Brain Computer Interfacing

From Neurons To Data

Session 1: Introduction & Neurons

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ORGANIZATIONAL ISSUES

Overview of the practical sessions

- Session 1: Introduction & Neurons
  - April 19th: Lecture
  - April 26th: Exercise
- Session 2: Neural Networks
  - May 3rd: Lecture
  - May 17th: Exercise
- Session 3: Individual Head
  - May 24th: Lecture
  - May 31st: Exercise
- Session 4: Electrodes & Electronics
  - June 7th: Lecture
  - June 14th: Exercise
- Session 5: Source Reconstruction
  - June 21st: Lecture
  - June 28th: Exercise
- Simulation Project: July 5th
- Auxiliary Date: July 19th

Structure

- Lecture: Knowledge base (for exercises)
- Exercises (graded):
  - Will be presented at the end of each lecture with short discussion
  - 1 week later: Tutorial
  - Online submission Monday 12 noon before the next lecture (minimum 2 weeks after last lecture)
  - Work in pairs allowed
- Simulation Project:
  group work on specific self-chosen topic

Online Learning Platform

We will use:

- ISIS (https://isis.tu-berlin.de/course/view.php?id=10314)
  - Distribution of the lecture slides
  - Distribution of supplementary material (derivations, papers,…)
  - Distribution of exercise task sheets
  - Collection of the solutions
- Jupyter (http://jupyter.org/)
  - Solution of programming tasks for at least the first 2 sessions
  - Can be used for the solutions of analytical tasks (also other formats excepted, see ISIS)
  - Also for handing in the solutions to Matlab-based exercises
- Matlab

  For head modeling & source reconstruction with specific toolboxes:
  - Fieldtrip (http://www.fieldtriptoolbox.org/):

    Data analysis, modeling, interfaces to other toolboxes:
    - Statistical Parametric Mapping (SPM): structural MRI analysis (included in fieldtrip)
    - OpenMEEG: Boundary Element Method (BEM) head modeling (included in fieldtrip but separate download necessary)

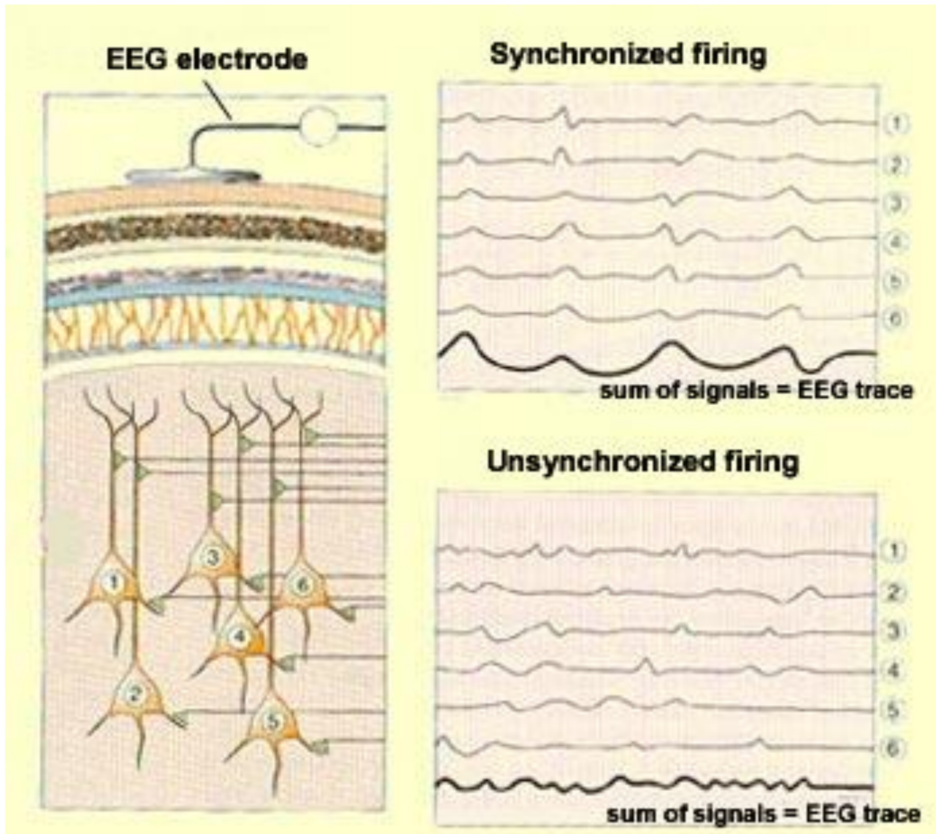
Grading system

- Only the exercises are graded!
- 20 points per exercise
- 5 exercise: 100 points

Notenschlüssel 1	
Mehr oder gleich 86	1,0
Mehr oder gleich 82	1,3
Mehr oder gleich 78	1,7
Mehr oder gleich 74	2,0
Mehr oder gleich 70	2,3
Mehr oder gleich 66	2,7
Mehr oder gleich 62	3,0
Mehr oder gleich 58	3,3
Mehr oder gleich 54	3,7
Mehr oder gleich 50	4,0
Weniger als 50	5,0

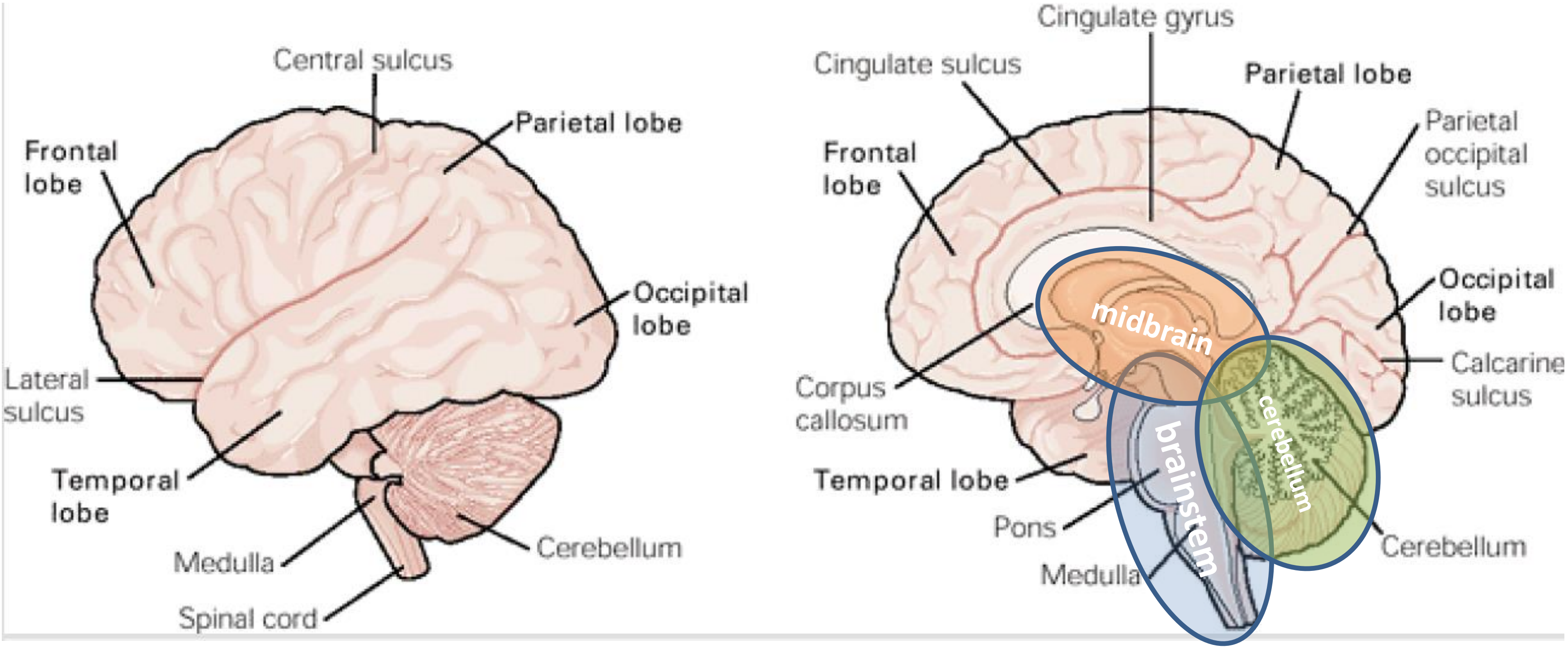
PART 1: NEURONS

The origin of EEG



Adapted from: *Neurosciences*, Bear, Connors, and Paradiso, Éditions Pradel, 2002

The brain - overview



The rest is cerebrum!

