Synaptic Plasticity : Spike-timing dependent plasticity (STDP)

Oct 14th, 2019

Michael Graupner

michael.graupner@parisdescartes.fr

CNRS UMR 8003 - Université Paris Descartes

slides : http://www.biomedicale.univ-paris5.fr/~mgraupe/

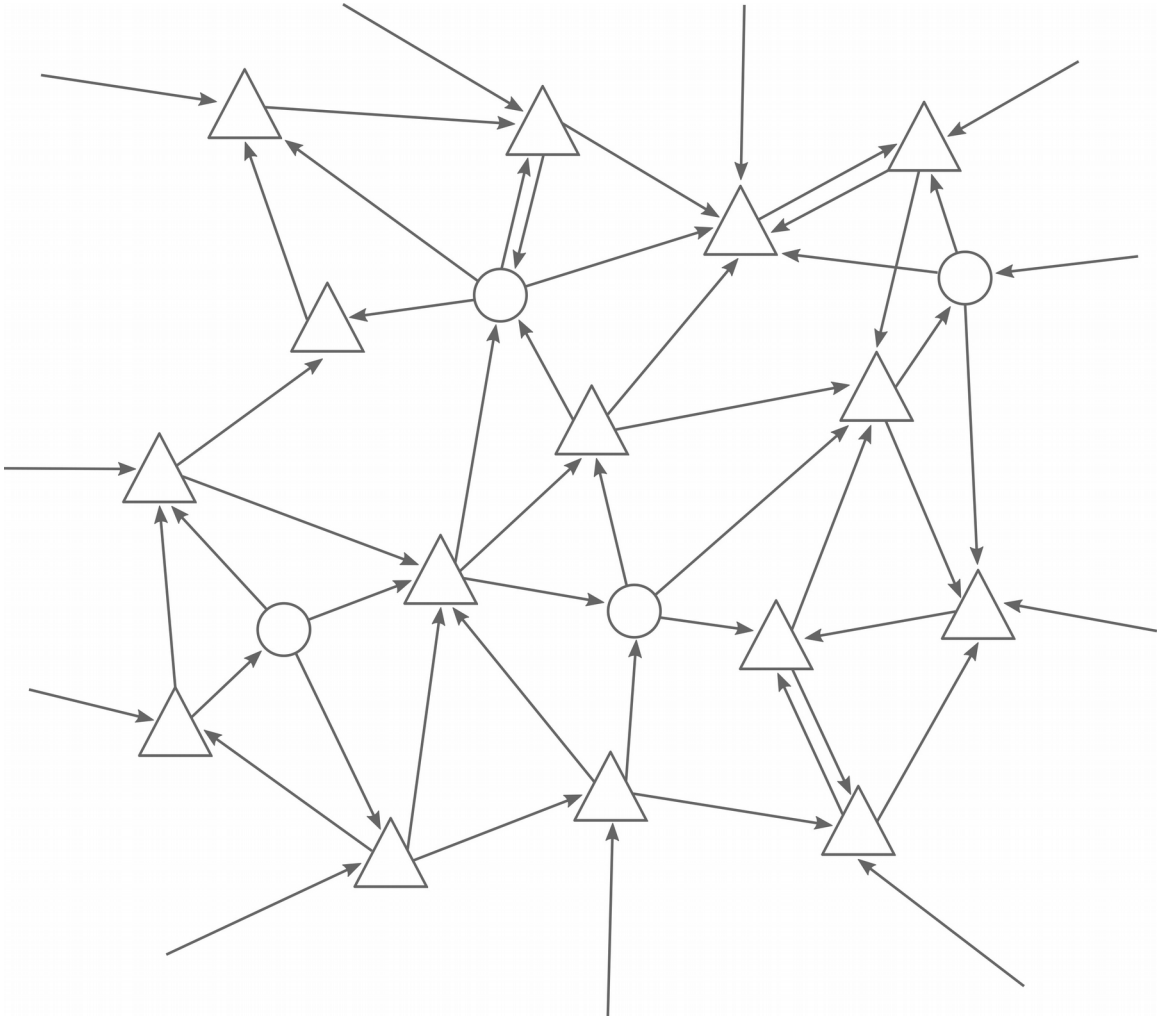
UNIVERSITÉ PARIS DESCARTES

At which university am I working ?

At which university am I working ?

