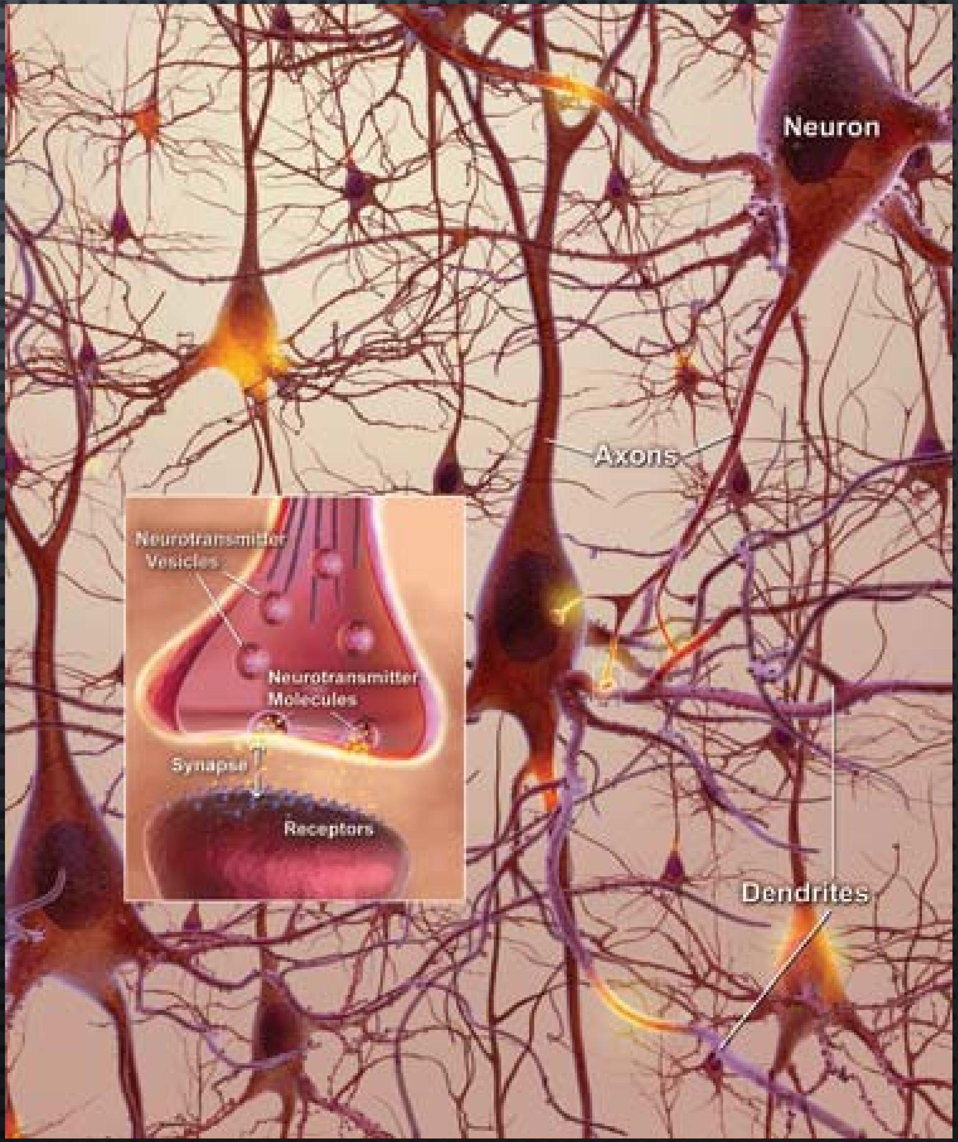
4 Learning mechanisms in biological neurons and their functional engineering models

Neurobiology ahead
(but now you love it ☻)

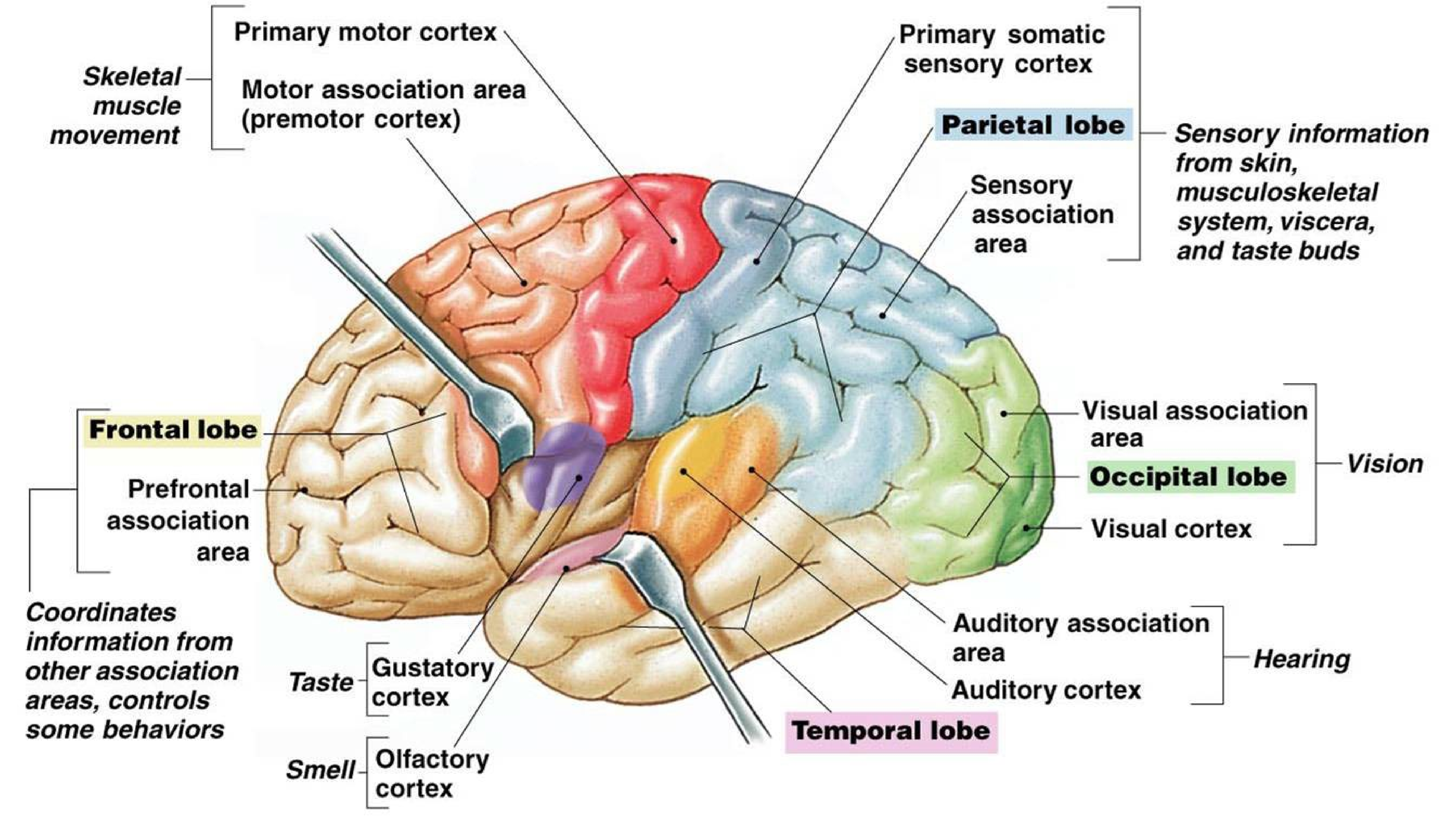
Neuroplasticity: a mechanism for biological learning

- Neuroplasticity is the ability of the brain to reorganise itself in both structure and function over time due to external and internal events
- Reorganisation can occur throughout the neural hierarchy – from single neurons to entire cortical areas
- Neuroplasticity is a continuous process that occurs at multiple timescales from milliseconds to days
- It is the underlying mechanism behind learning and memory formation