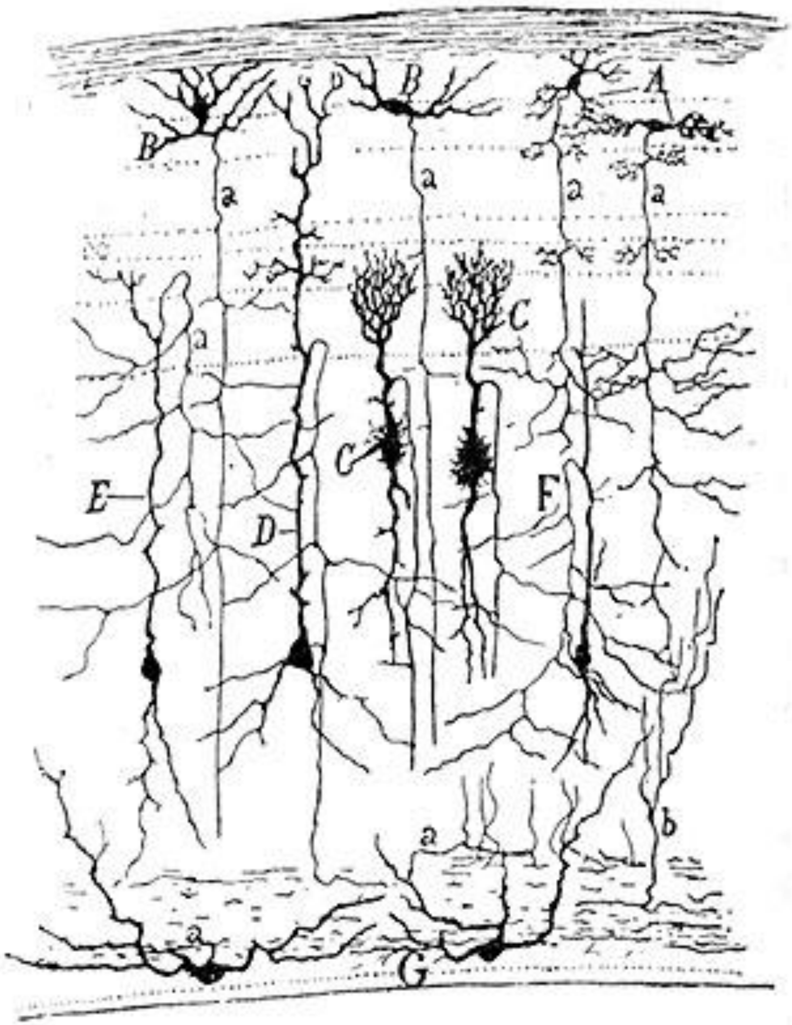
Adapted from: *Neurosciences*, Bear, Connors, and Paradiso, Éditions Pradel, 2002

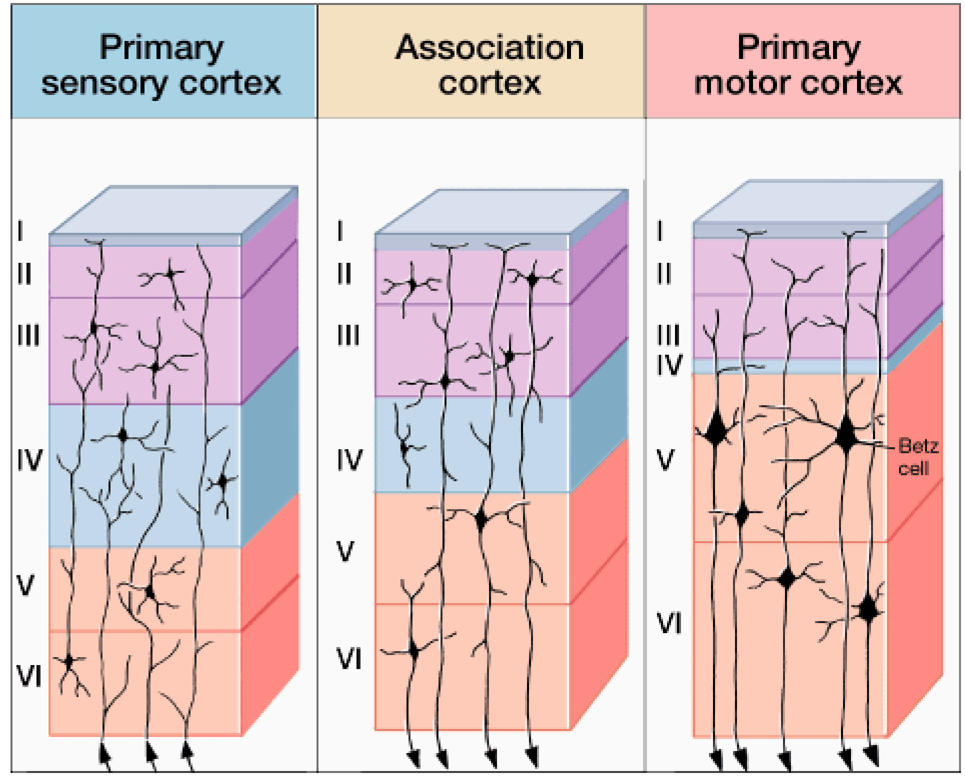
- Neocortex is the largest part of the cerebral cortex which is the outer layer of the cerebrum!
- Neocortex is the main area of higher-brain functions: perception, cognition, motor commands, reasoning, …

Facts about neurons

- 10^{11} (one hundred billion) neurons in the human brain
- On average 7.000 synaptic connections each
- Neocortex: 80% excitatory, 20% inhibitory
- three-year-old child has about 10^{15} synapses
- No of synapses declines with age (adult $\approx 10^{14}$)

Neurons in the neocortex



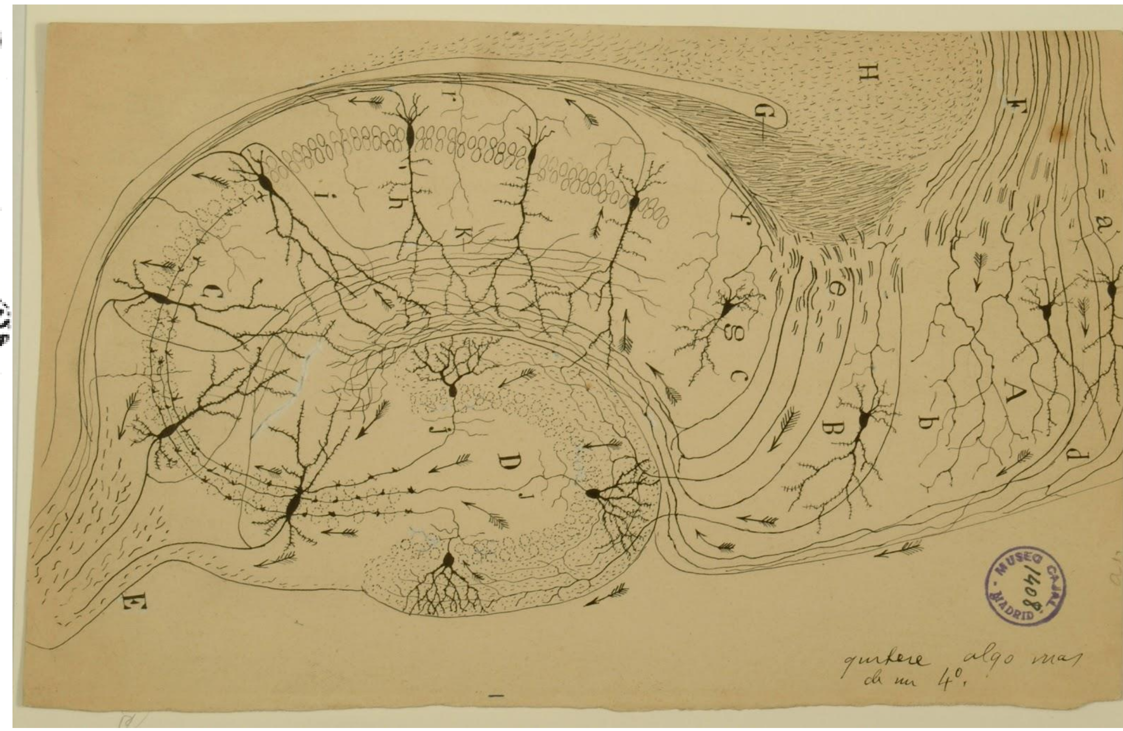


I Granule Layer: Dendrites & Axons
II projection to other cortical areas
III projection to other cortical areas
IV receive input from outside the cortex
V projection out of the cortex
VI projection out of the cortex

