pair with 90 deg phase difference is known as quadrature pair. (Better than saying “sin/cos”, because phasors in the Fourier expansion may have arbitrary different phase.)
Receptive fields

Another organizing principle, besides retinotopy, is spatial organization according to frequency and orientation of filters.

This is called **topographic organization**.

The phase of the filters, in contrast, is random.

All attempts to model topography seem to require complex cell like mechanisms.

Topographic organization is ubiquitous across the cortex.

An attempt to synthetically reproduce features showing topographic organization

(a) x-position, (b) y-position, (c) orientation, (d) frequency, (e) phase

from: Natural Image Statistics (Hyvärinen, Hurri, Hoyer; 2009)
Saccades

(picture from Wikipedia)