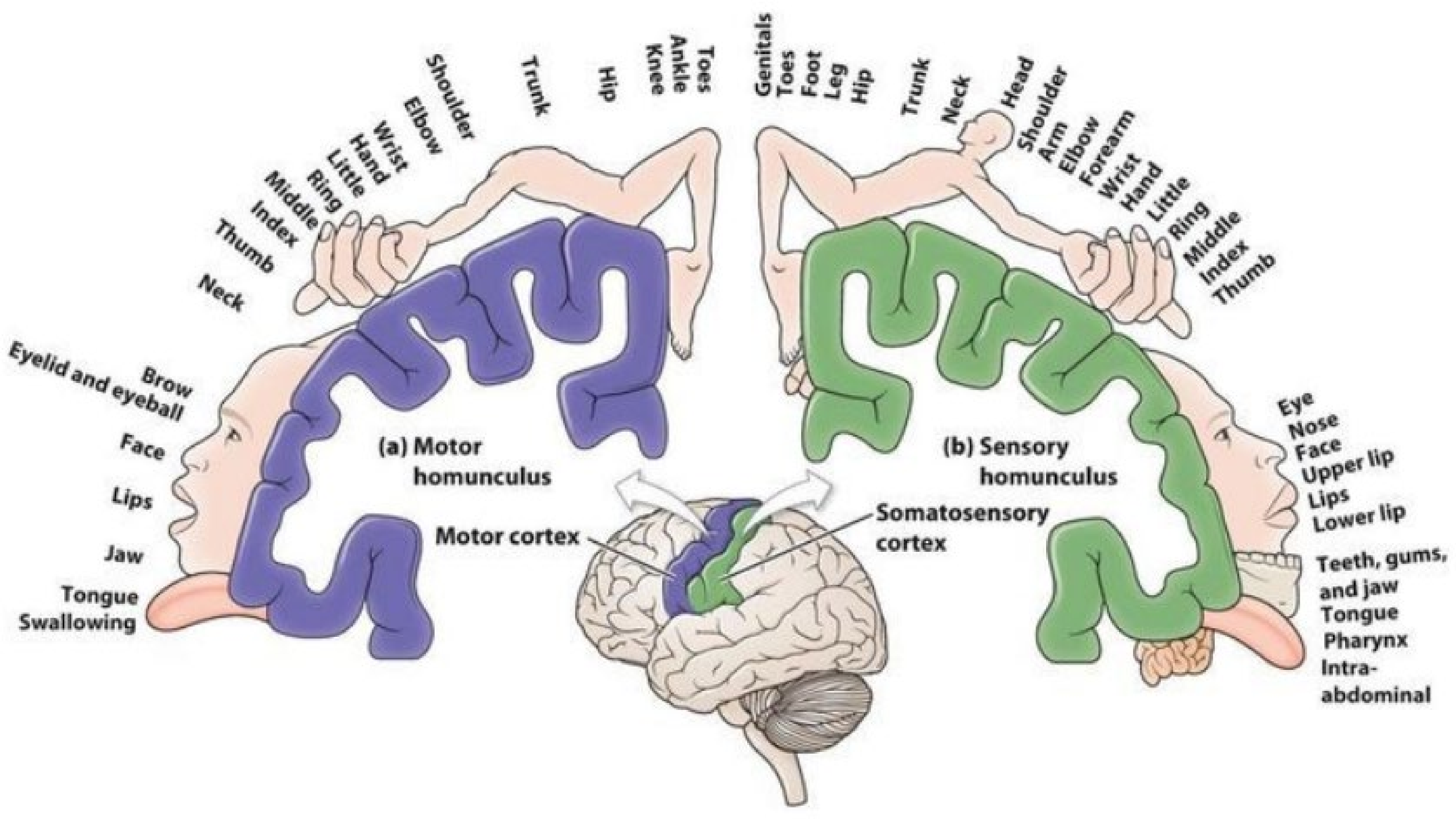
Encyclopedia Britannica

Brain areas

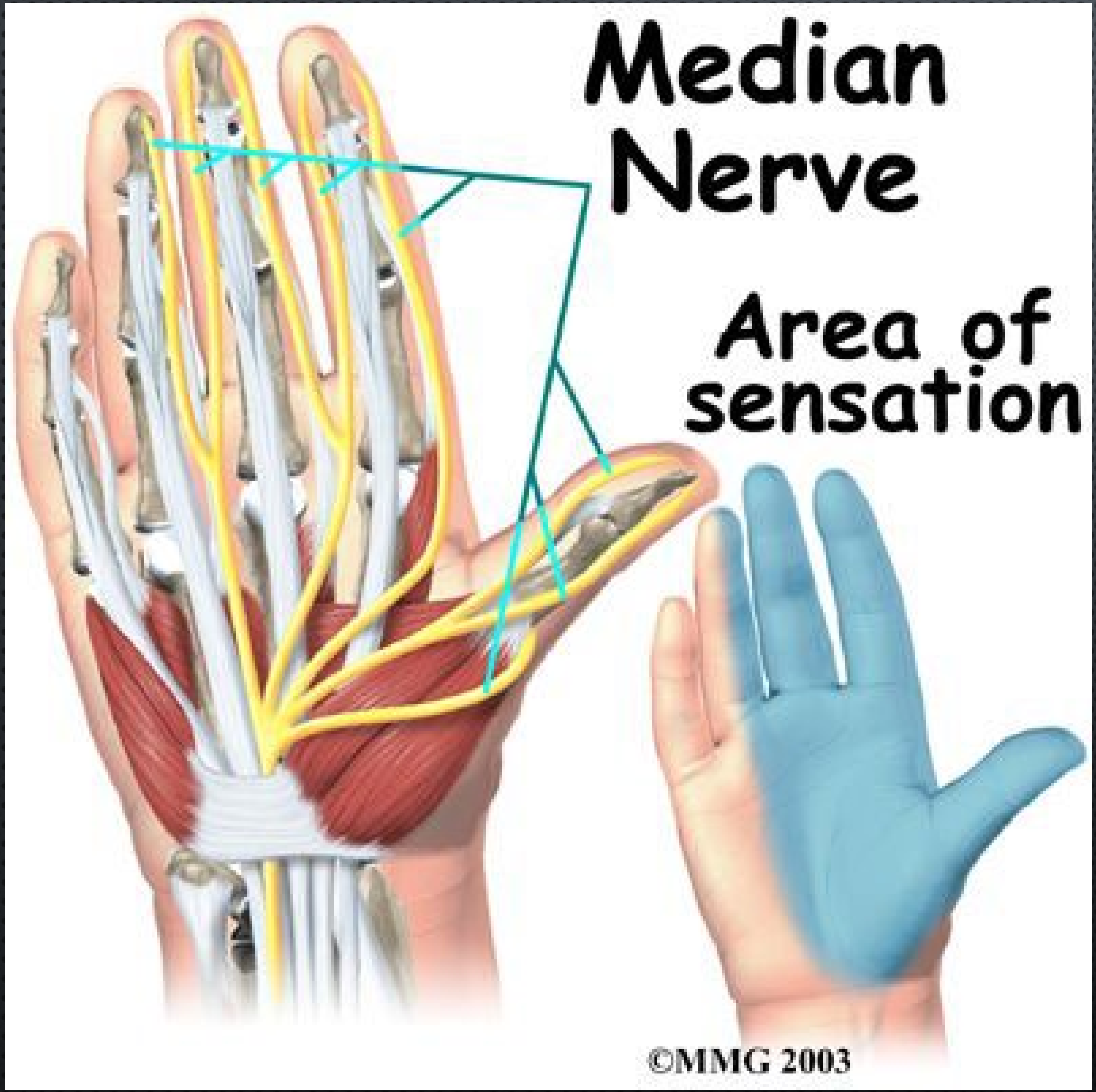


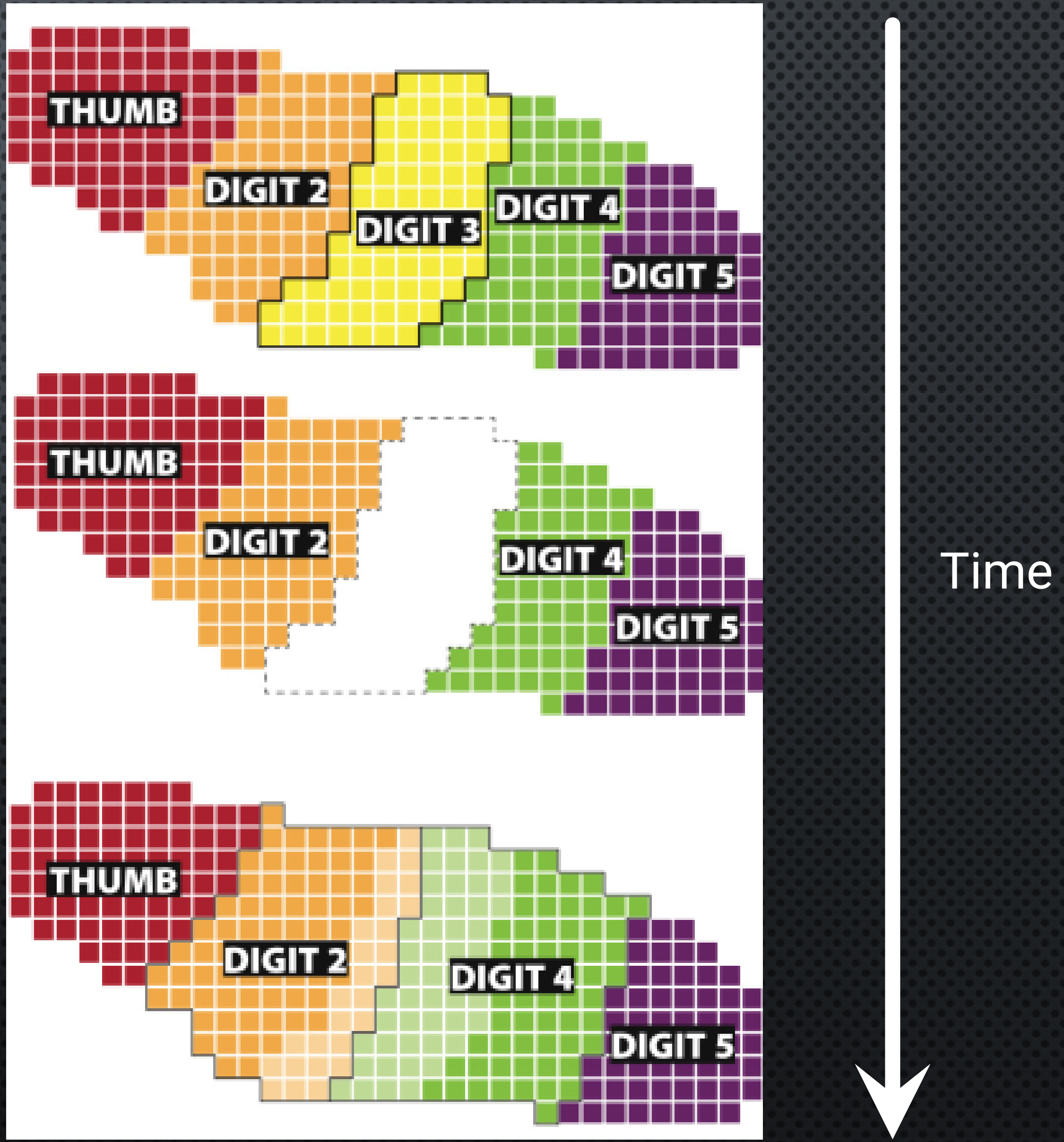
Primary motor cortex
Skeletal muscle movement
Motor association area (premotor cortex)
Primary somatic sensory cortex
Parietal lobe
Sensory information from skin, musculoskeletal system, viscera, and taste buds
Sensory association area
Frontal lobe
Prefrontal association area
Coordinates information from other association areas, controls some behaviors
Visual association area
Occipital lobe
Vision
Visual cortex
Taste
Gustatory cortex
Smell
Olfactory cortex
Auditory association area
Hearing
Auditory cortex
Temporal lobe

Neuroplasticity at the cortical level



Neuroplasticity at the cortical level





Types of neuroplasticity

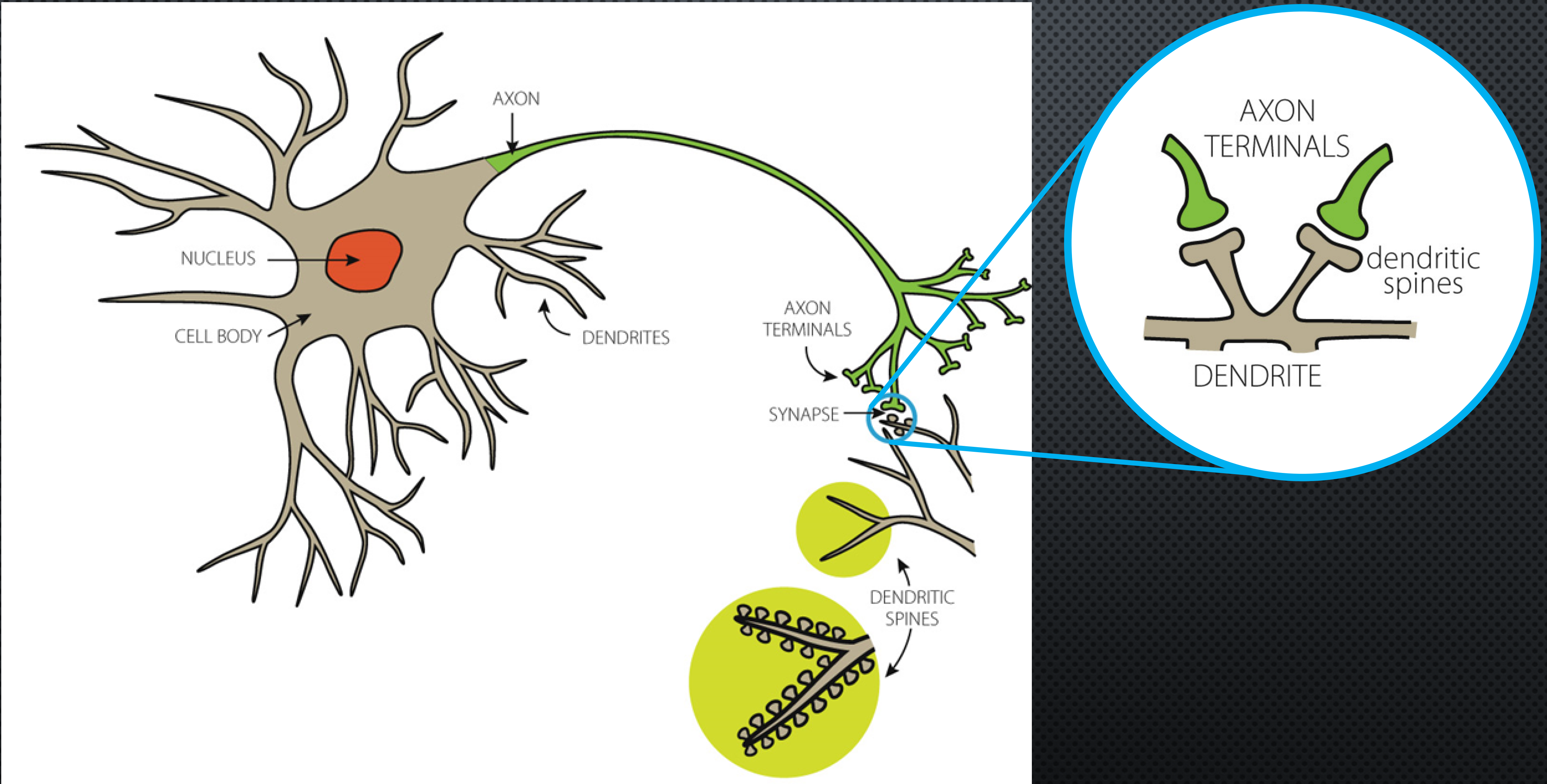
Structural plasticity

- mechanism describing the generation of new neural connections
- long-term changes
- Biological mechanisms:
    - Synapses – changes in number
    - Synaptic receptors – changes in density
    - Dendritic arborization (complexity of the dendritic tree)
    - Dendritic spines – changes in density
    - Axonal arborization (sprouting)
    - Glial and neuron interactions
    - Vascular processes and angiogenesis (new blood vessel growth)
    - Cell proliferation (including neurogenesis)

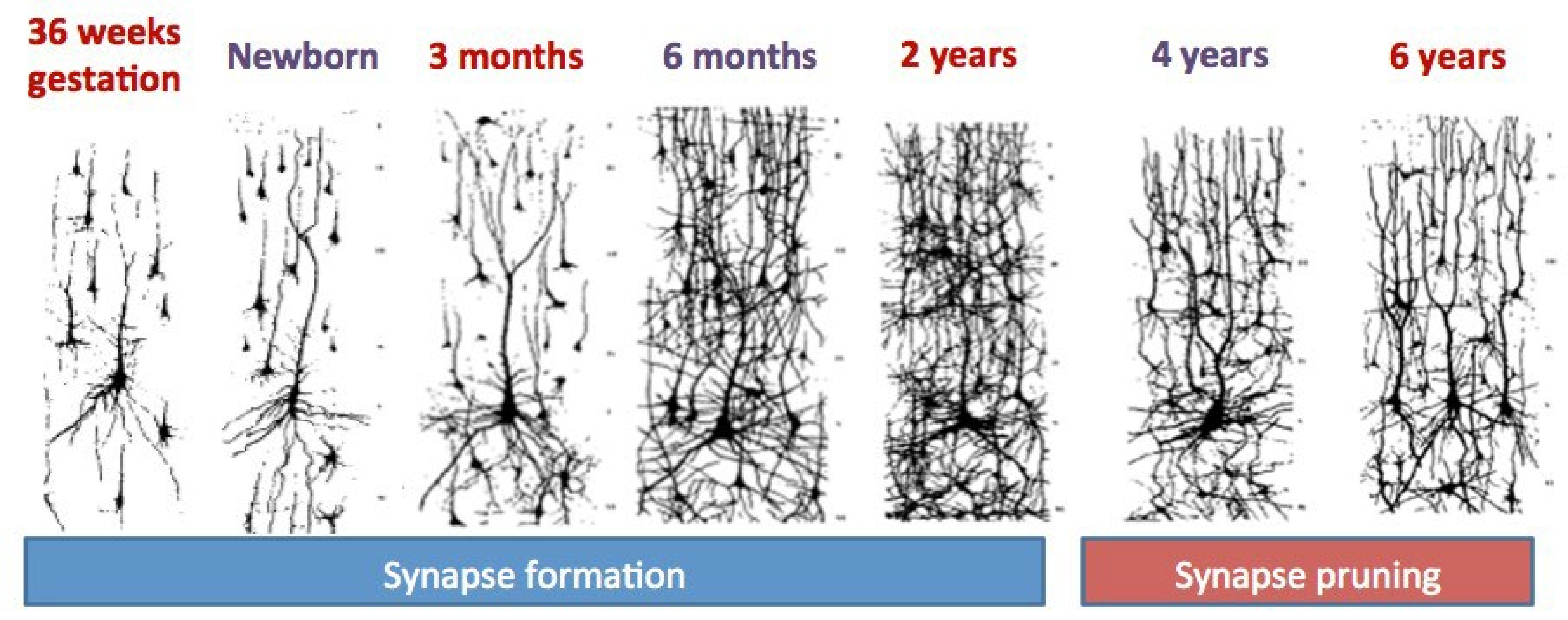
Functional plasticity

- mechanism of changing the strength of existing neural connections
- short term changes
- Biological mechanisms:
    - Synapses – changes in strength. Widely known as synaptic plasticity