Adapted from: *Neurosciences*, Bear, Connors, and Paradiso, Éditions Pradel, 2002

Other Neurons/Areas

Purkinje Cell
(cerebellum)

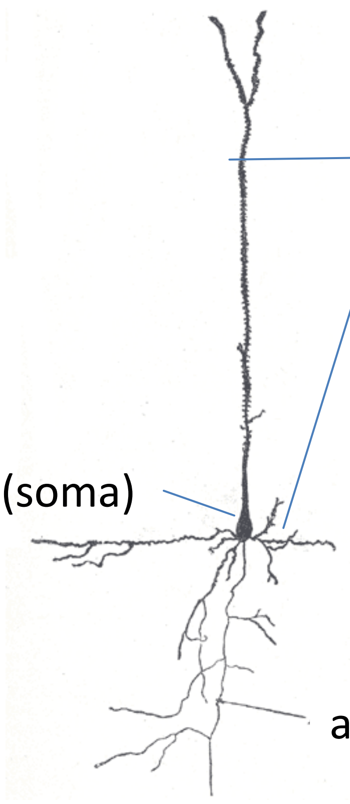


Hippocampus

Pictures from Ramon y Cajal around 1900

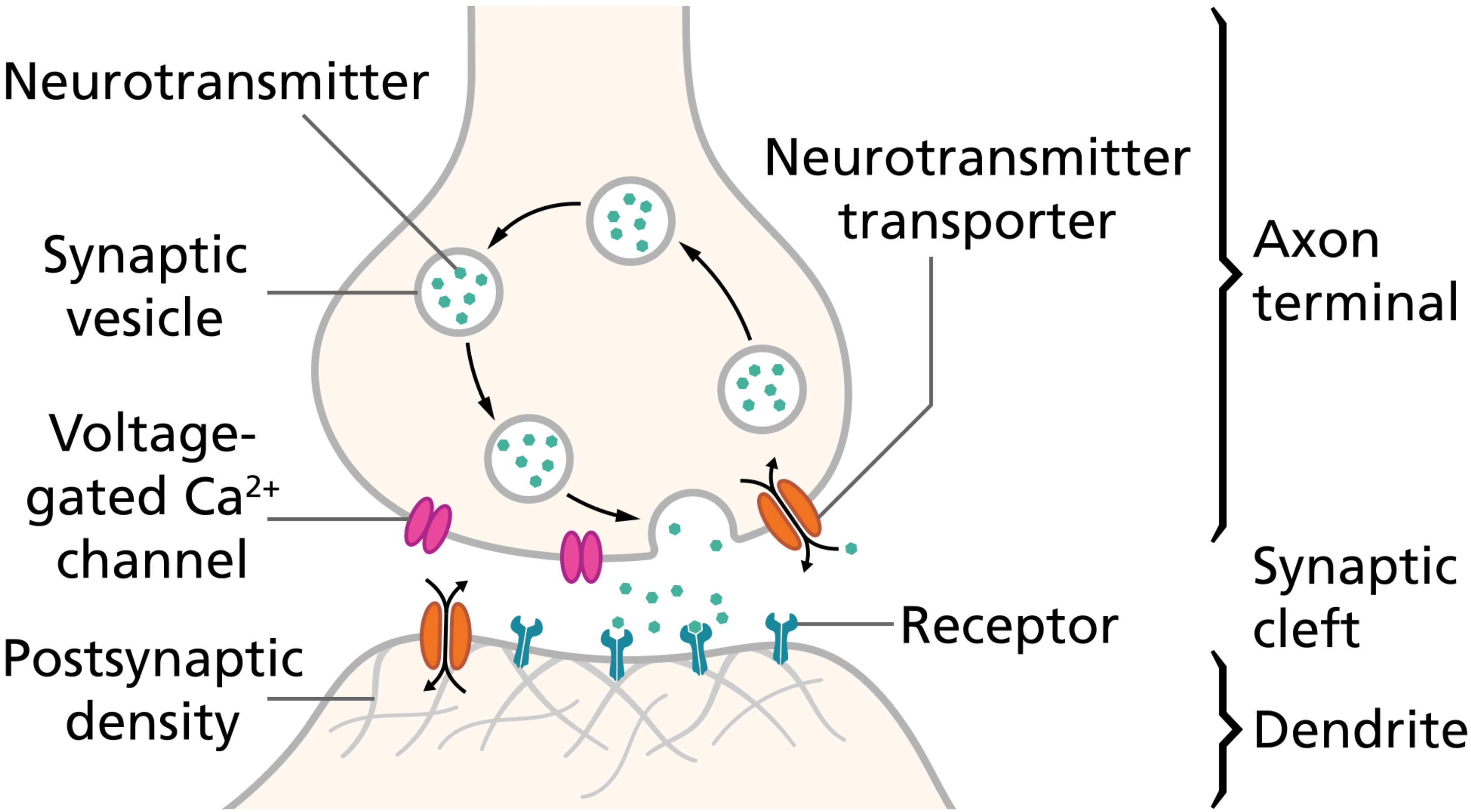
Back to single neurons

Keywords	*Function*
Synapses	**INPUT**
Axon hillock	**INTEGRATION**
Action Potential	
Synapses	**OUTPUT**