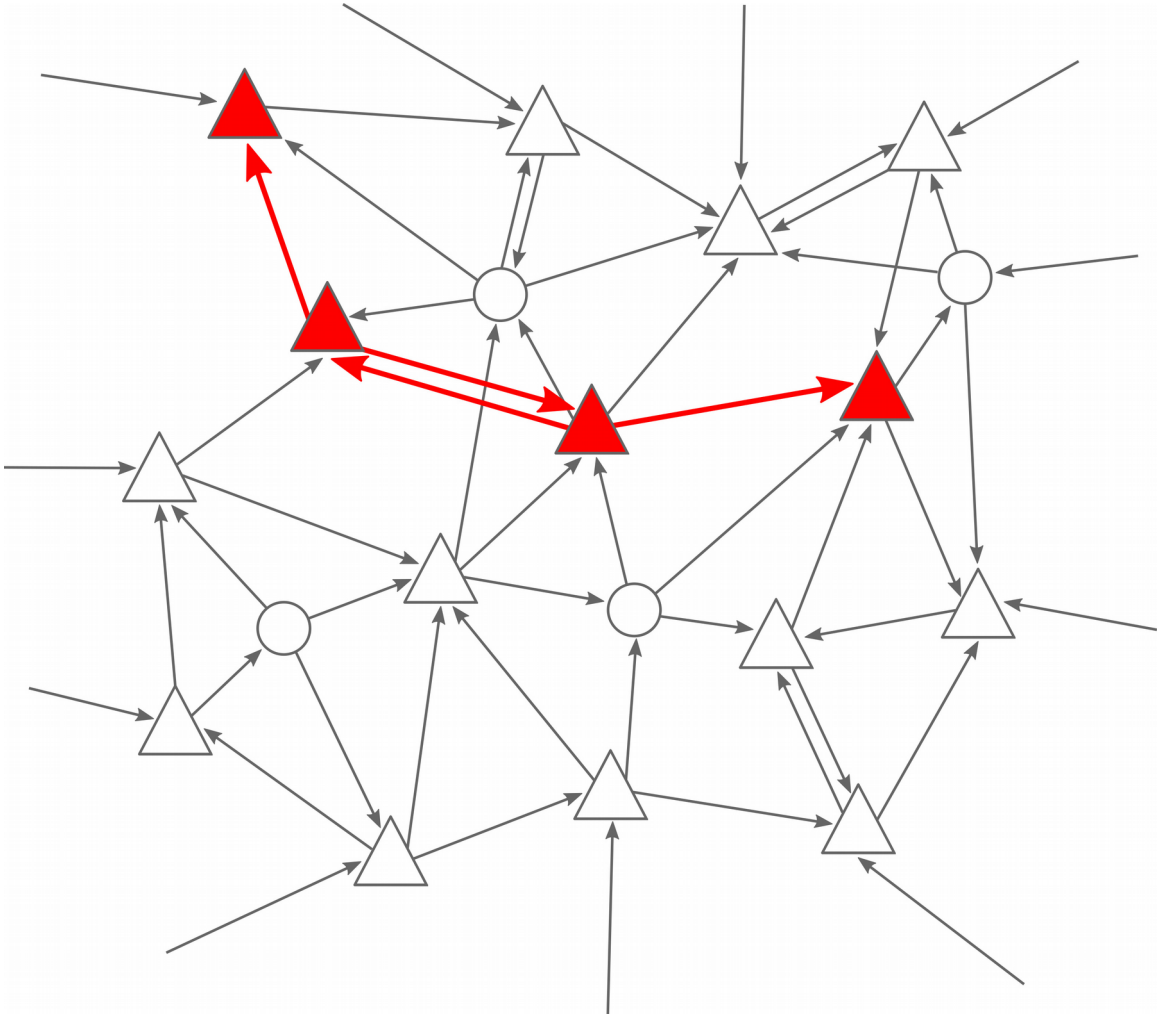
→ What happens in your brain when you learn ?