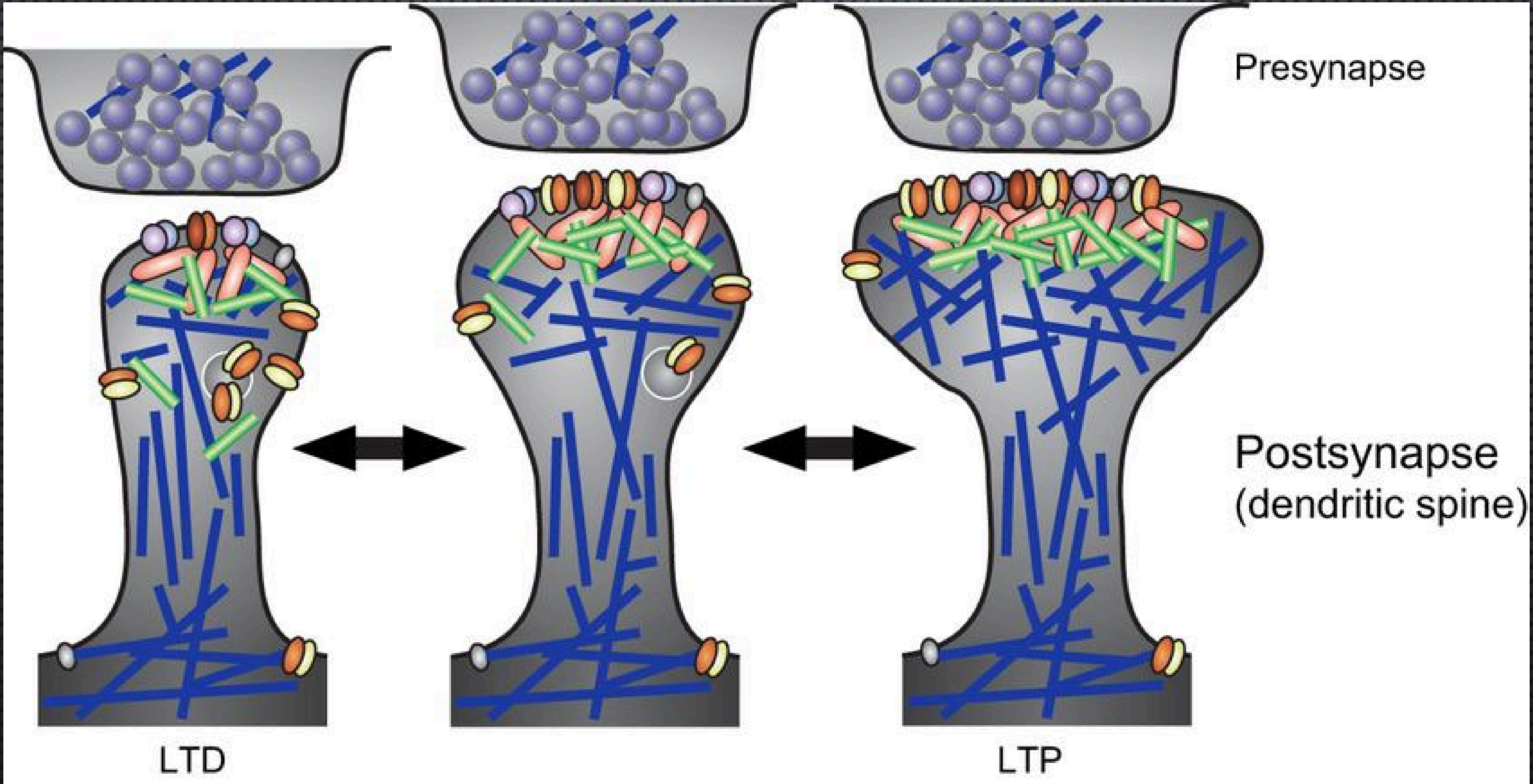
Recap: neuron structure



Structural plasticity: number of synapses

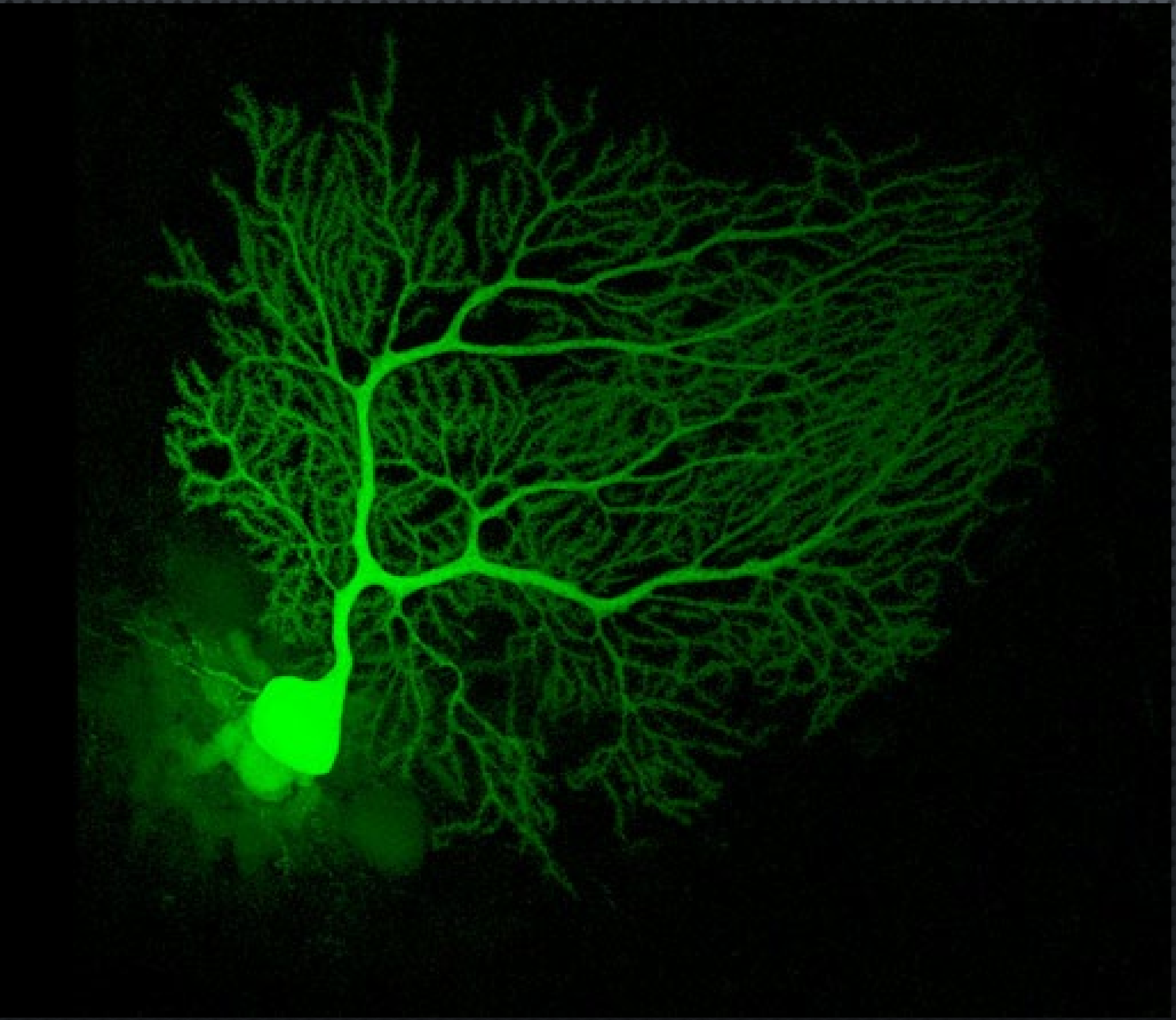


Structural plasticity: synaptic receptor density



Kessels and Qualmann, *Jour. Cell Sci.*, 2015

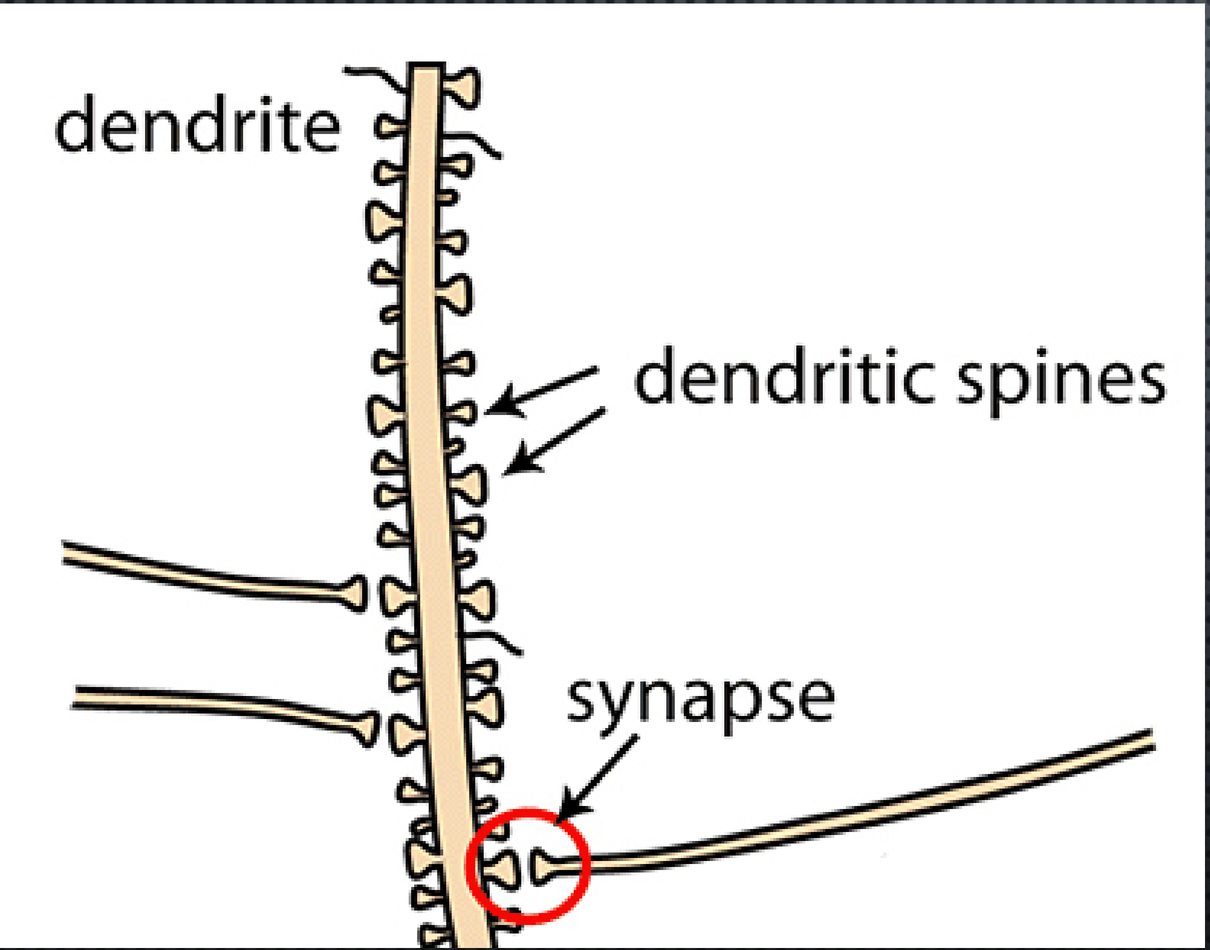
Structural plasticity: dendritic arborization



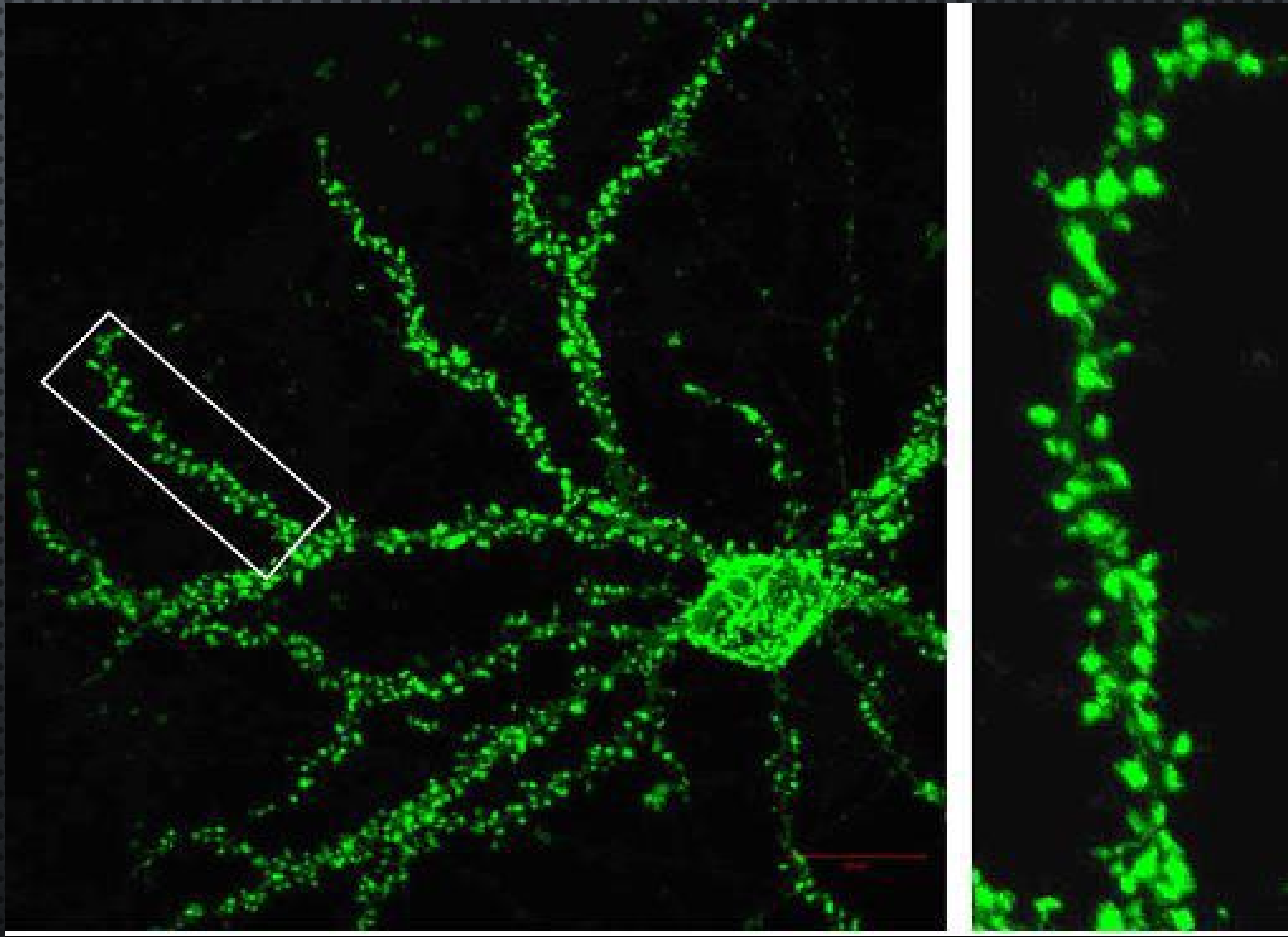
Purkinje neuron in the cerebellum

Hippocampal CA1 pyramidal neuron

Structural plasticity: dendritic spine density

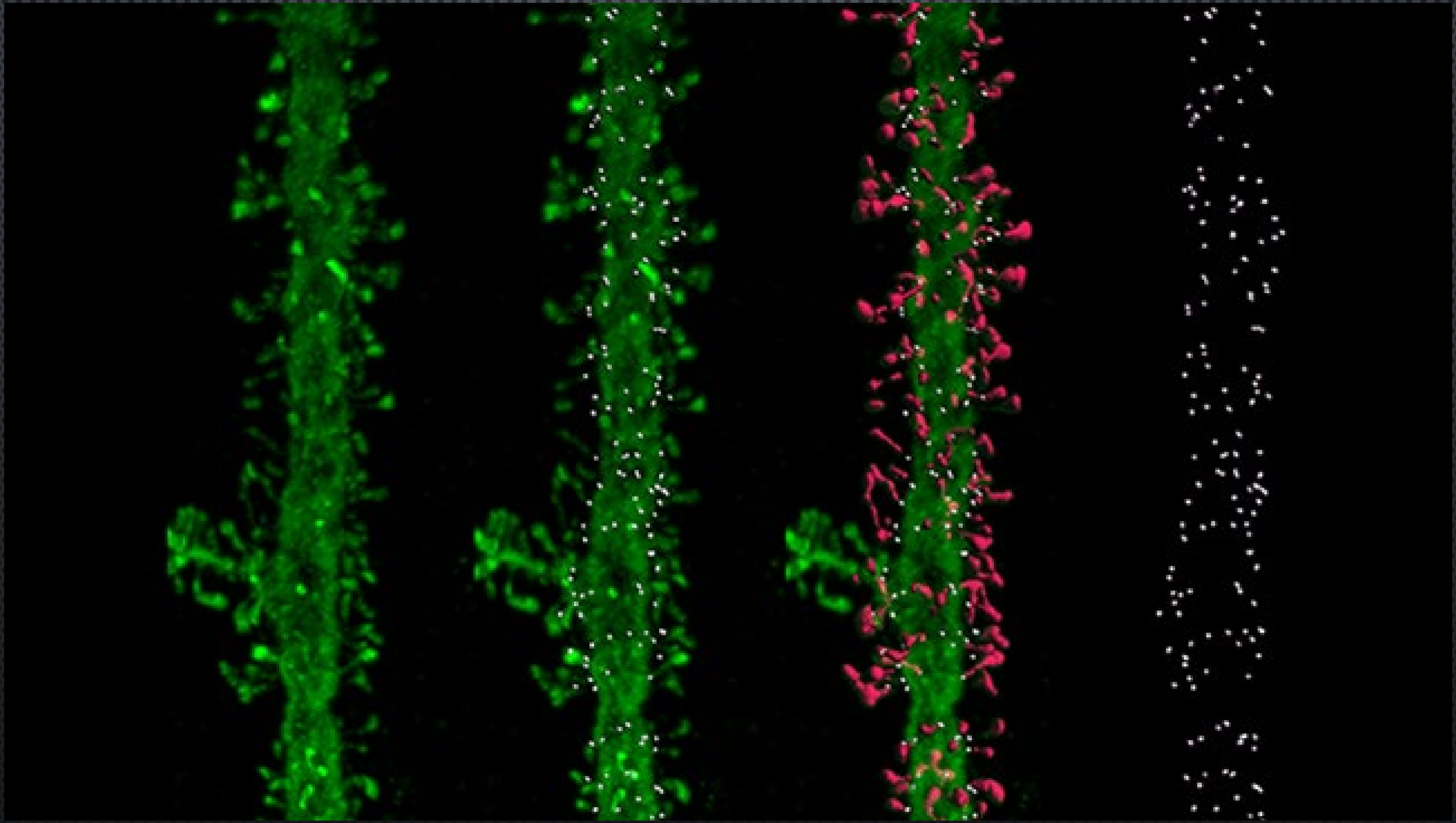


https://neuwritesd.org/2017/03/16/mind-the-gap-spaced-learning-and-dendritic-spines/