Picture from Henry Gray (1918) Anatomy of the Human Body

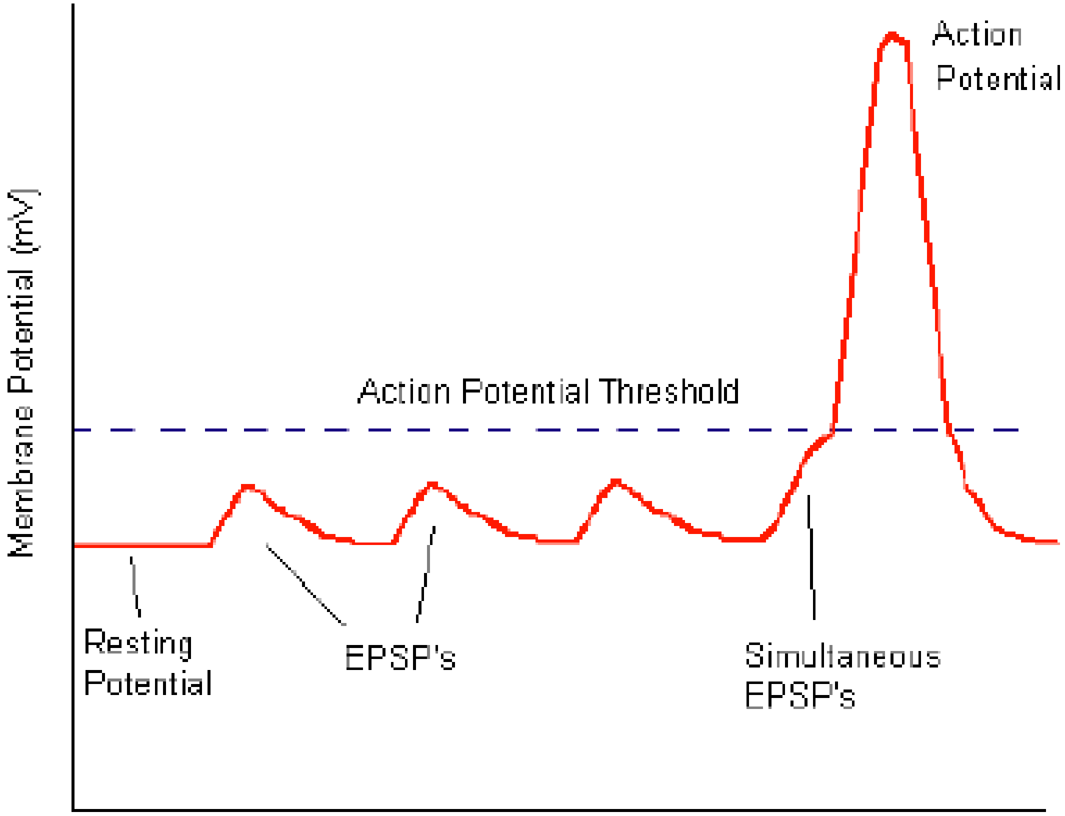
Synapses



Picture from https://en.wikipedia.org/wiki/Synapse

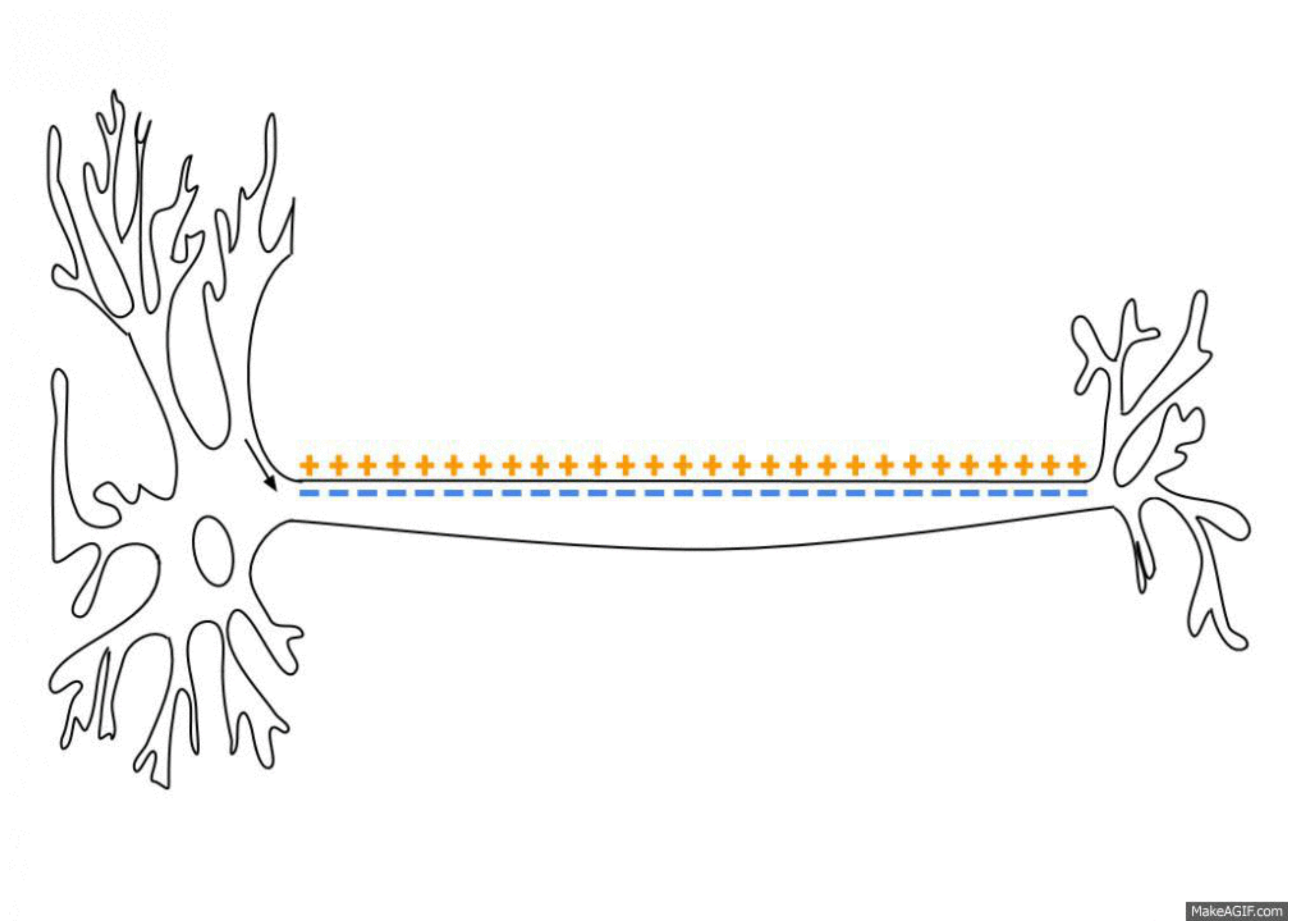
→ Inhibitory and excitatory post-synaptic potentials (IPSPs/EPSPs)