Learning on the neuronal network level

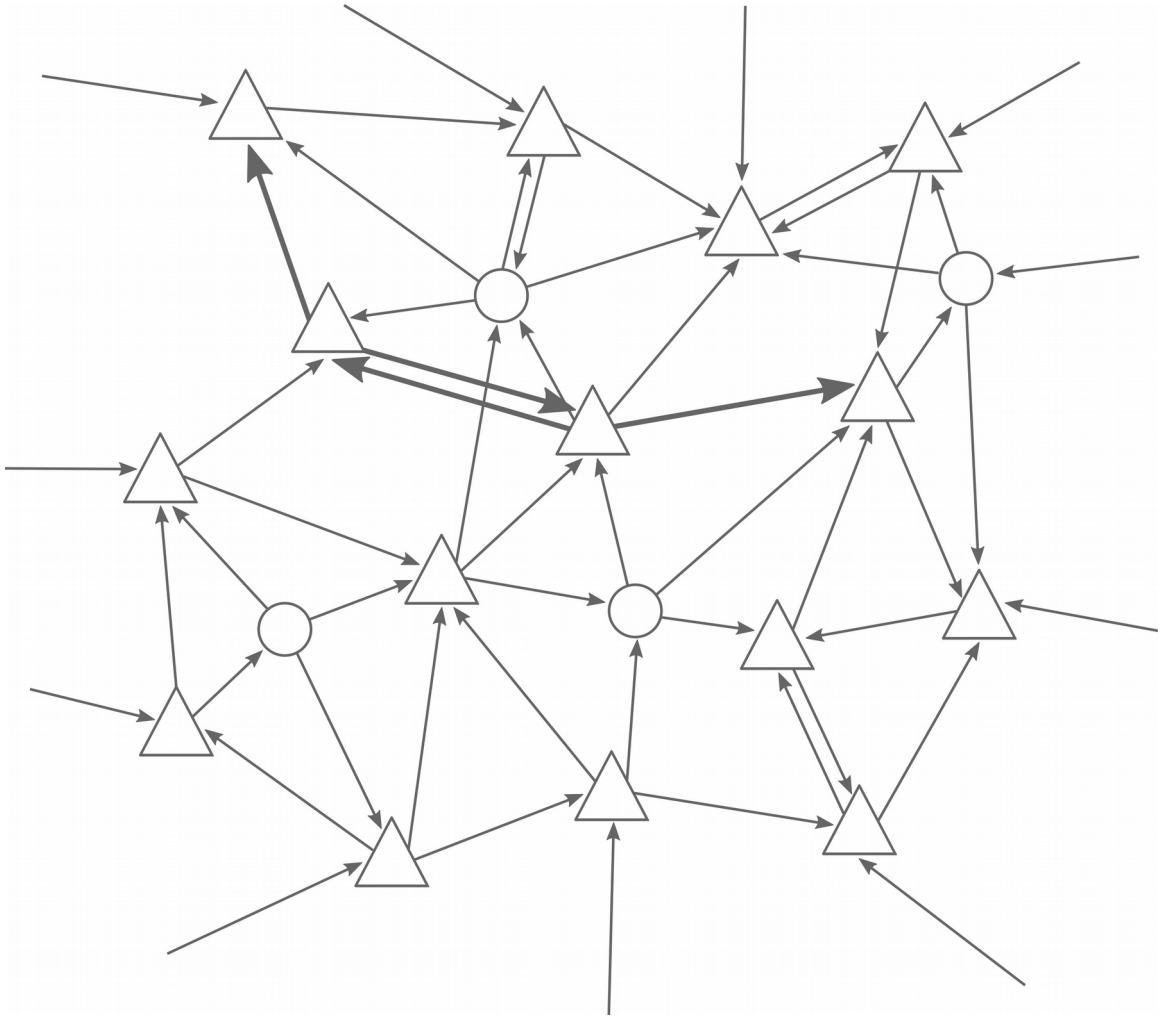


Learning on the neuronal network level

Stimulus / Experience



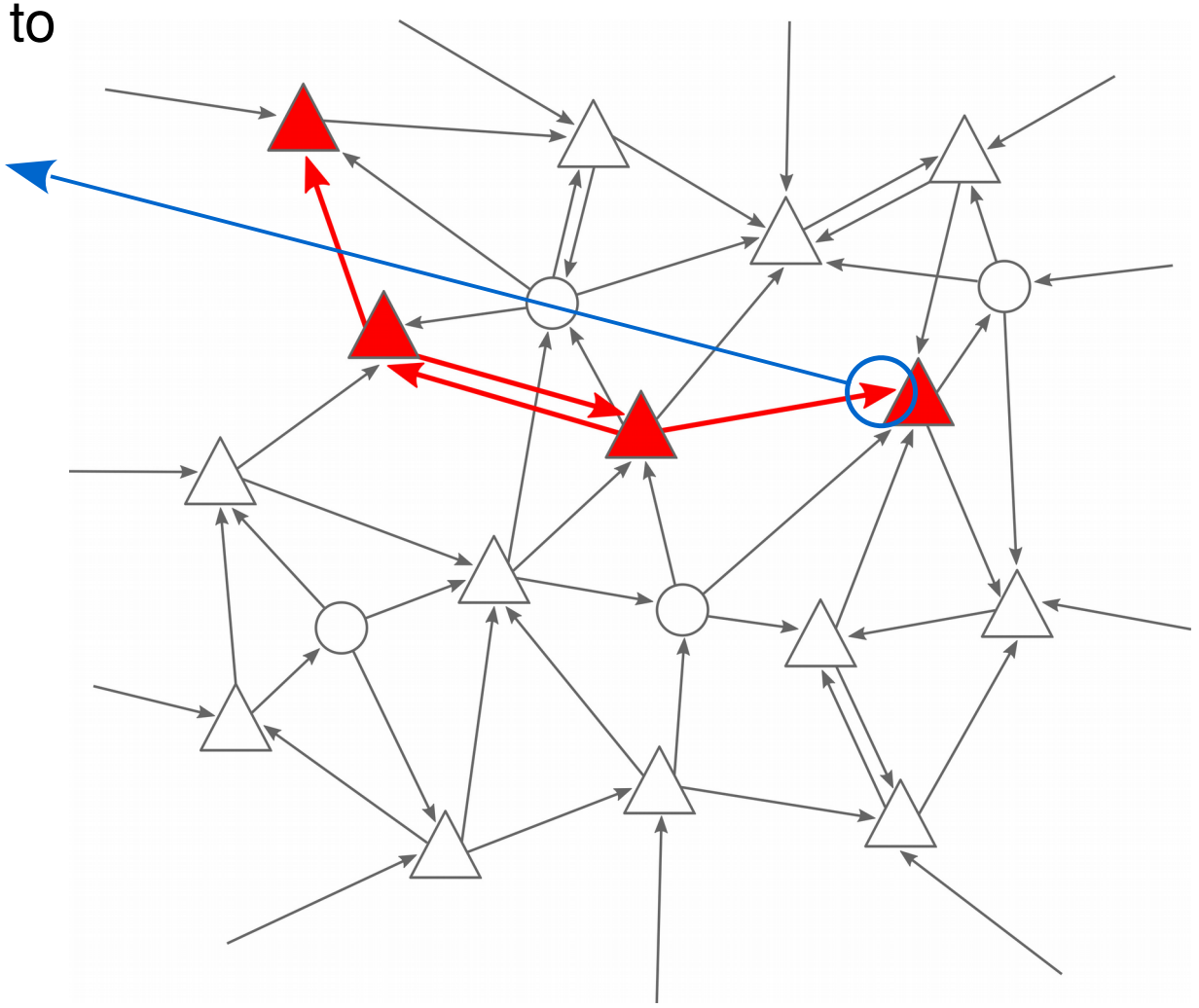
Learning on the neuronal network level



Focus of today's lecture