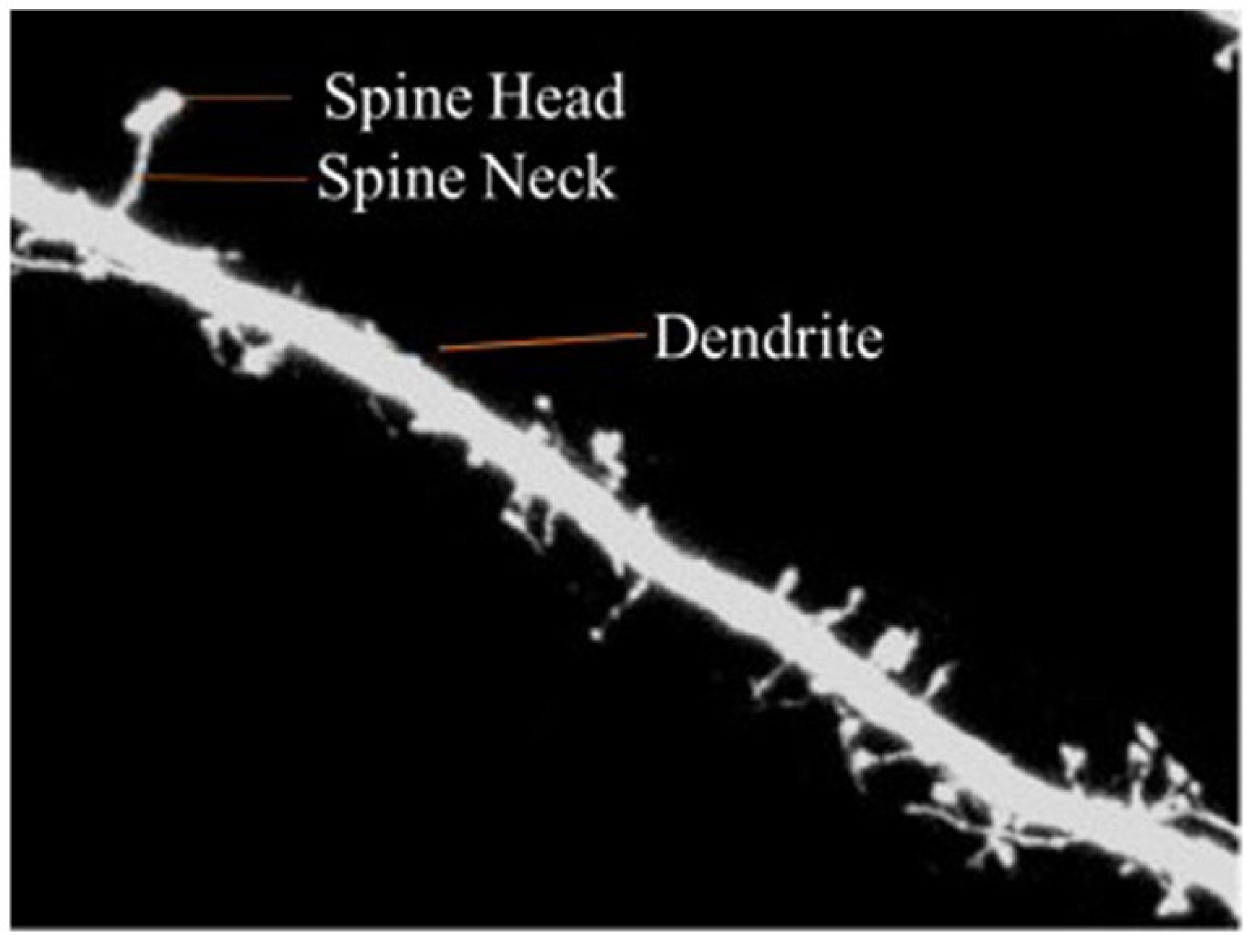
http://www.lacasamorett.com/foxgallery/dendritic-spines.html