Behavior of a single neuron: Action Potentials



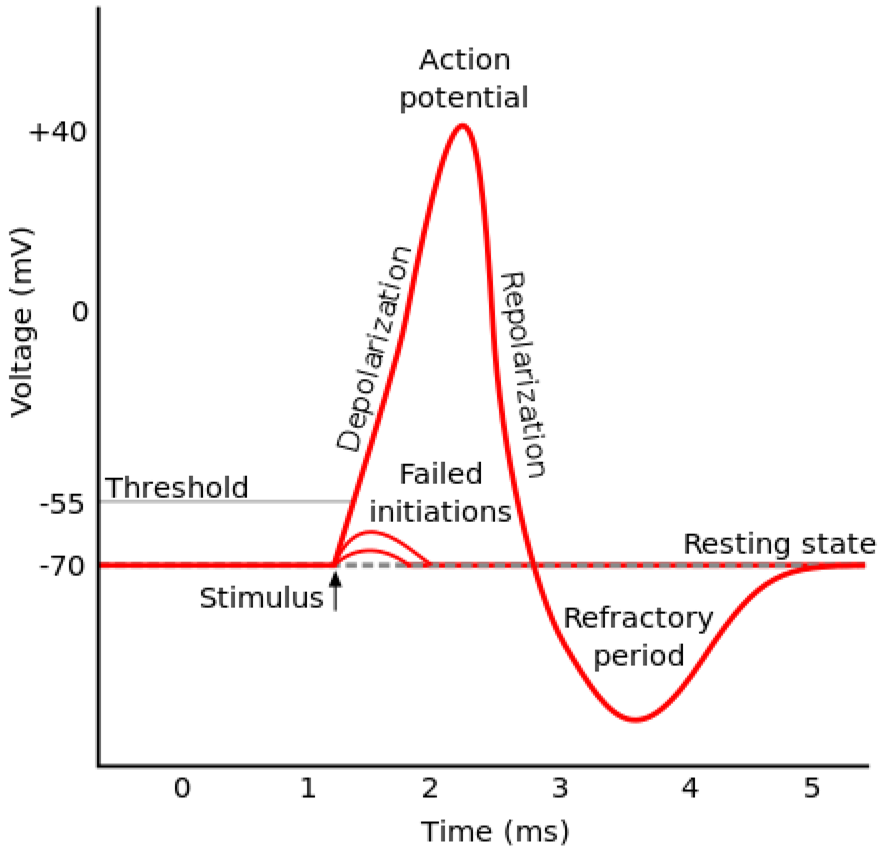
- all-or-none firing

The action potential on the axon



From https://en.wikipedia.org/wiki/Action_potential

Action Potentials



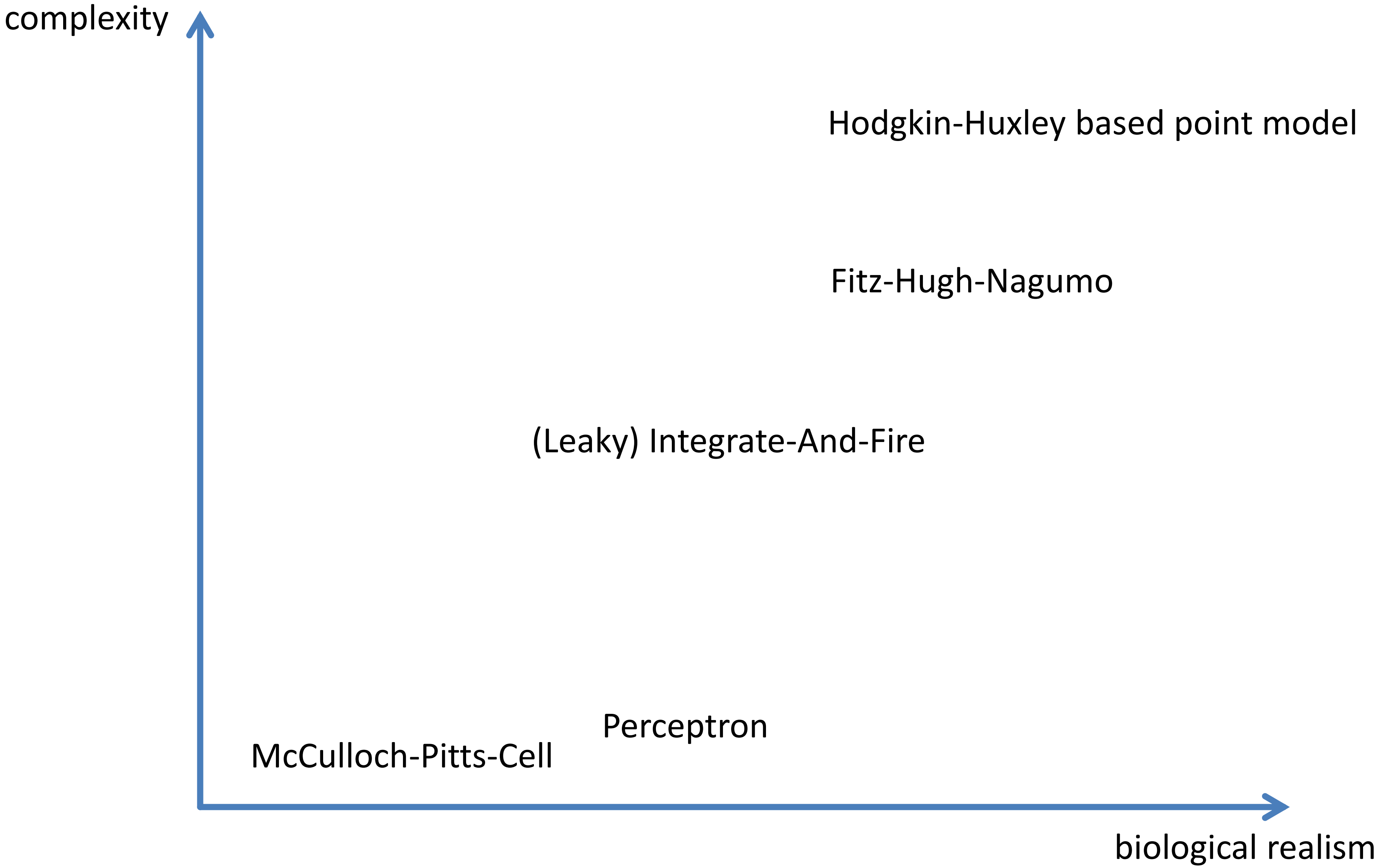
From https://en.wikipedia.org/wiki/Action_potential

Synaptic Plasticity

- EPSPs and IPSPs are variable/adaptive
- E.g. Hebb Rule: What fires together, wires together
  →Correlations lead to strengthening (e.g. temporal, spatial)

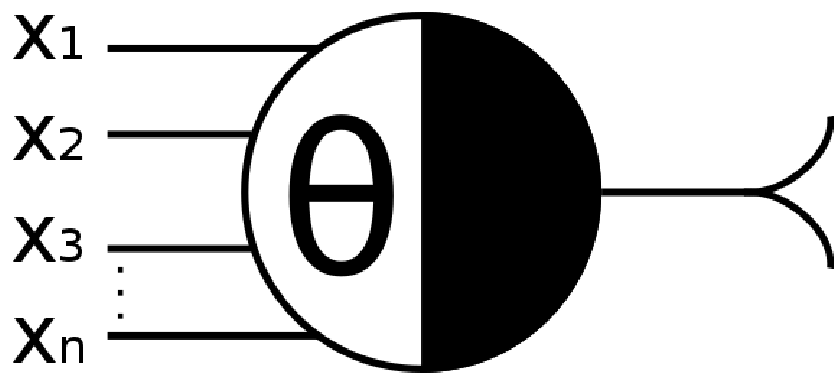
FUNCTIONAL MODELS OF NEURONS

models of neurons



McCulloch-Pitts-Cell

- Only binary signals ({0,1})
- Excitatory and inhibitory inputs {→{-1,0,1})
- Real-numbered thershold θ



From https://de.wikipedia.org/wiki/McCulloch-Pitts-Zelle

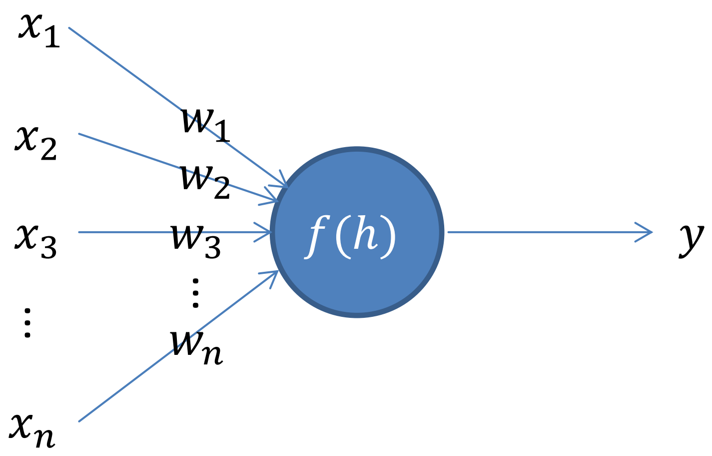
Missing:

- Input strength (firing frequency)
- Synaptic weights
- Integration over time
- Refractory period
- Output strength (firing frequency)

Perceptron

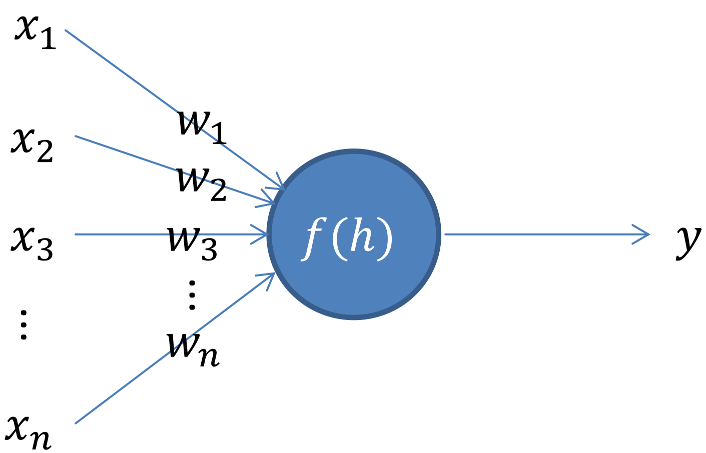
- Weighted real-numbered input x
- continuous output y
- threshold b

$$y = f\left(\sum_{i=1}^{n} w_i x_i - b\right)$$



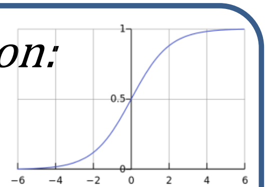
Comparison

Artificial Neurons: Perceptron



Mostly logistic function:

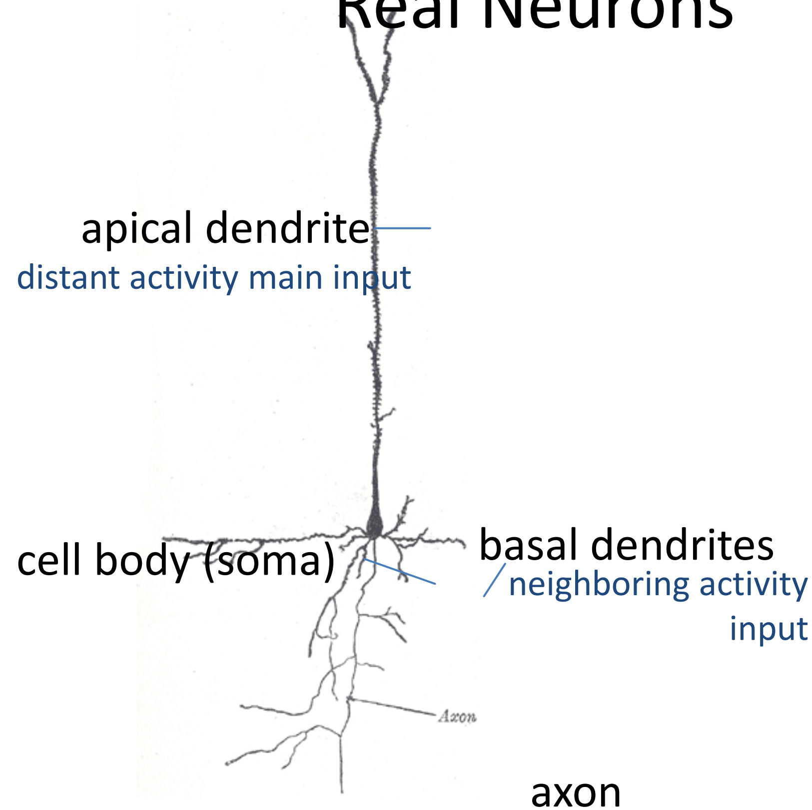
$$f(h) = \frac{1}{1 + e^{-ah}}$$



… or other sigmoid function

$$h = \sum_{i=1}^{n} w_i x_i - \mathrm{b} \quad \rightarrow \quad y = f\left(\sum_{i=1}^{n} w_i x_i - b\right)$$