Which activity pattern leads to a change in the connection between the neurons ?

Which role does the timing of pre- and postsynaptic action potentials play ?

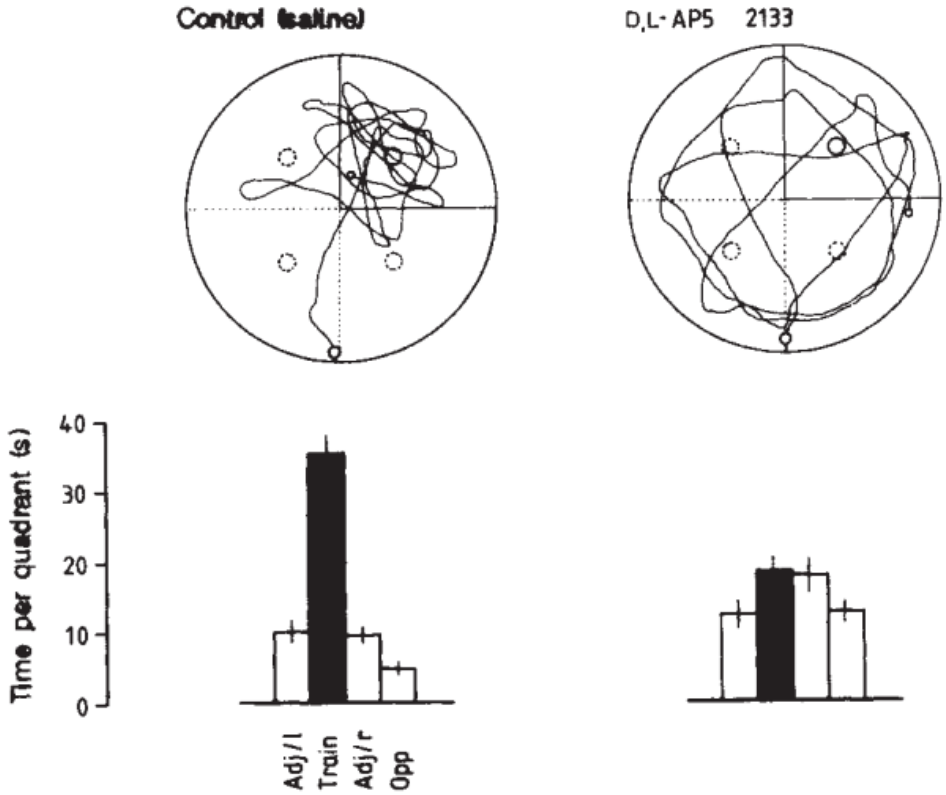


Experimental evidence : synaptic plasticity <-> memory

Morris water maze

[Morris *et al.*, 1986]