Structural plasticity: dendritic spine density

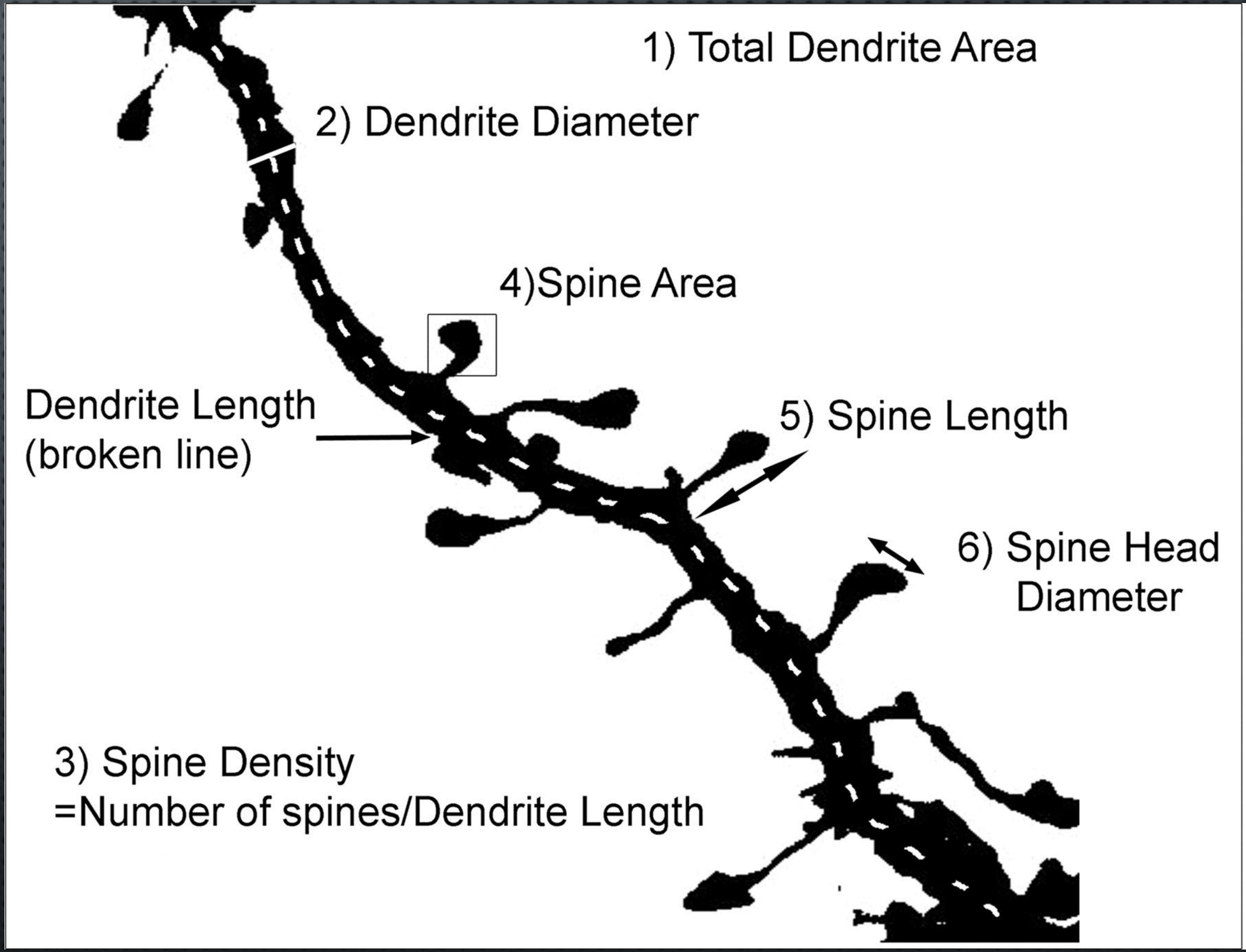


Morales et al., *Jour. Neuro.*, 2014

Structural plasticity: dendritic spine density

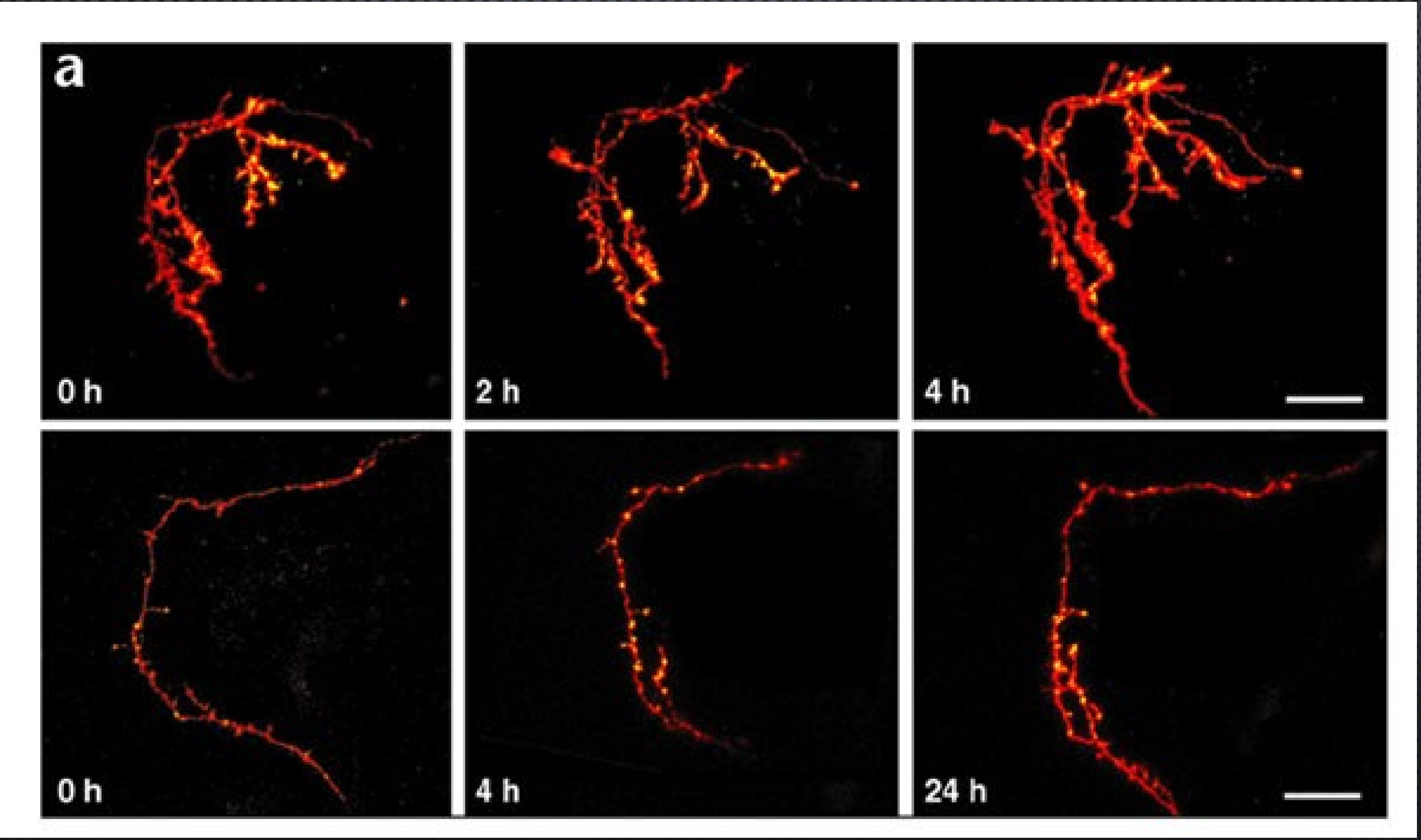


Wang et al., *PeerJ*, 2016



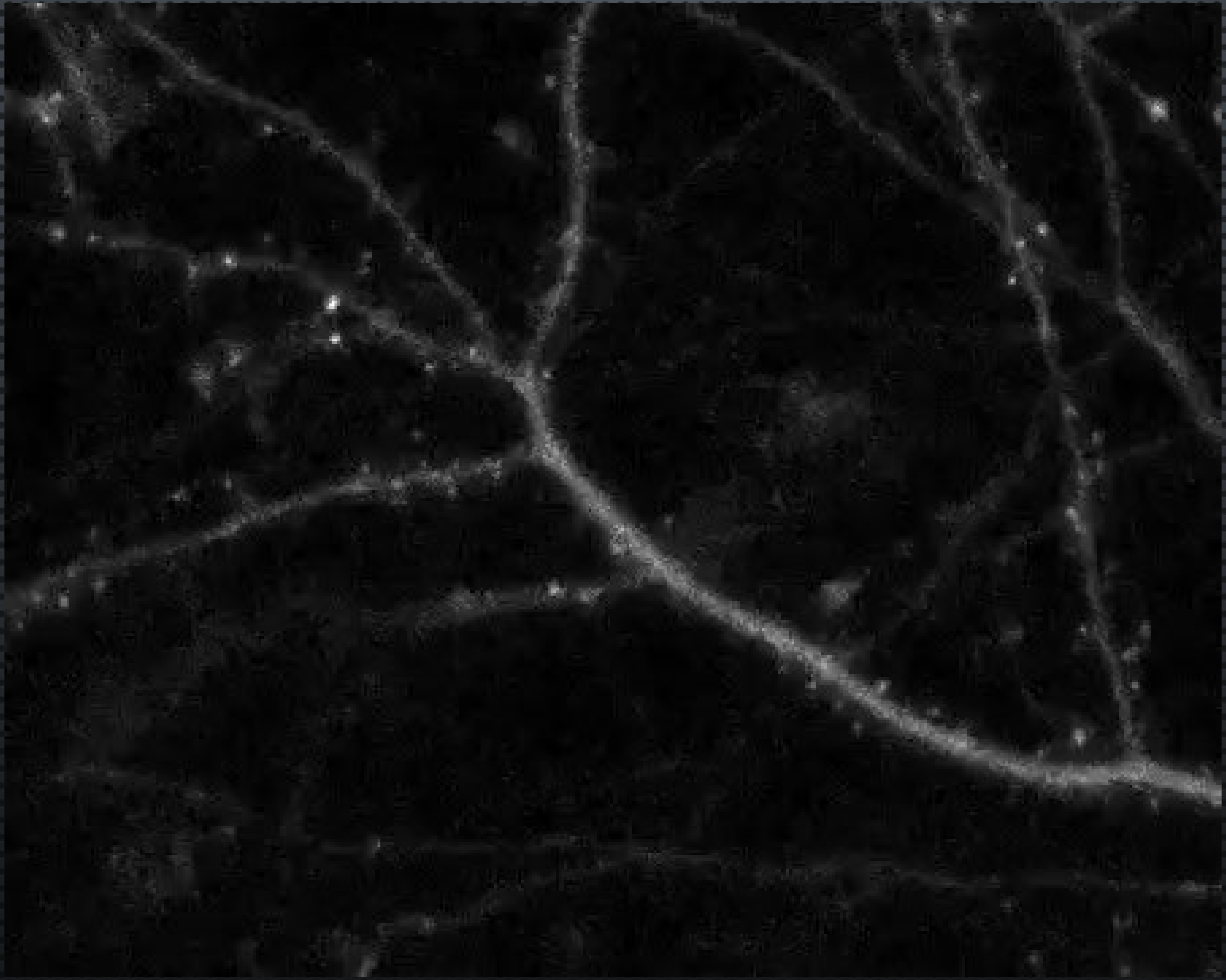
Smith et al., PNAS, 2009

Structural plasticity: axonal arborization



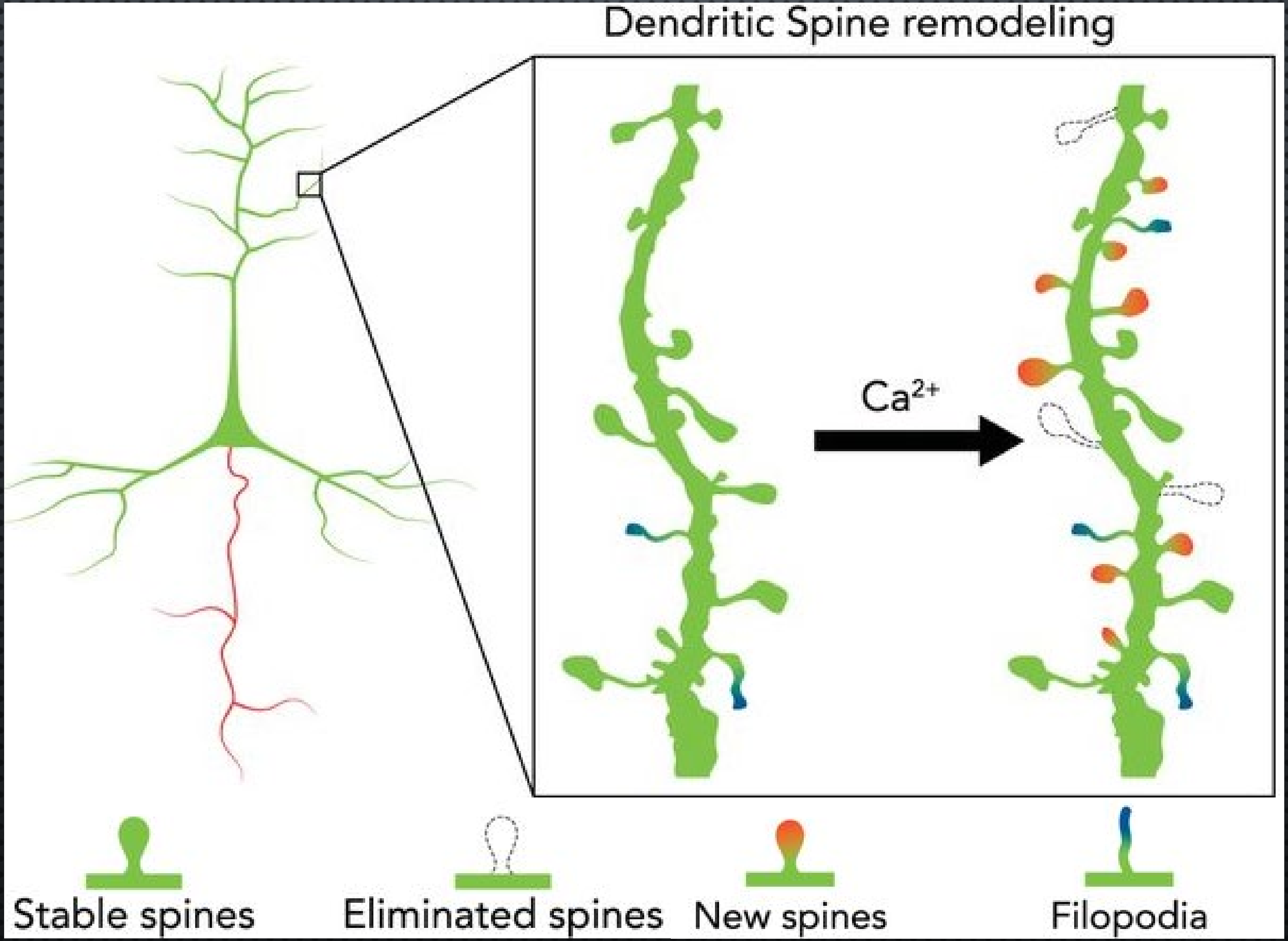
Alsina et al., *Nat. Neuro.*, 2001

Structural plasticity in action

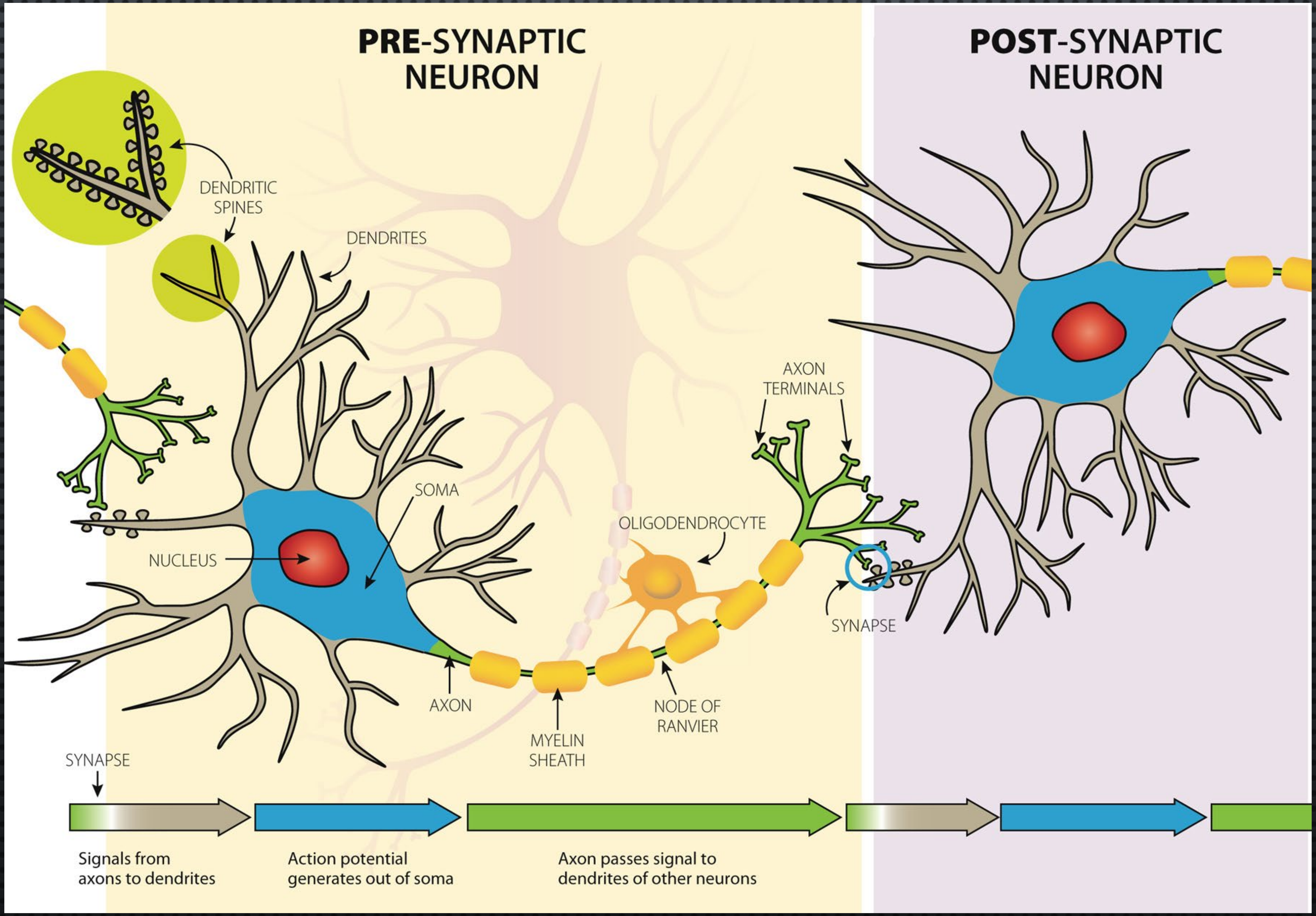


Minerbi et al., *PLOS Biol.*, 2009

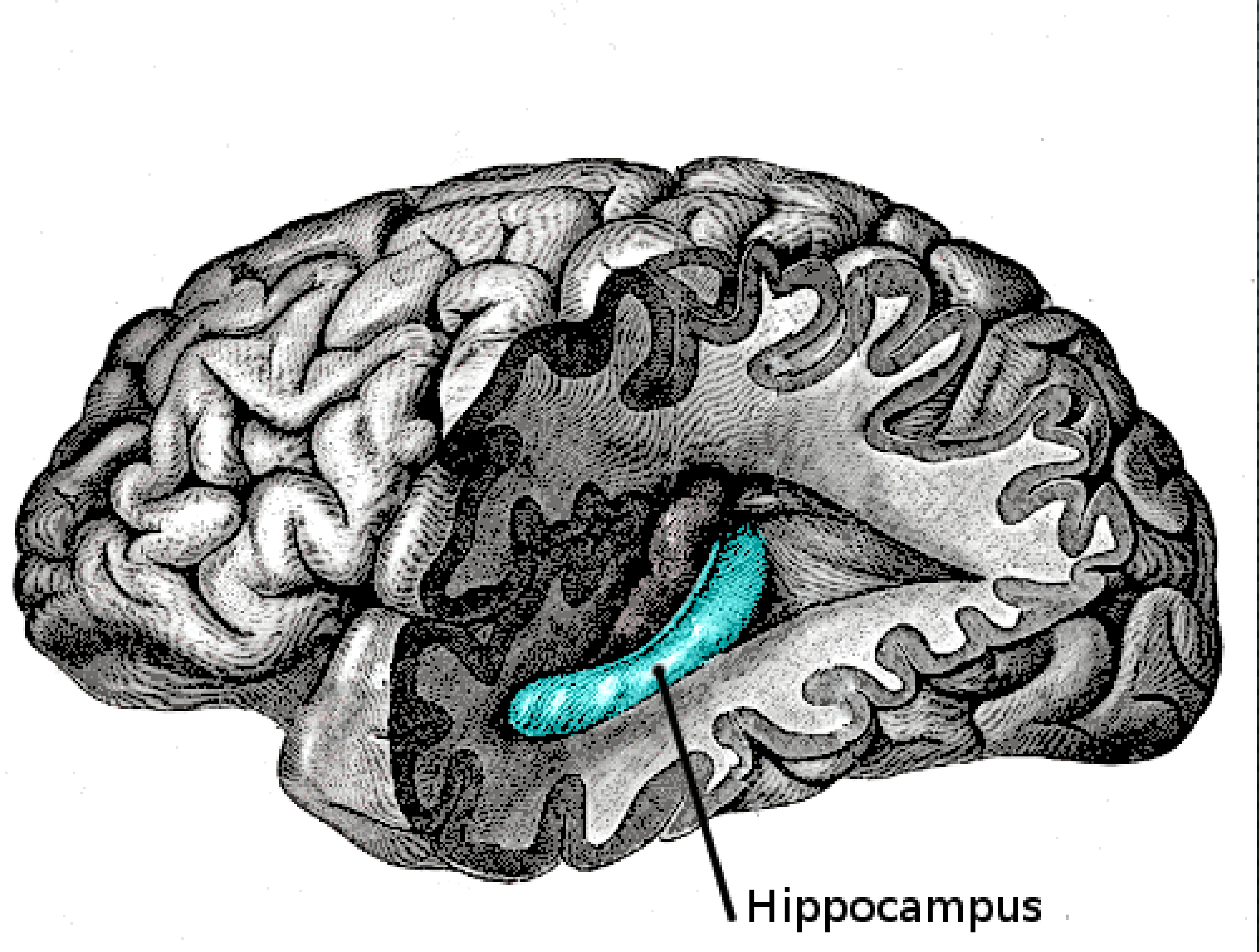
Structural plasticity in the hippocampus



Functional (synaptic) plasticity

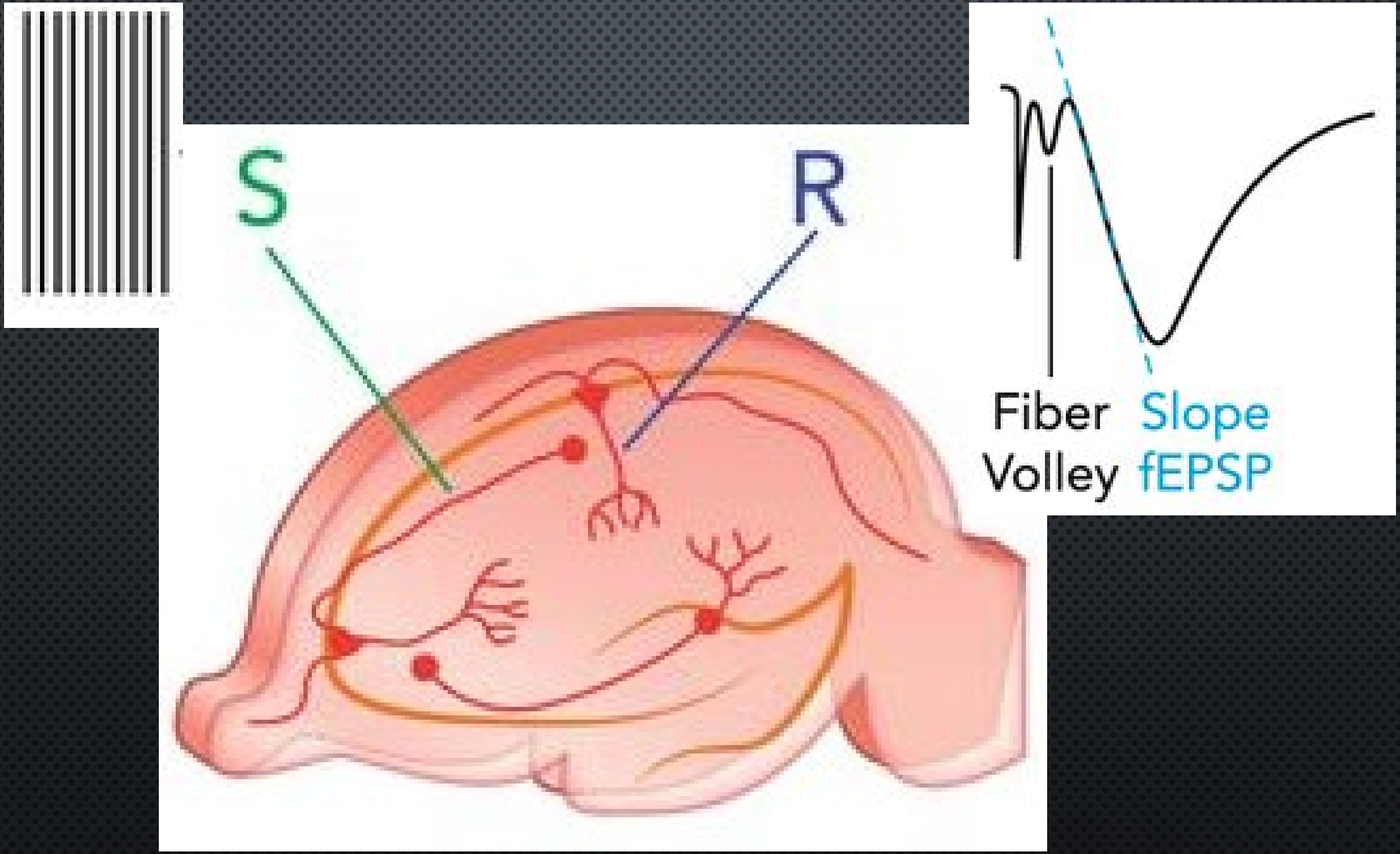


Synaptic plasticity in the hippocampus



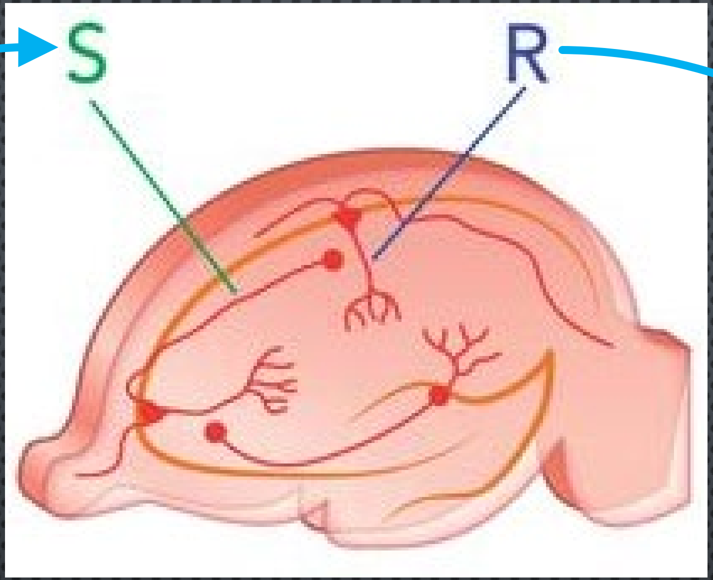
http://www.fil.ion.ucl.ac.uk/memo/brain.html