Real Neurons



axon

output (here to spinal cord/cranial nerves)

Betz-Cell:

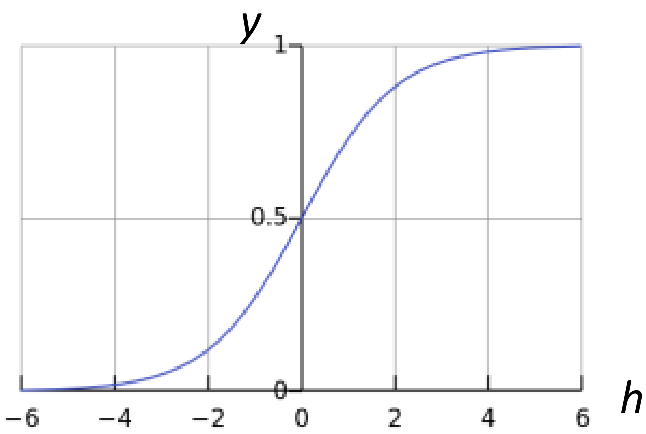
- pyramidal cell
- primary motor cortex

From Henry Gray (1918) Anatomy of the Human Body

Artificial Neurons: Which funcion and why?

Logistic function

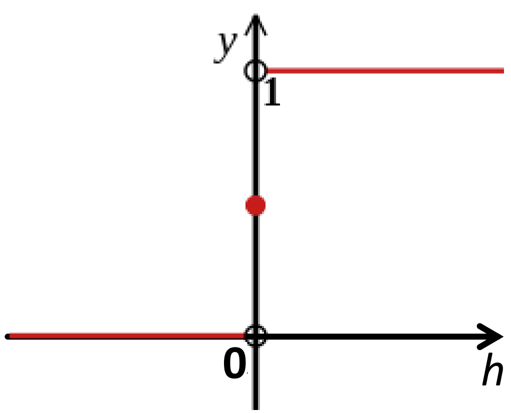
$$f(h) = \frac{1}{1 + e^{-ah}}$$



$$\lim_{h \to \infty} f(h) = 1$$
$$\lim_{h \to -\infty} f(h) = 0$$

Sign function

$$(sign(h) + 1)/2 = \lim_{a \to \infty} \frac{1}{1 + e^{-ah}}$$



$$f(h) = \begin{cases} 1 & for\ h \geq 0 \\ 0.5 & for\ h = 0 \\ -1 & for\ h \geq 0 \end{cases}$$

Sigmoid function?

- Interpretations:
  - Sigmoid shape?
    - All-or-none firing of single neuron?
    - Firing Frequency ?

    → both interpretations possible!
  - Probabilistic behaviour of neurons

- Also other functions possible:
  - Radial Basis Function
  - Euclidean Distance
  - …

Weight vector

- Weighting the effect of different inputs on a neuron
- Inner product → similarity measure!?

$$y = f\left(\sum_{i=1}^{n} w_i x_i - b\right) \qquad \boldsymbol{w} = \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} \qquad \boldsymbol{y} = f\left(\boldsymbol{w} \cdot \boldsymbol{x} - b\right)$$

Still Missing:

- Input strength (firing frequency)
- Synaptic weights
- Integration over time
- Refractory period
- Output strength (firing frequency)

MORE REALISTIC NEURON MODELS

Integrate-and-fire neuron model

$$
\begin{aligned}
\tau_i \frac{\mathrm{d}U_i}{\mathrm{d}t} &= I_i^{\mathrm{PSC}} \\
X_i(t_k) &= \Theta(U_i(t_k) - \theta_i) \\
U_i(t_k) &\leftarrow E\,.
\end{aligned}
$$

Here, $U_i(t)$ describes the membrane potential of unit i, X_i and θ_i model the action potentials and the firing thresholds as in (1.66), and t_k are the firing times where the membrane potential is reset to its resting value E (indicated by the arrow).

Leaky integrate-and-fire neuron model

$$\tau_i \frac{\mathrm{d}U_i}{\mathrm{d}t} + U_i = \sum_j w_{ij} f(U_j)$$

$$X_i(t_k) = \Theta(U_i(t_k) - \theta_i)$$

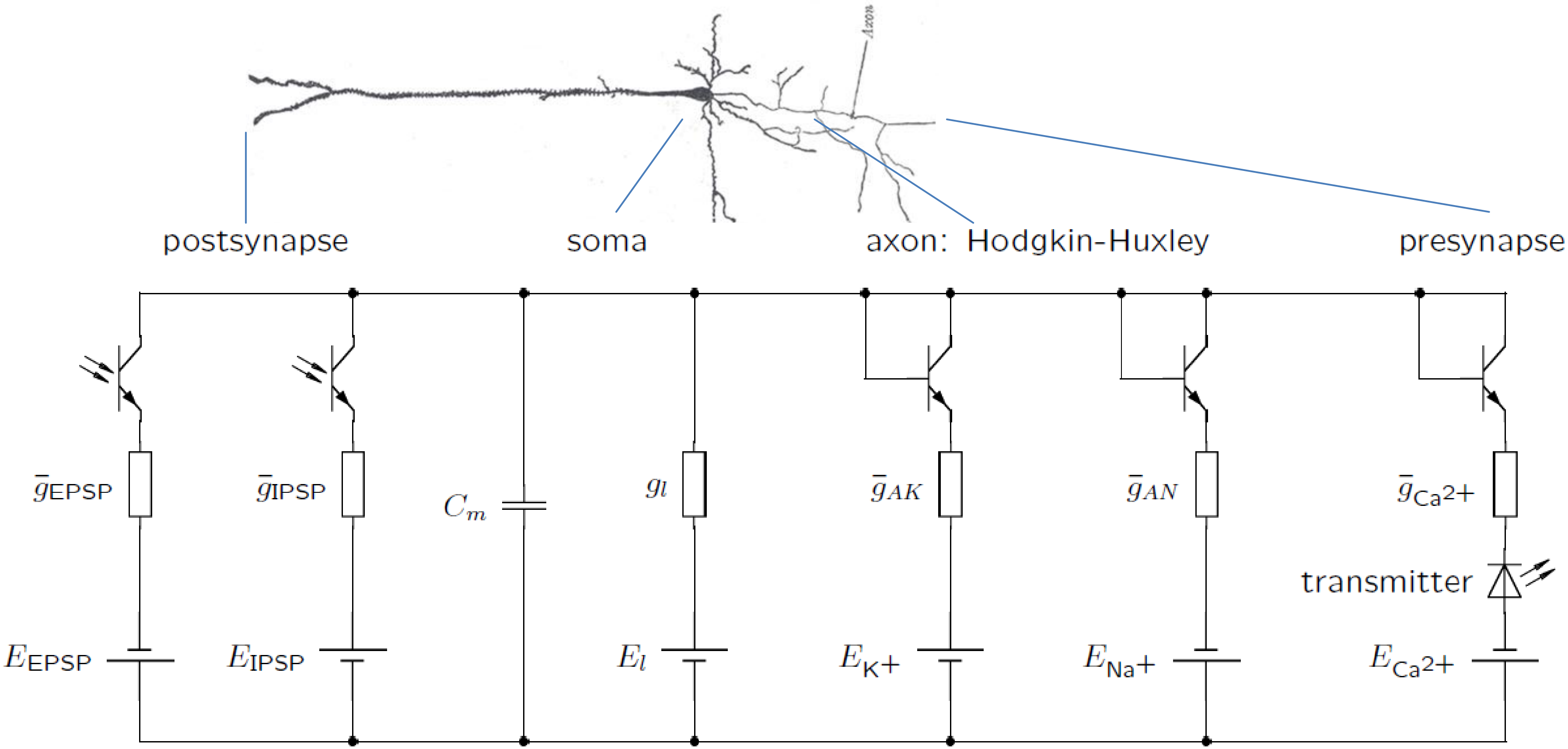
$$U_i(t_k) \leftarrow E .$$

Here, $U_i(t)$ describes the membrane potential of unit i, X_i and θ_i model the action potentials and the firing thresholds as in (1.66), and t_k are the firing times where the membrane potential is reset to its resting value E (indicated by the arrow).