Relation between LTP and learning/memory



- NMDA receptor required to learn platform location [Morris *et al.*, 1986]
- NMDA receptor required to form spatial memories (place fields)

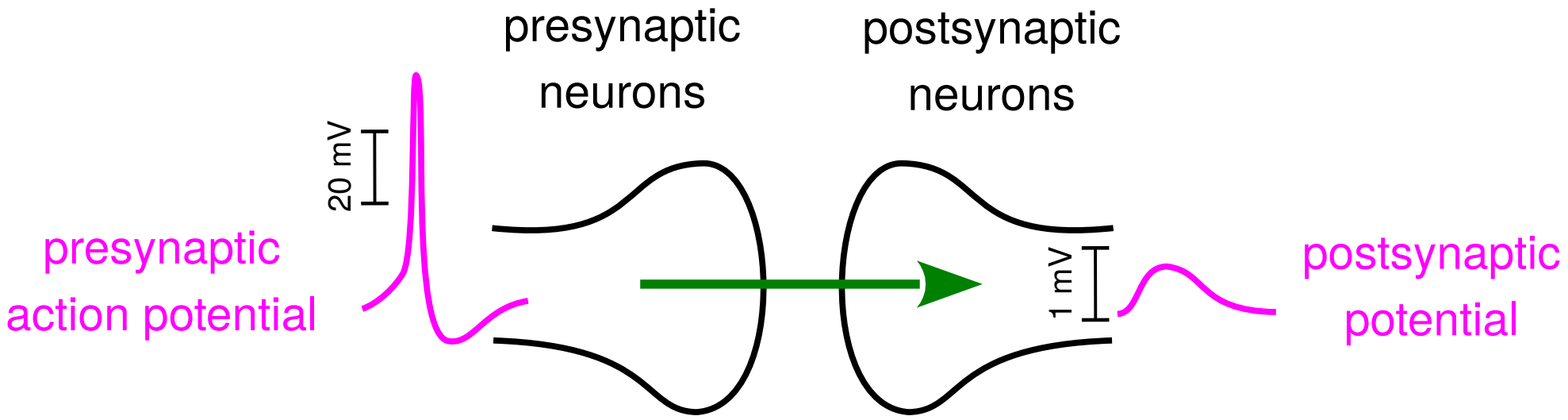
[McHugh *et al.* 1996]

Outline : STDP ... spike-timing dependent plasiticity

1. STDP : introduction and history
2. Phenomenology of STDP
3. Induction mechanisms
4. Biophysical models of STDP
5. STDP *in vivo*

Outline

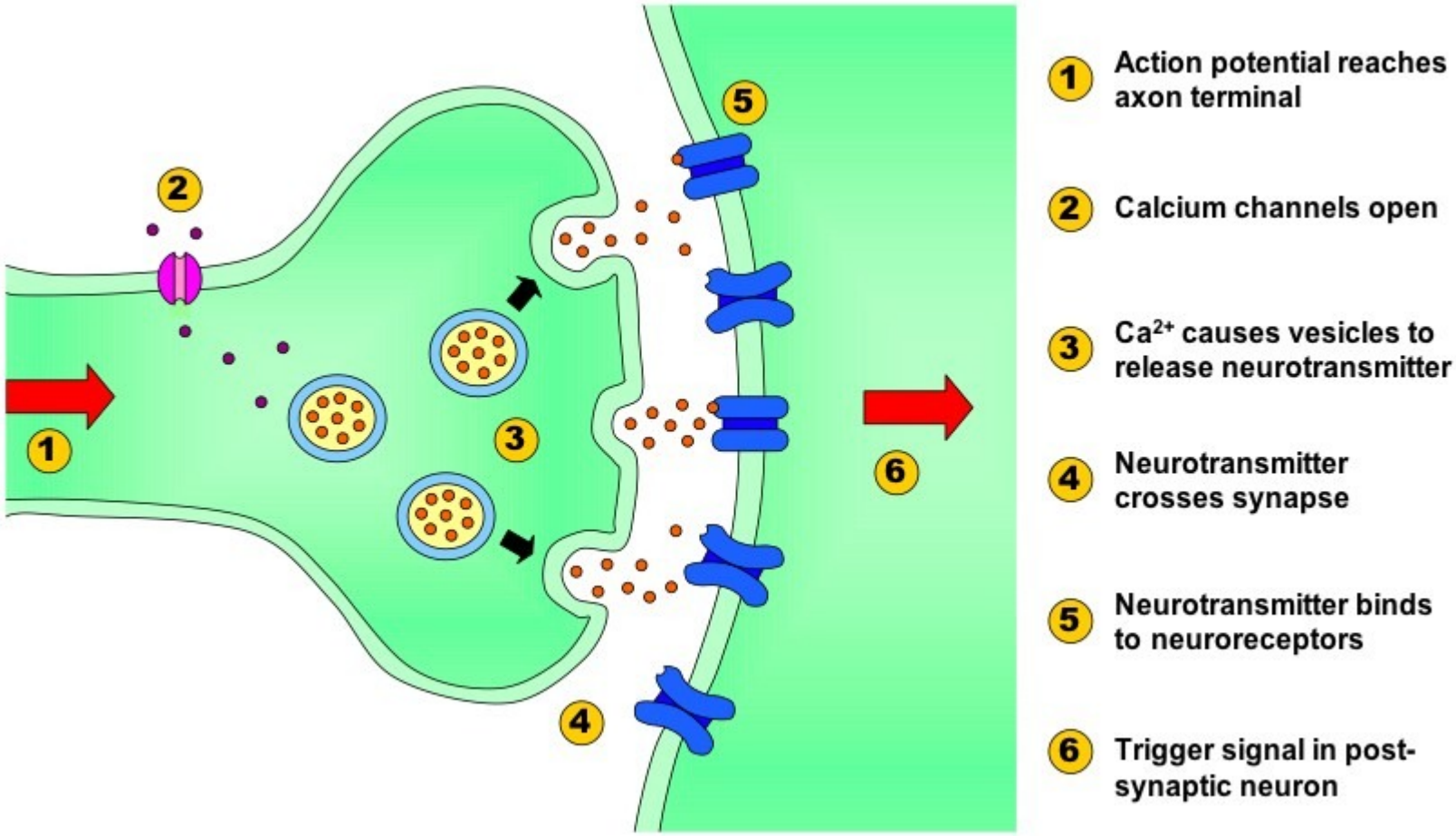
Chemical synapse : transmits electrical signals



electrical signal → chemical signal → electrical signal

- directional transmission
- conversion of signals allows for flexibility/plasticity