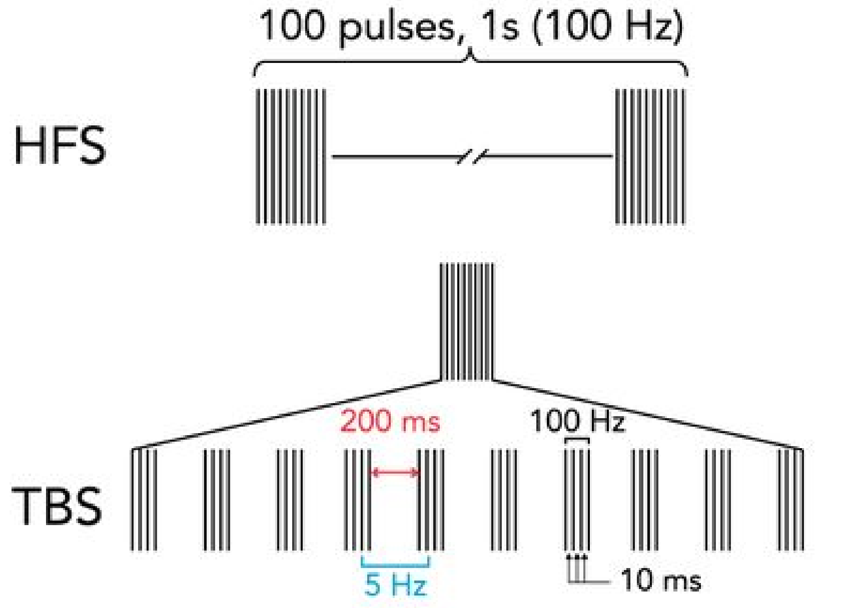
Mechanisms underlying synaptic plasticity

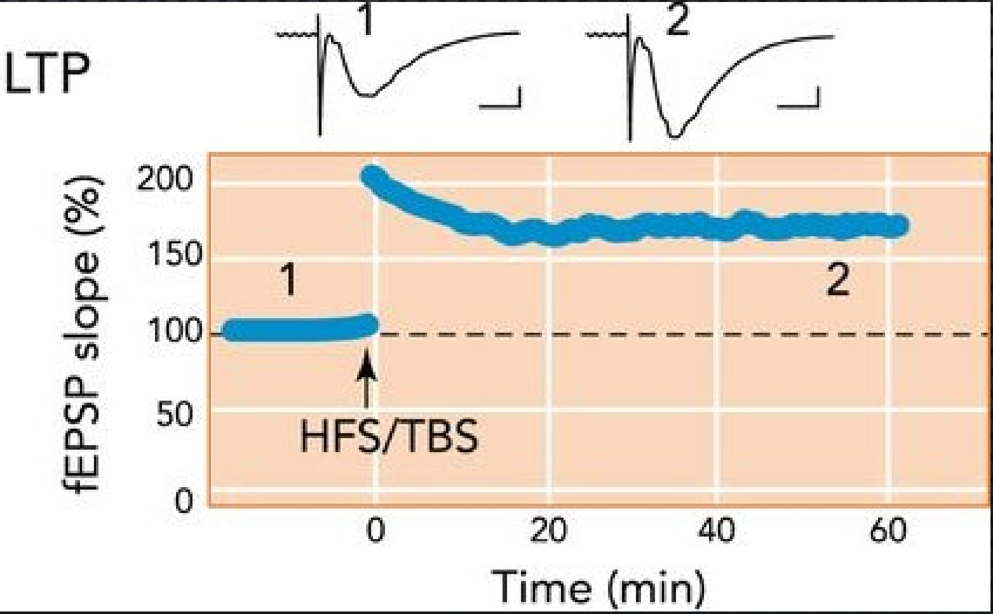


Hidalgo and Arias-Cavieres, *Physiology*, 2016

Long Term Potentiation (LTP)

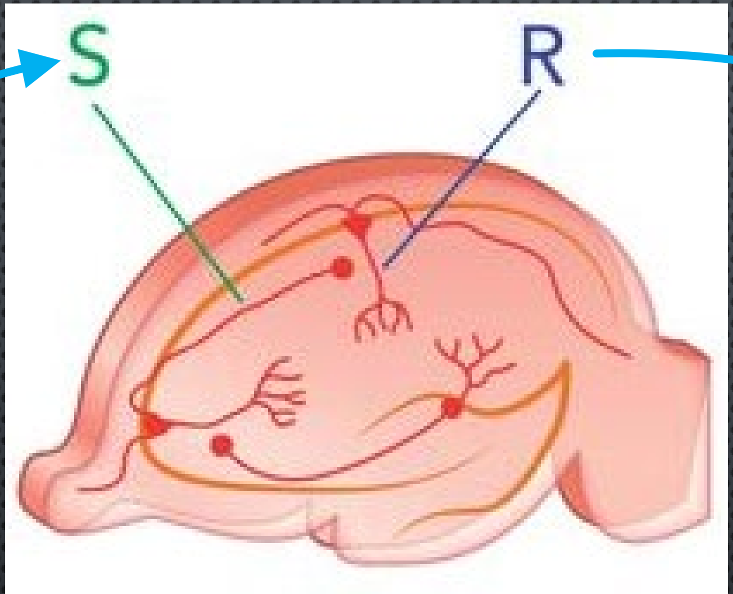


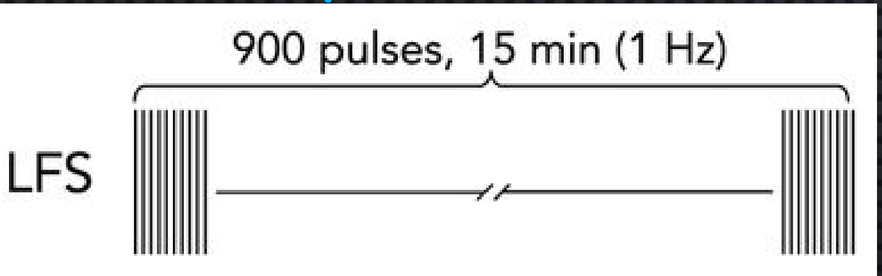


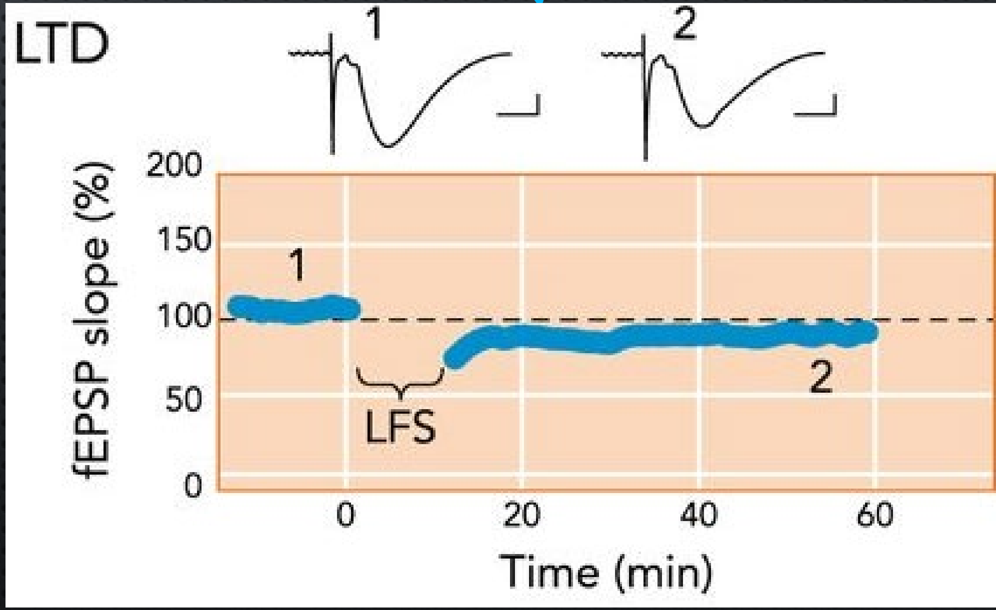


Hidalgo and Arias-Cavieres, *Physiology*, 2016

Long Term Depression (LTD)