Still Missing:

- Input strength (firing frequency)
- Synaptic weights
- Integration over time
- Refractory period
- Output strength (firing frequency)

Hodgkin-Huxley based point model



Fitz-Hugh Nagumo

- Based on Hodgkin-Huxley model:

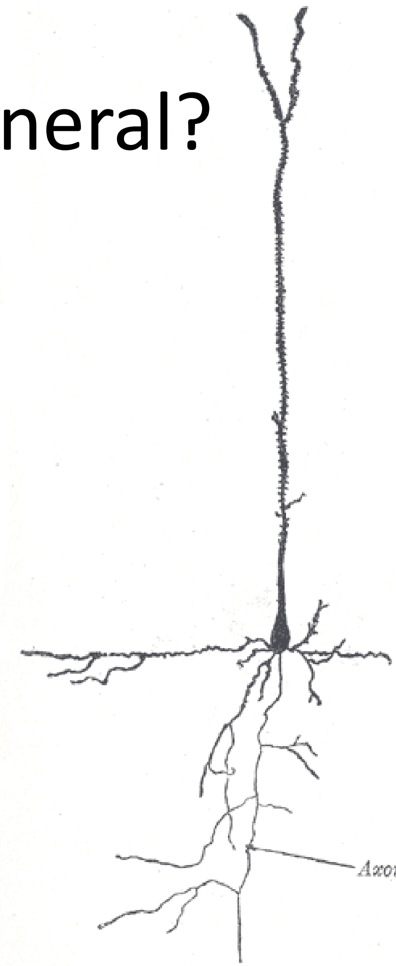
$$\frac{dv}{dt} = v - \frac{1}{3}v^3 - w + I_{ext}$$
$$r\frac{dw}{dt} = v - a - bw$$

  - V describing sodium-based depolarisation
  - W descirbing potassium based repolarisation and refractory period

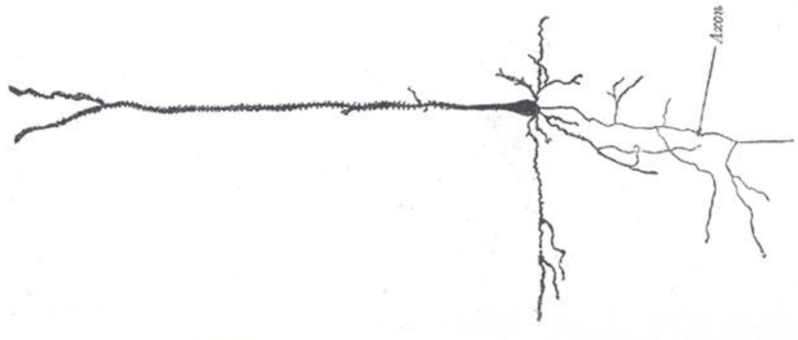
ELECTRICAL FIELDS OF NEURONS

Where does the electric field of a single neuron come from?

- What do you think?
- What causes electrical fields in general?



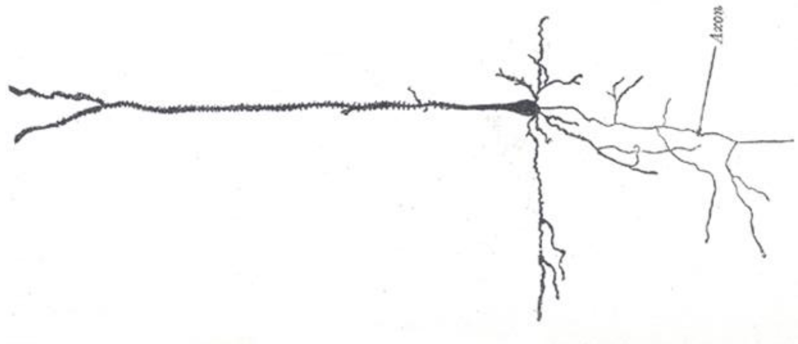
Electrical Fields of Neurons



What causes the electric field surrounding a neuron?

- Seperated charges?
- A current flow?
  - Strong focal currents?
  - Spatially spread currents?

Electrical Fields of Neurons



Which parts of the neurons produce the field?

- Dendrites? Yes
- Soma? Yes
- Axon? No, because the action potential propagates locally through ion-channels (not spatially spread)

Is a single neuron measurable by EEG?

- Realistic source current density of a single neuron: $J \approx \frac{100mA}{m^2}$ (Buzsaki et al 2012)
- Realistic source current for 1µV EEG-signal:
  $I_S \approx \frac{1}{100\Omega} 1\mu V = 10nA$
- $J \approx \frac{10nA}{2\pi(3\mu m)^2} = 1000\mathrm{A/m^2}$ → too much for 1 neuron!

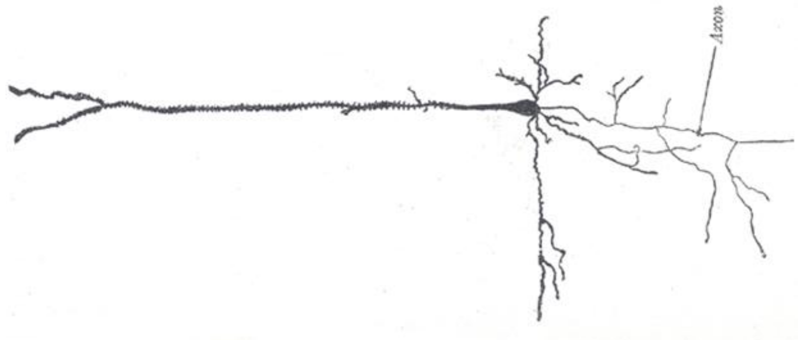
→Synchronously active assemblies of parallel neurons necessary!

Which Neurons produce fields measurable by EEG?

- Spatially spread currents necessary
- Spatial alignment in parallel necessary

→ Mainly pyramidal cells of the neocortex

Electrical Fields of Neurons

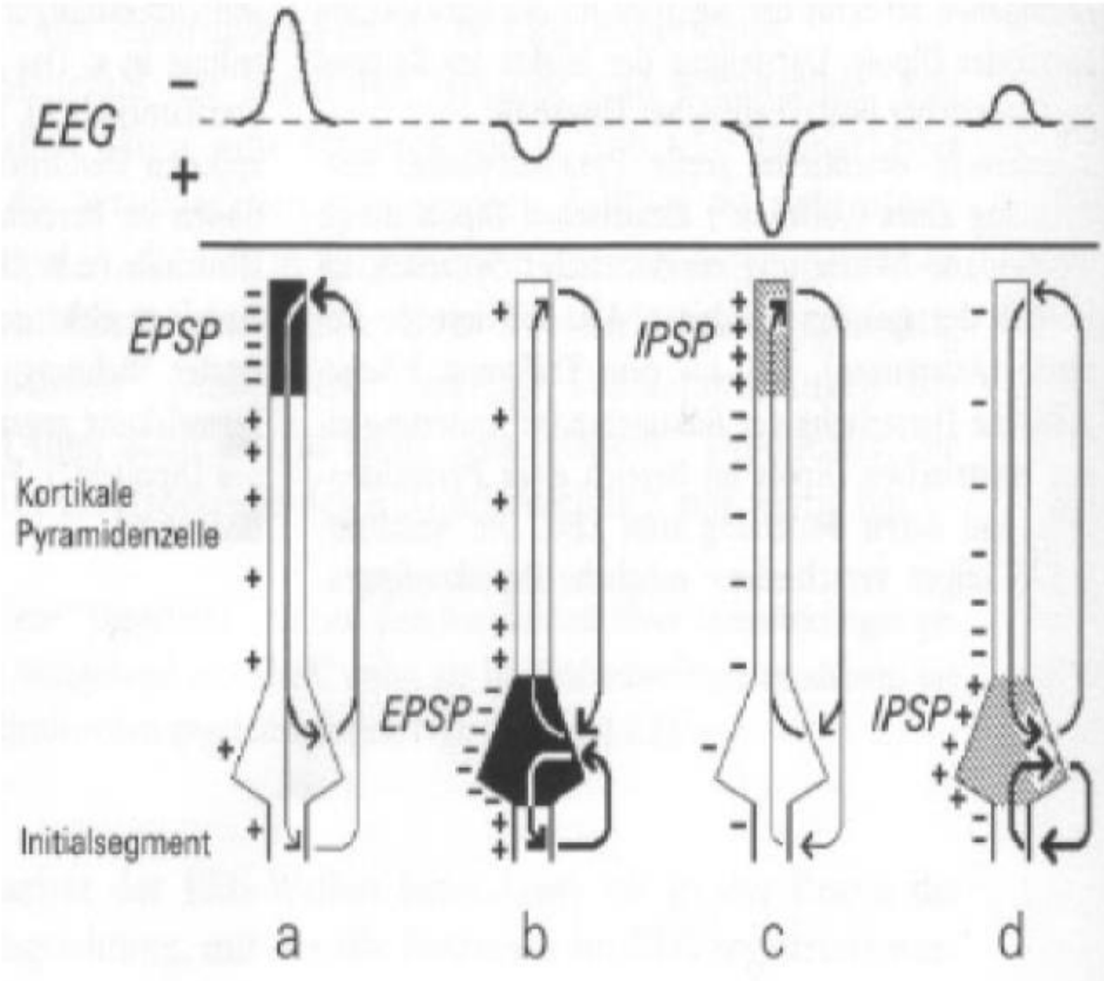


Is it inhibitory or excitatory post-synaptic potentials (IPSPs/EPSPs) producing the field?