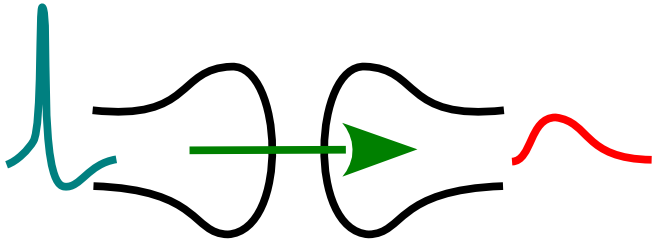
Chemical synapse : underlying biological machinery



http://outreach.mcb.harvard.edu/animations/synaptic.swf

Chemical synapse : excitatory or inhibitory

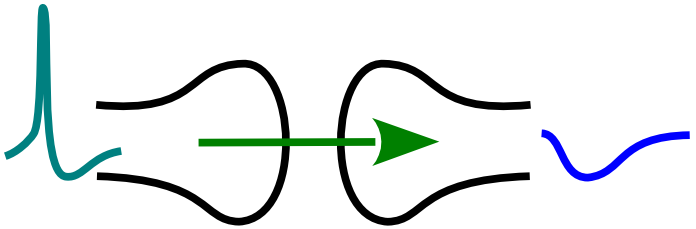
Excitatory synapse



depolarization:
excitatory postsynaptic potential (EPSP)

neurotransmitter	receptor
glutamate	AMPA, NMDA
acetylcholine	nAChR, mACHR
catecholamines	G-protein-coupled receptors
serotonin	5-HT_3, ...
histamine	G-protein-coupled receptors

Inhibitory synapse



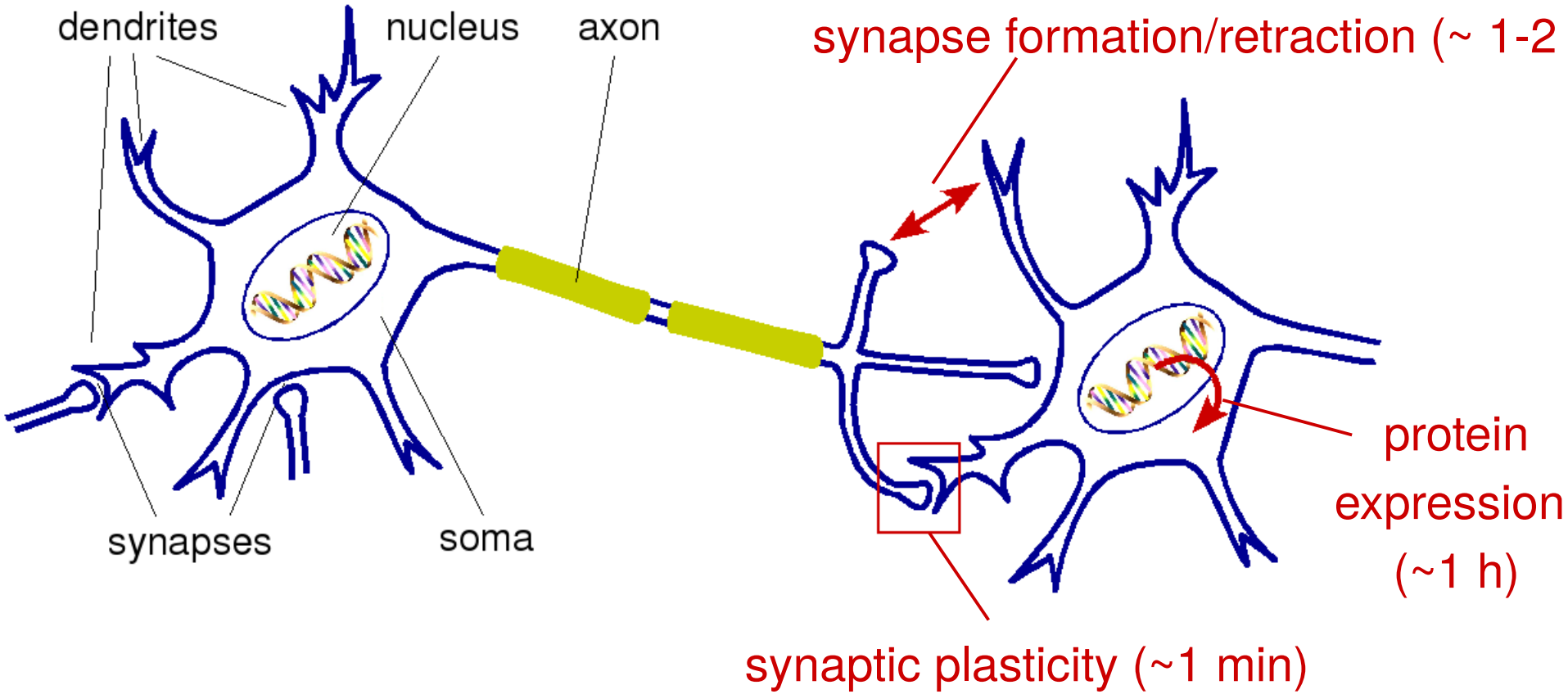
hyperpolarization:
Inhibitory postsynaptic potential (IPSP)