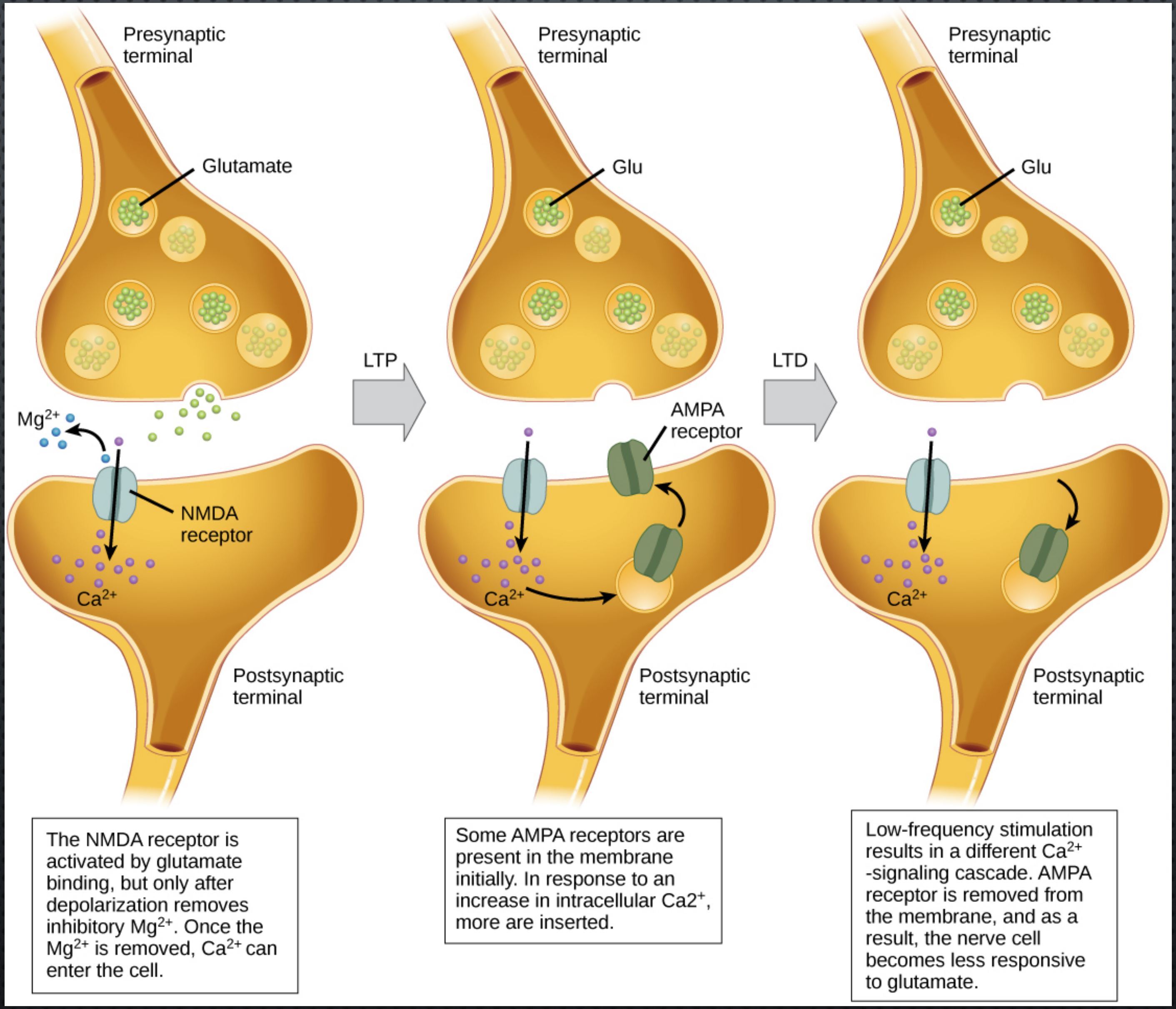






Hidalgo and Arias-Cavieres, *Physiology*, 2016

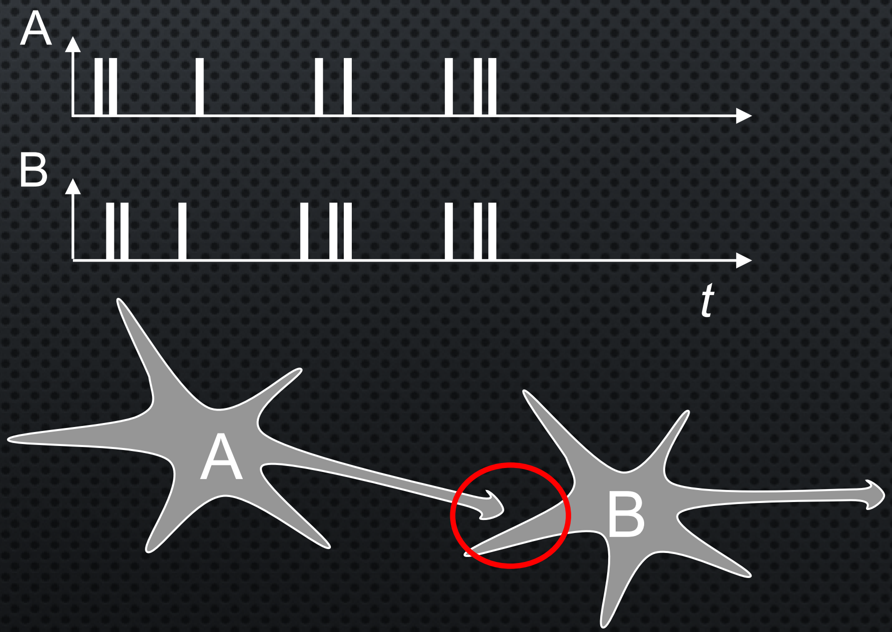
Chemical basis for LTP and LTD



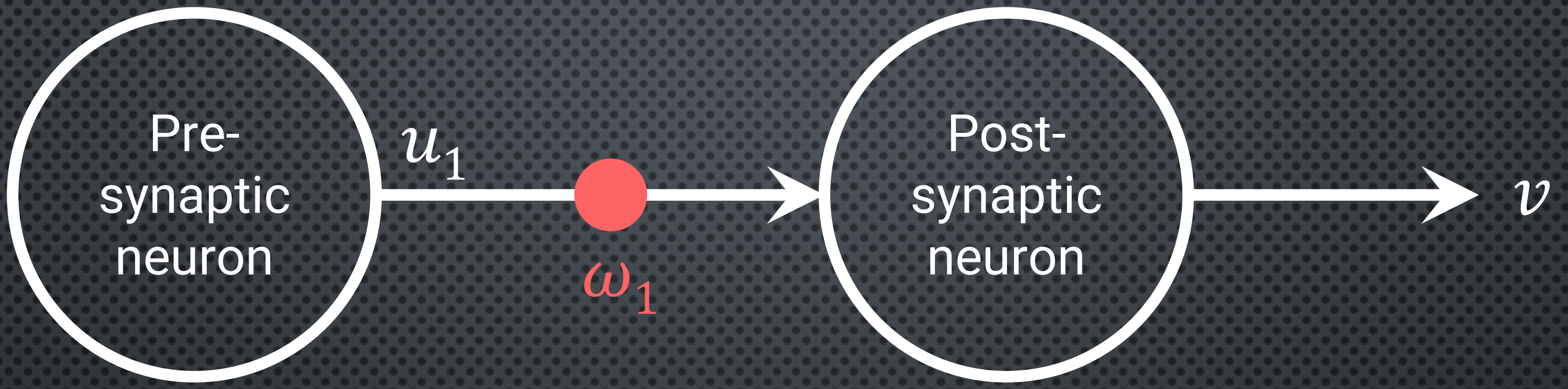
https://archive.cnx.org/contents/939dbad7-f735-4ea2-bd5f-75384ffbc06b@1/derived-copy-of-how-neurons-communicate

Hebbian learning

- Postulated in 1949 by Canadian psychologist Donald O. Hebb in his book "The organization of behaviour"
- *"When an axon of a cell A is near enough to excite cell B or repeatedly or persistently takes part in firing it, some growth or metabolic change takes place in both cells such that A's efficiency, as one of the cells firing B, is increased."*
- The functional basis for this change is correlation between presynaptic and postsynaptic activity – "neurons that fire together, wire together"
- Hebbian learning is temporal correlation-based, associative, unsupervised learning



Hebbian learning: a simple model



ω_1 always grows → **UNSTABLE !**

$$\frac{d\omega_1}{dt} = \mu \cdot v \cdot u_1$$

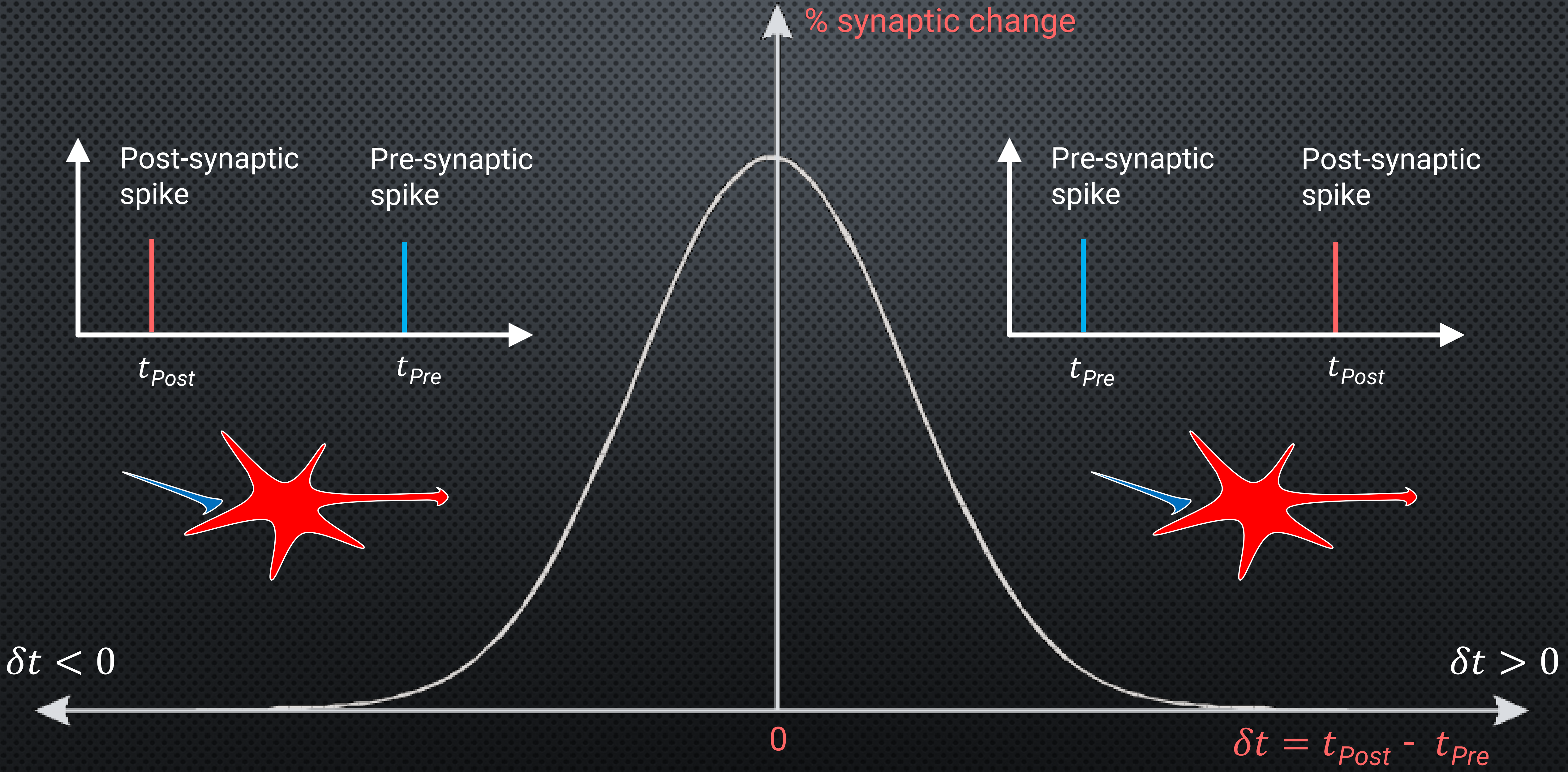
Output of pre-synaptic neuron / input to post-synaptic neuron