- EPSPs are mostly coming from distal apical dendrites
- IPSPs are mostly coming from basal dendrites

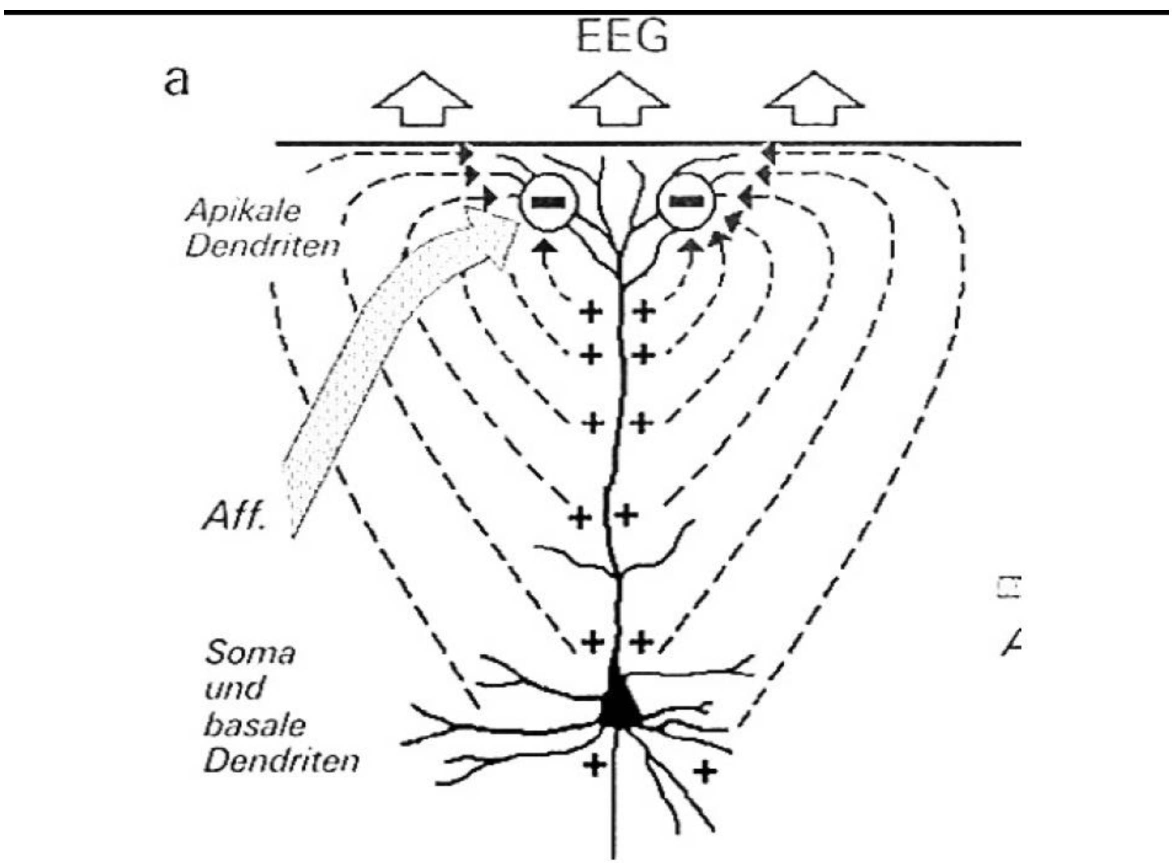
→rather EPSPs but both can have an effect

EPSPS/IPSPS



Picture from Ritter

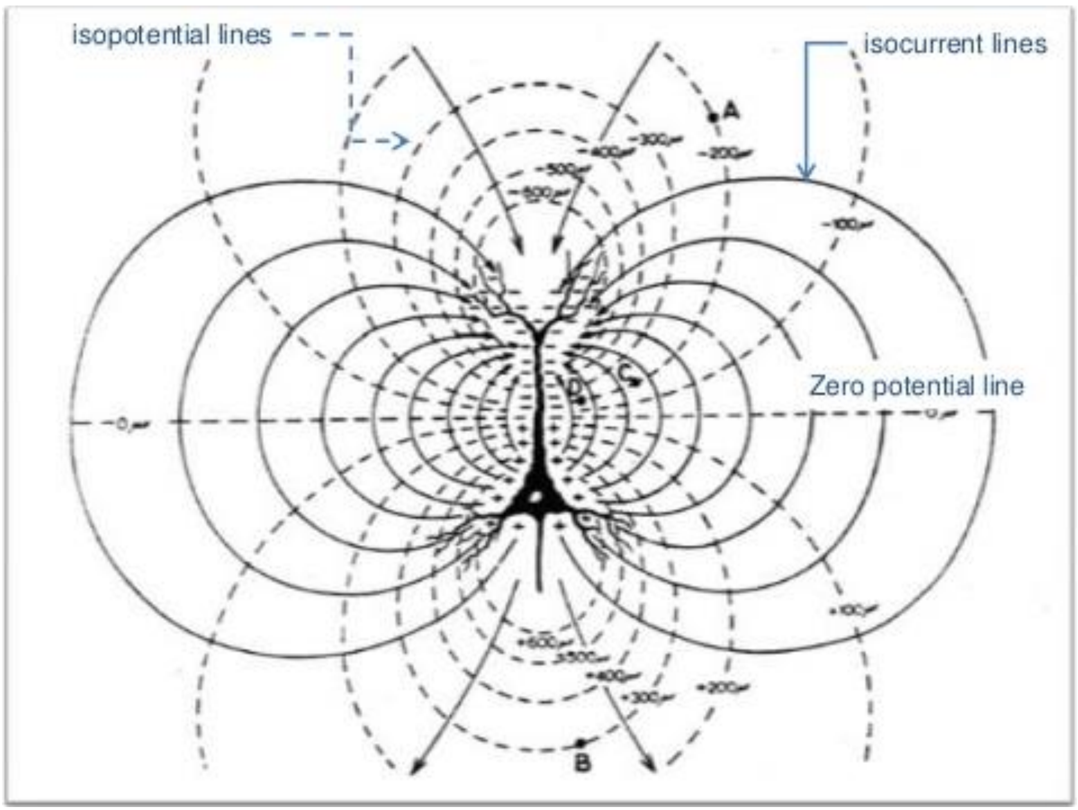
Electrical Fields of Neurons



Dipole character of pyramidal cells

adapted from Ritter

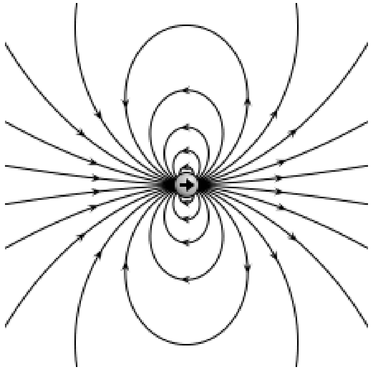
Equivalent Current Dipole



Dipolar Field

– current dipole (Neuronal activity)

- analytic solution $\varphi(\vec{r}) = \frac{1}{4\pi\varepsilon_0}\frac{\vec{p}\cdot\vec{e}_r}{|\vec{r}|^3}$
- Current density $\vec{J}_P = \sigma\vec{E} = -\sigma\nabla\varphi$



Picture from https://en.wikipedia.org/wiki/Dipole

THANKS FOR YOUR ATTENTION