neurotransmitter	receptor
GABA	GABA_A, GABA_B
glycine	GlyR

Different forms of plasticity

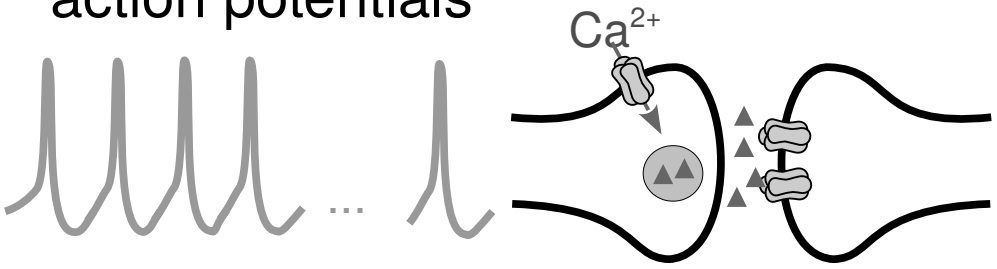
structure of neurons

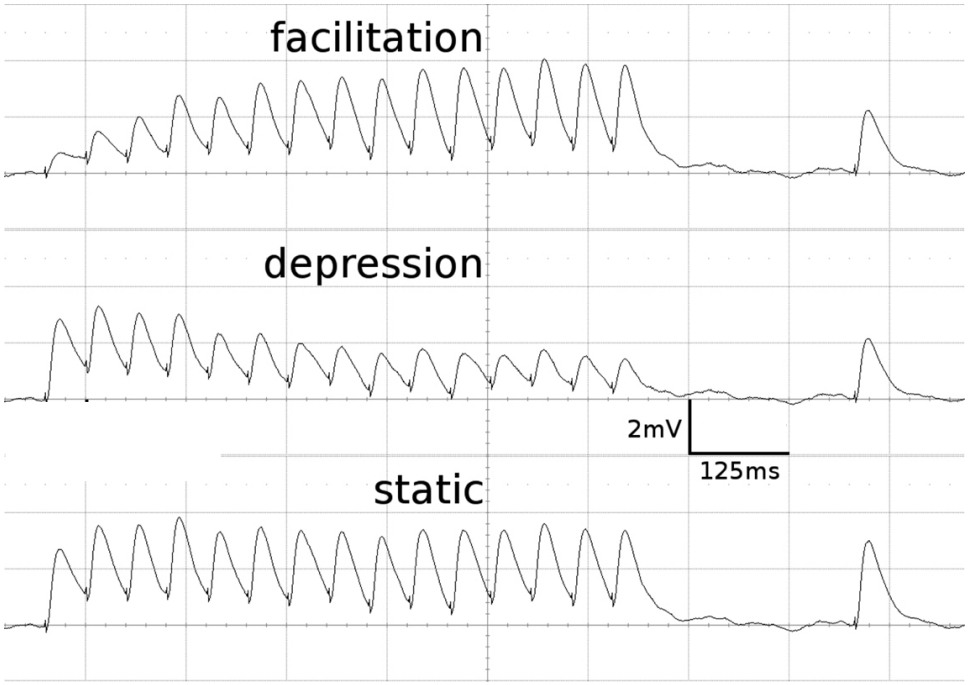
changes related to neural activity



Short-term synaptic plasticity

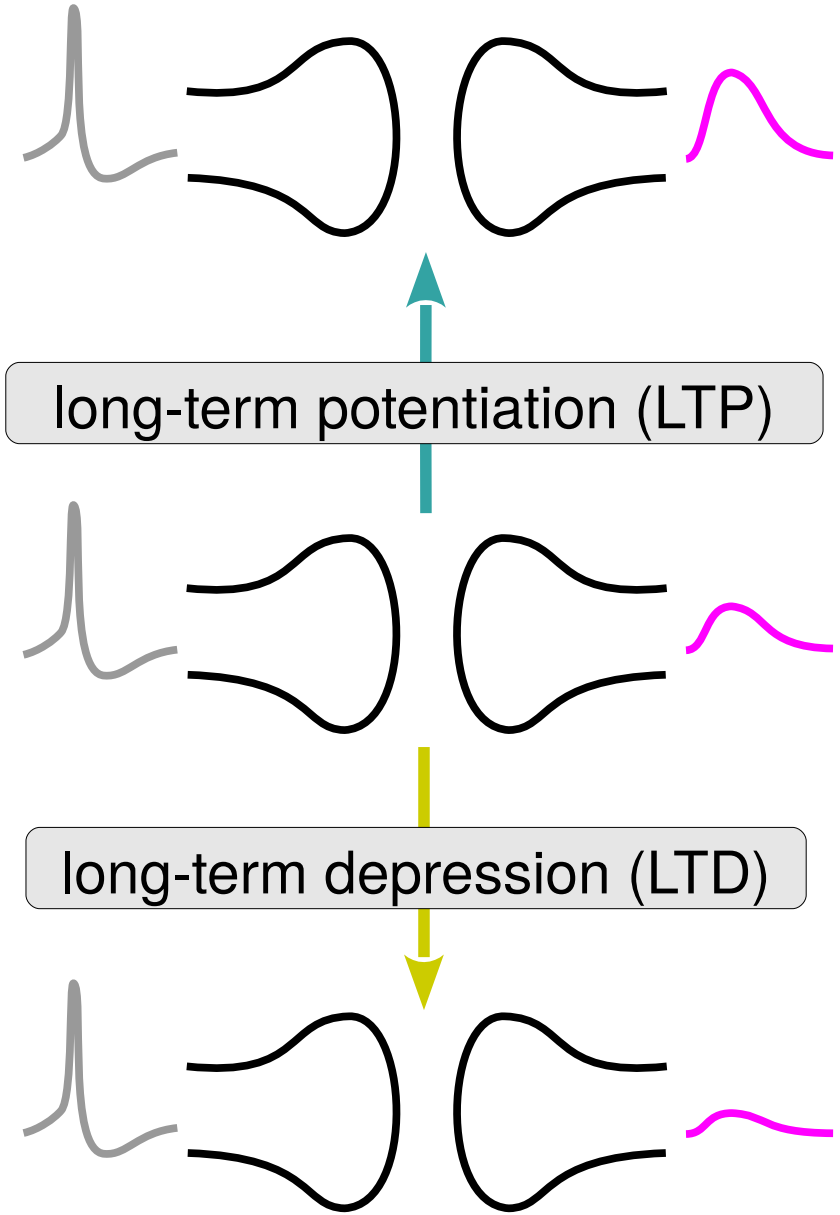
train of presynaptic action potentials





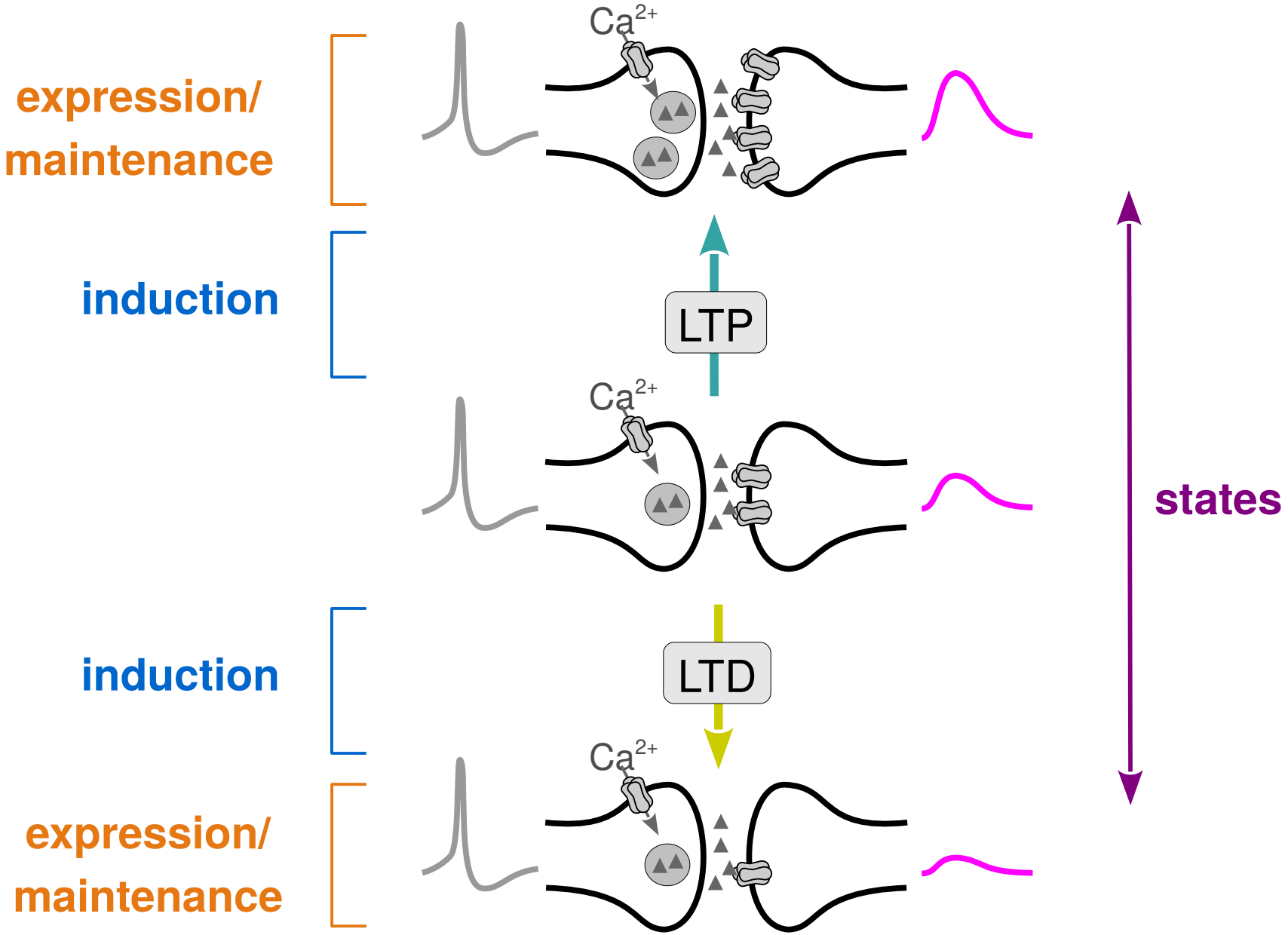
- transient change in transmission efficacy
- time scale of changes ~1 sec