Output of post-synaptic neuron

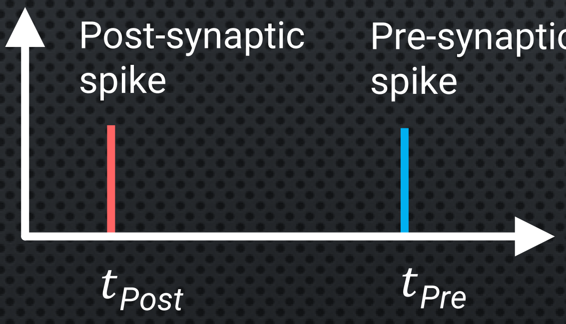
Change in synaptic weight

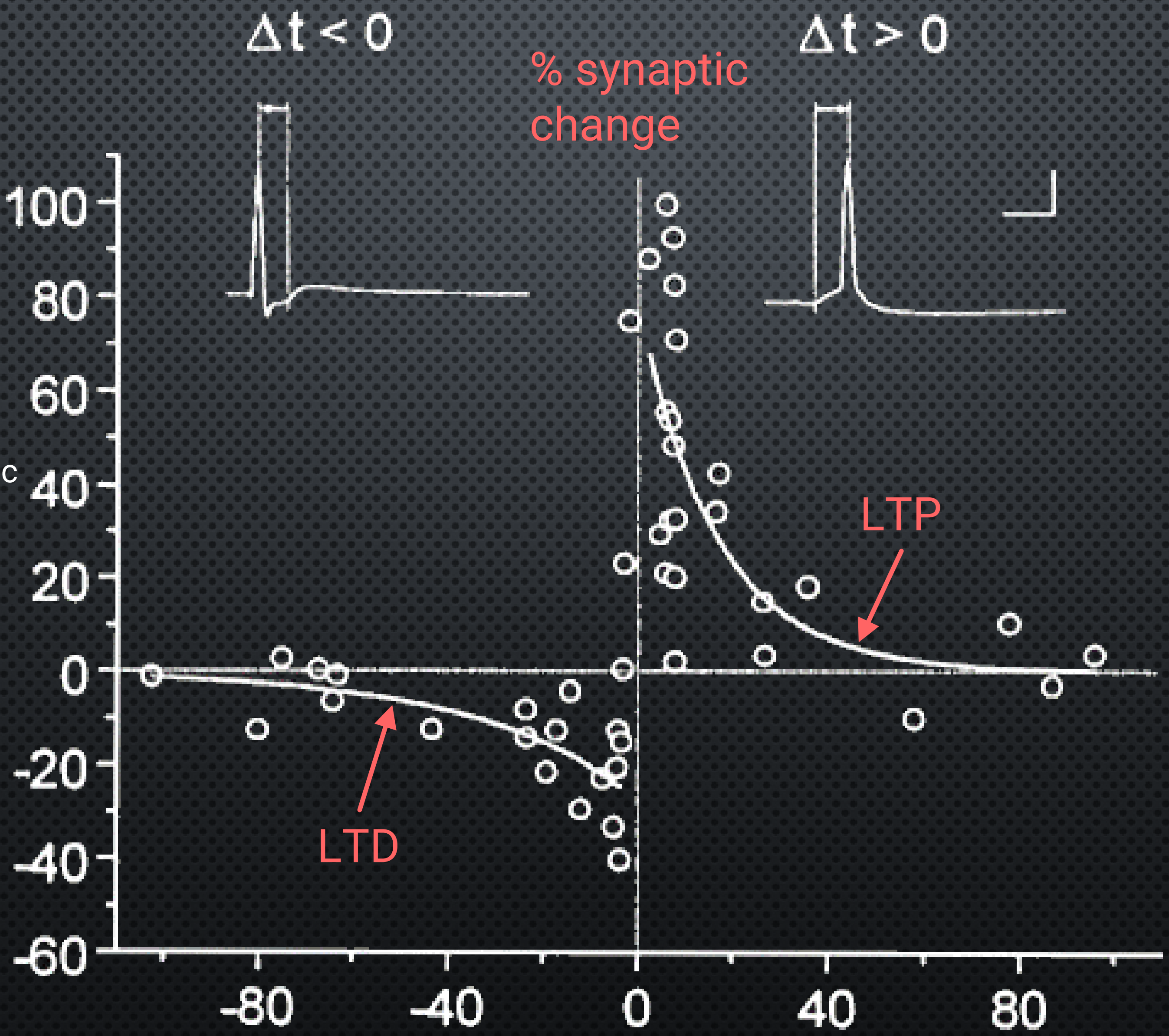
Learning rate $(\mu \ll 1)$

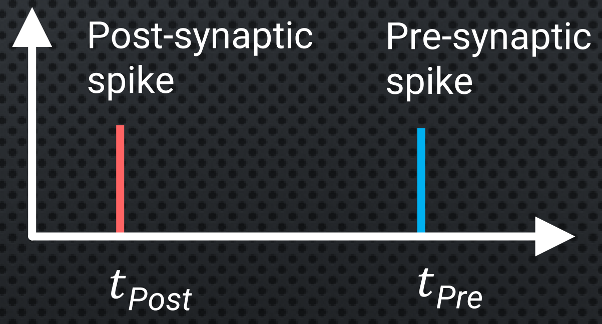
Hebbian learning: LTP



Spike-timing dependent plasticity (STDP): LTP and LTD



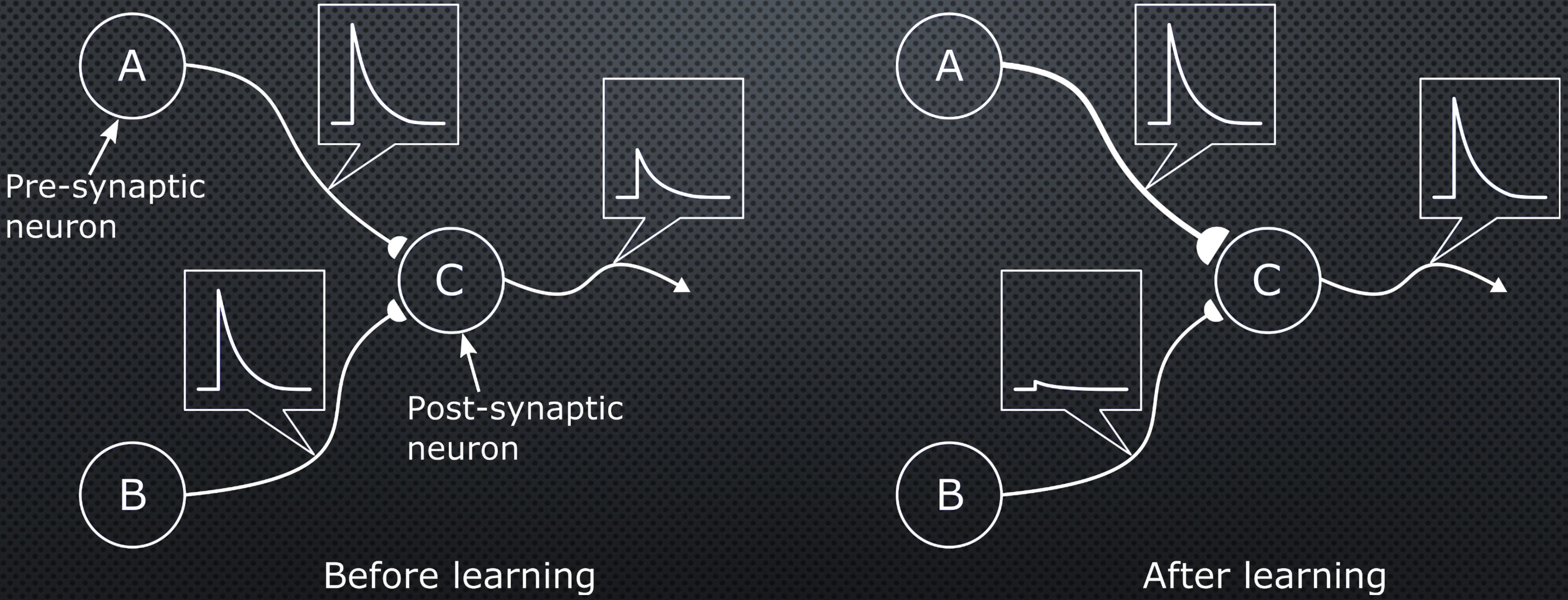




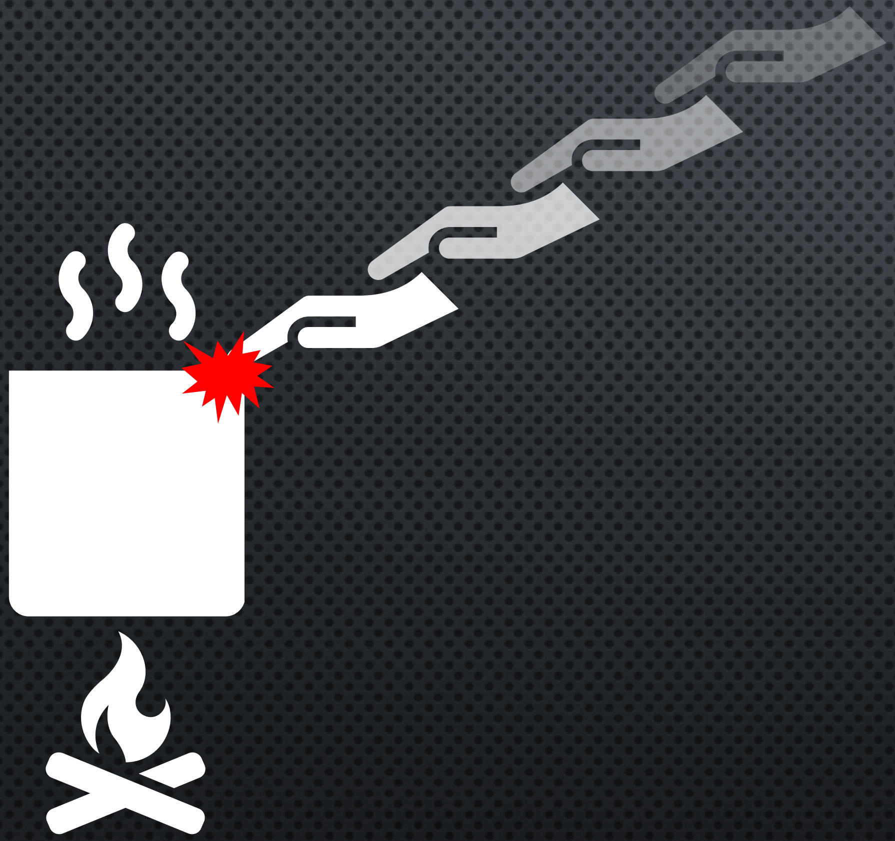
Other forms of functional plasticity

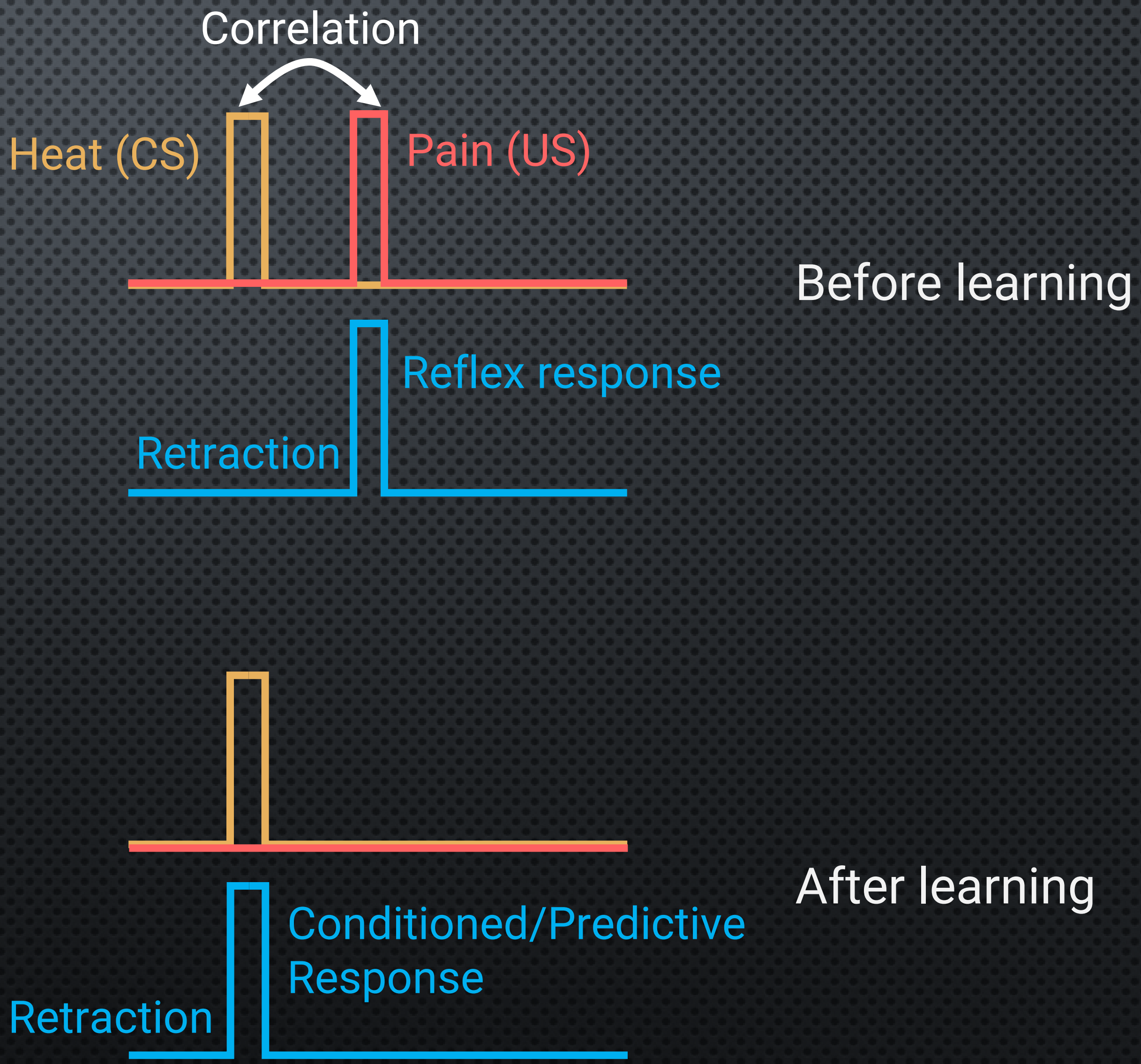
Homosynaptic plasticity	changes in synapse strength occur only at post-synaptic targets that are specifically stimulated by a pre-synaptic target
Heterosynaptic plasticity	activity of a third neuron can releases chemical neuromodulators that induce changes in synaptic strength between two other neurons
Non-synaptic plasticity	intrinsic excitability, i.e. sensitivity to synaptic input, of neurons can be altered and is manifested as changes in the firing characteristics of the neuron itself
Homeostatic plasticity	capacity of neurons to regulate their own excitability relative to network activity, a compensatory adjustment that occurs over the timescale of days

Heterosynaptic plasticity



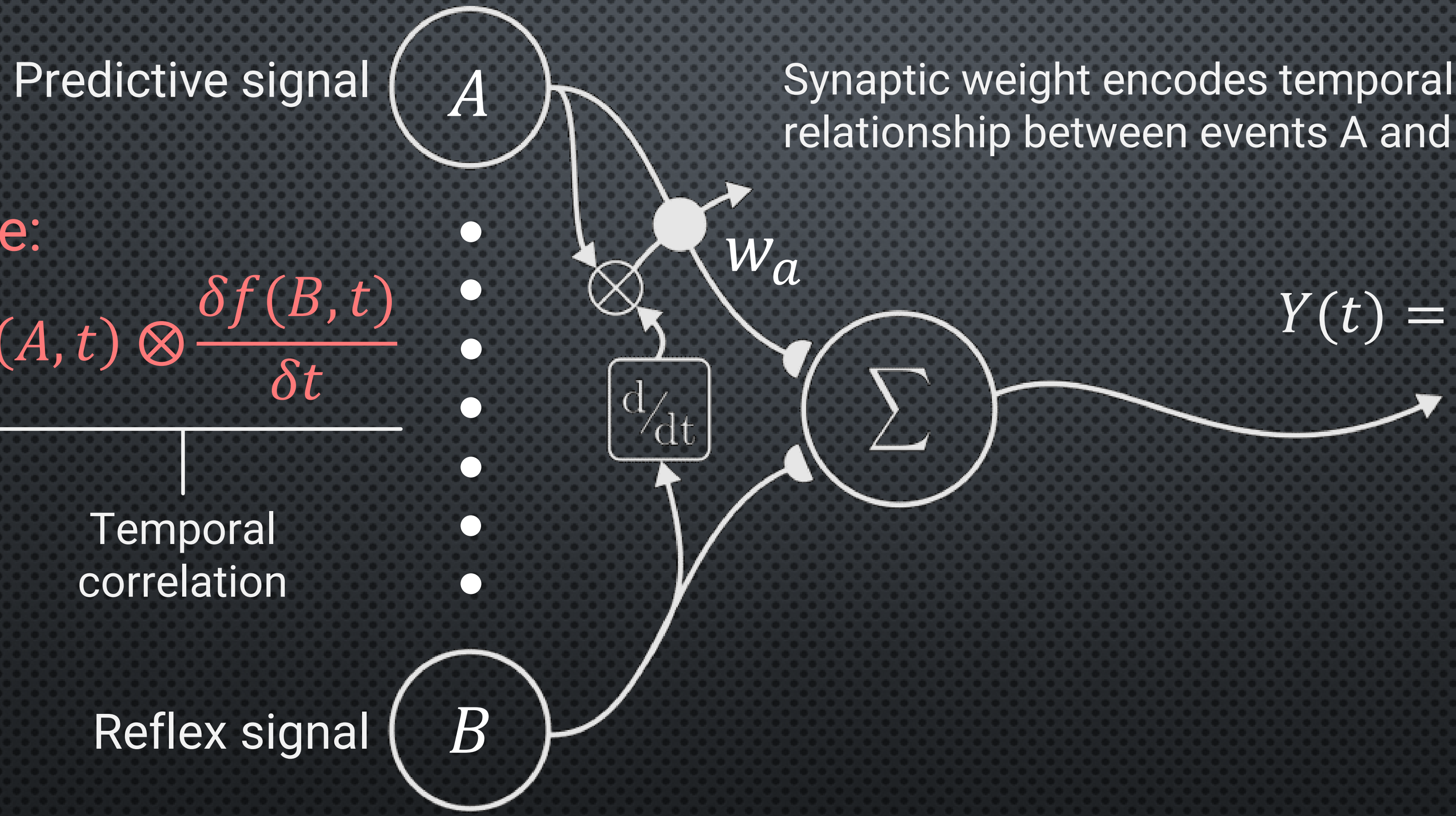
Learning quickly from temporal correlations





Input correlation learning (ICO learning)

Synaptic weight encodes temporal relationship between events A and B



$$Y(t) = w_a \cdot f(A,t) + f(B,t)$$

Learning rule:

$$\underbrace{\frac{\delta w_a}{\delta t} = \eta}_{\text{Learning rate}} \cdot \underbrace{f(A,t) \otimes \frac{\delta f(B,t)}{\delta t}}_{\text{Temporal correlation}}$$

⊗ Cross-correlation

Plastic synapse

Excitatory synaptic input

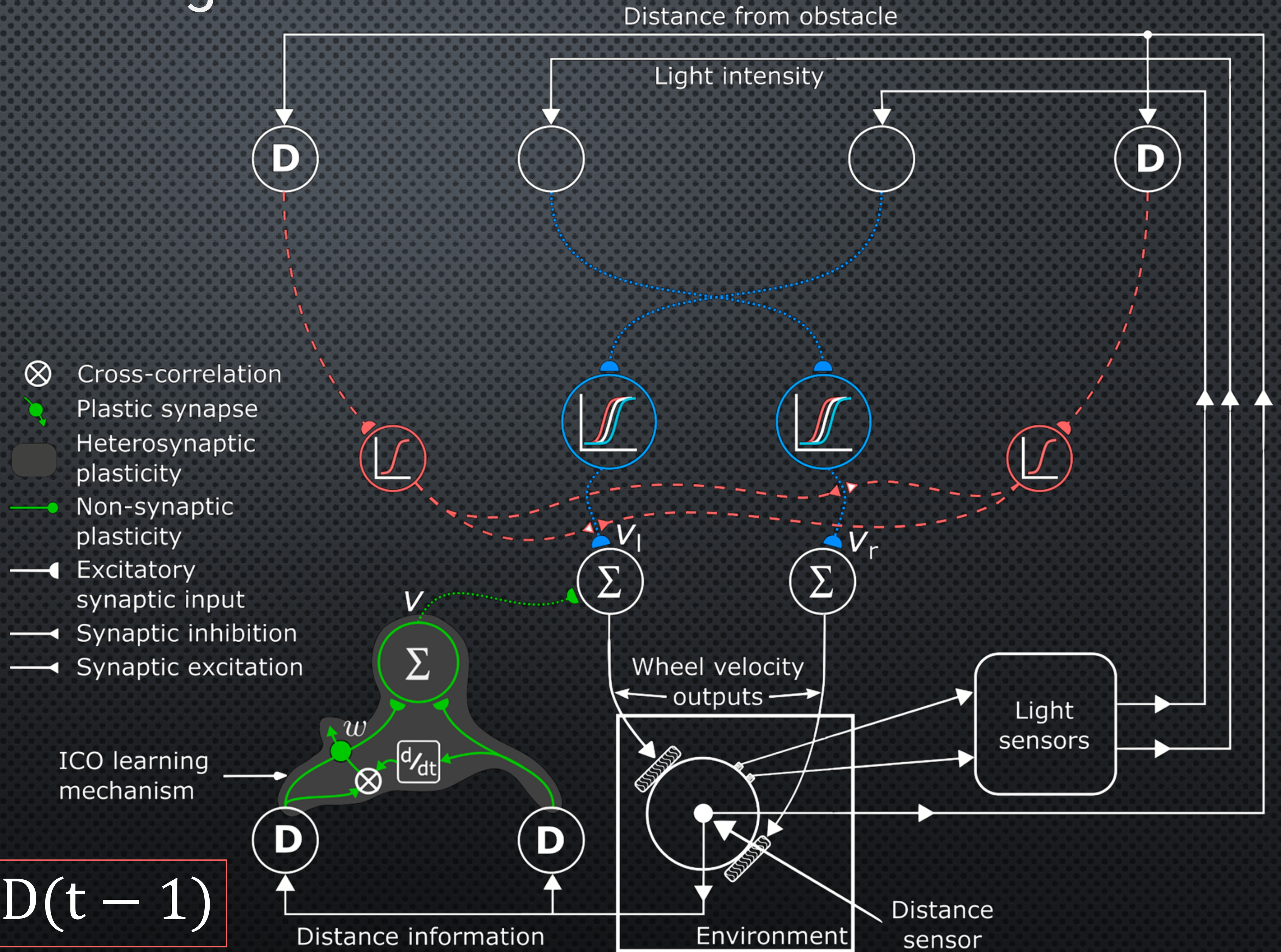
Porr et al., 2006

Artificial brain with learning

Learning rule:

$$\frac{dw}{dt} = \mu \cdot \mathrm{D} \cdot \frac{Dt}{dt}$$

$$\boxed{v = \omega \cdot \mathrm{D(t)} + \mathrm{D(t-1)}}$$



Matlab exercise: obstacle avoidance learning

- Download “Assignment 3.pdf” and “obstacle_avoidance_ learning.m”

- Follow instructions in PDF file