Long-term synaptic plasticity

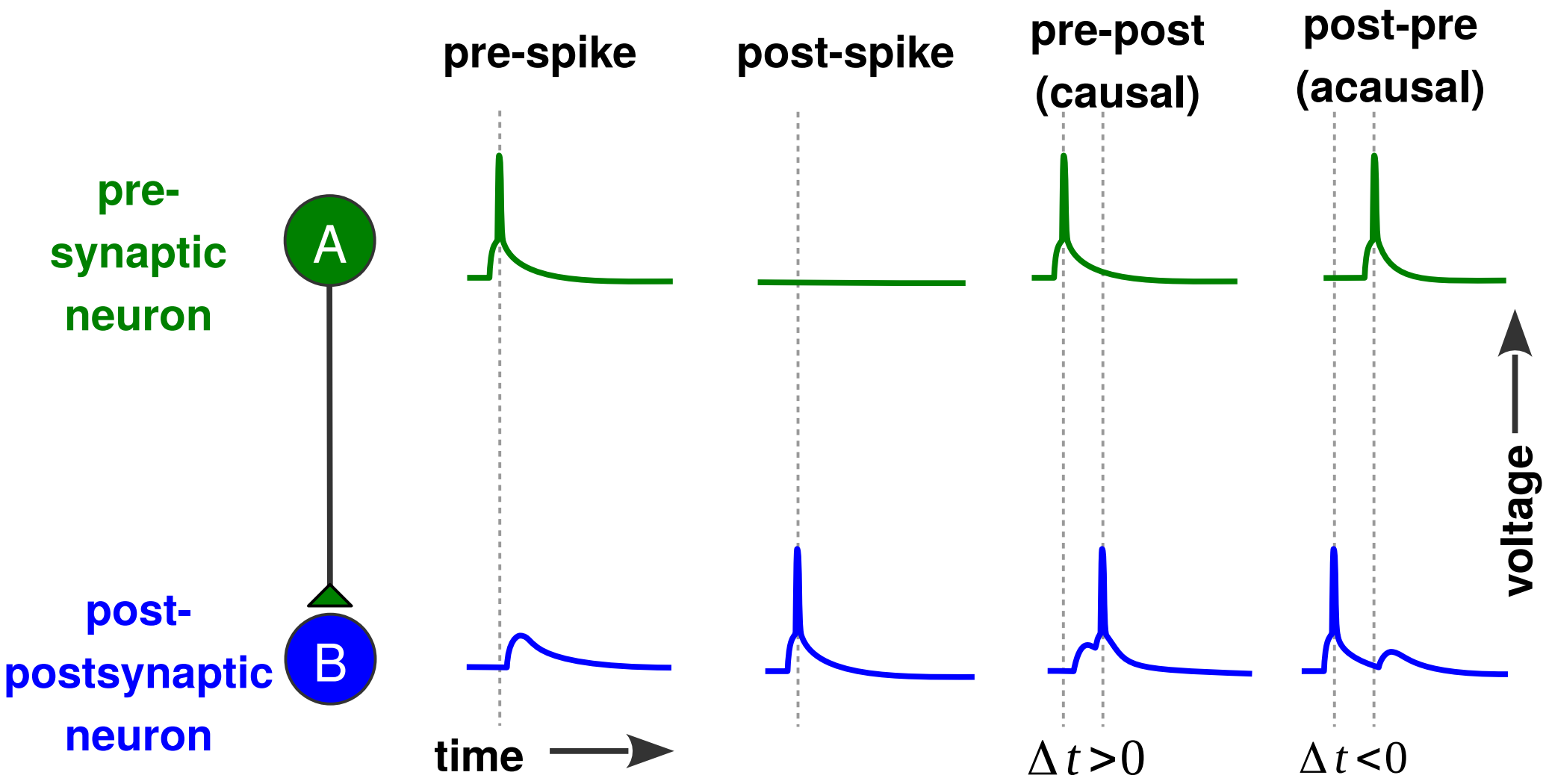


- long-lasting change (>60 min) in transmission efficacy
- time scale of induction ~ 1 min

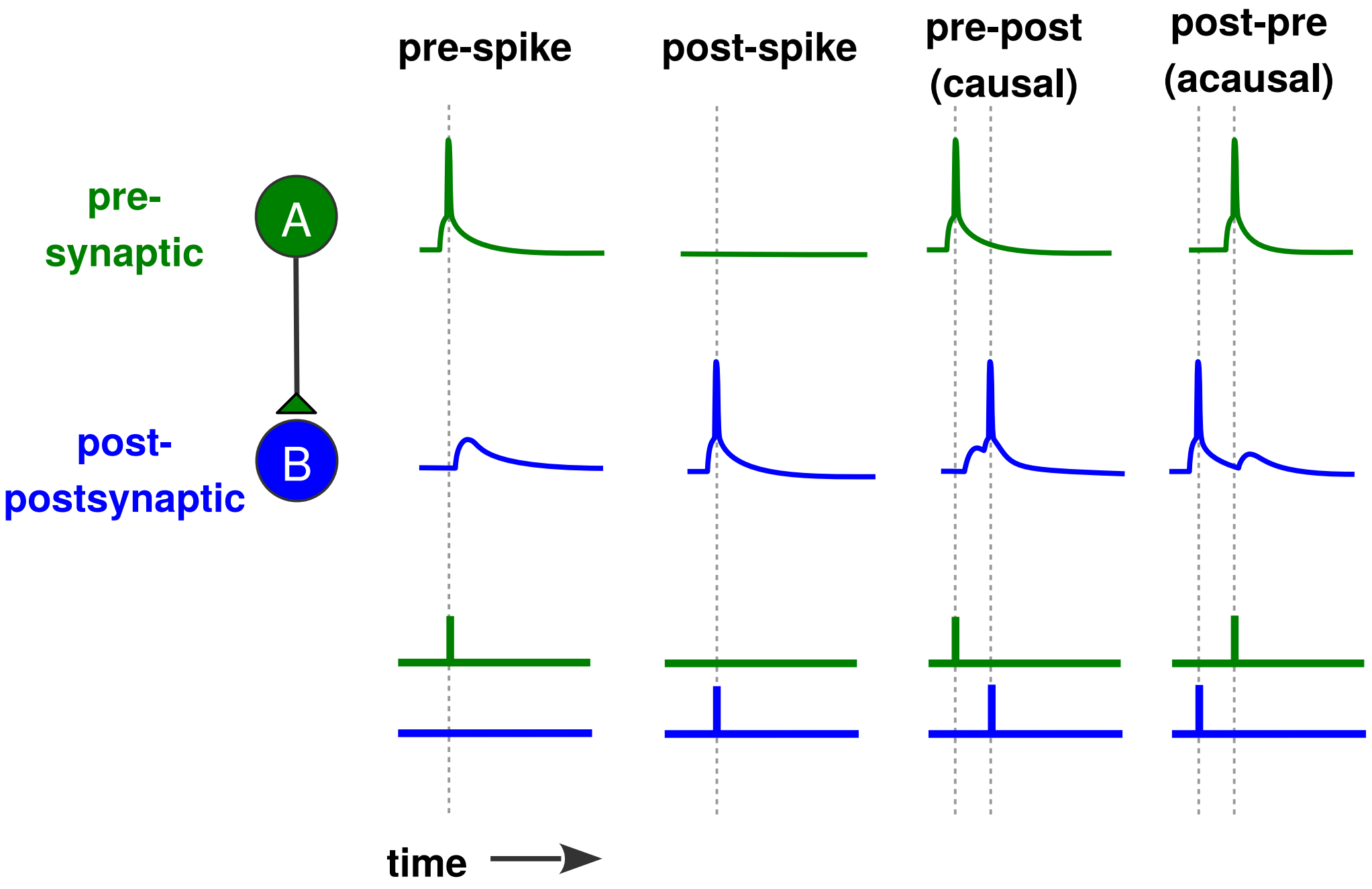
Synaptic plasticity: induction, maintenance & states



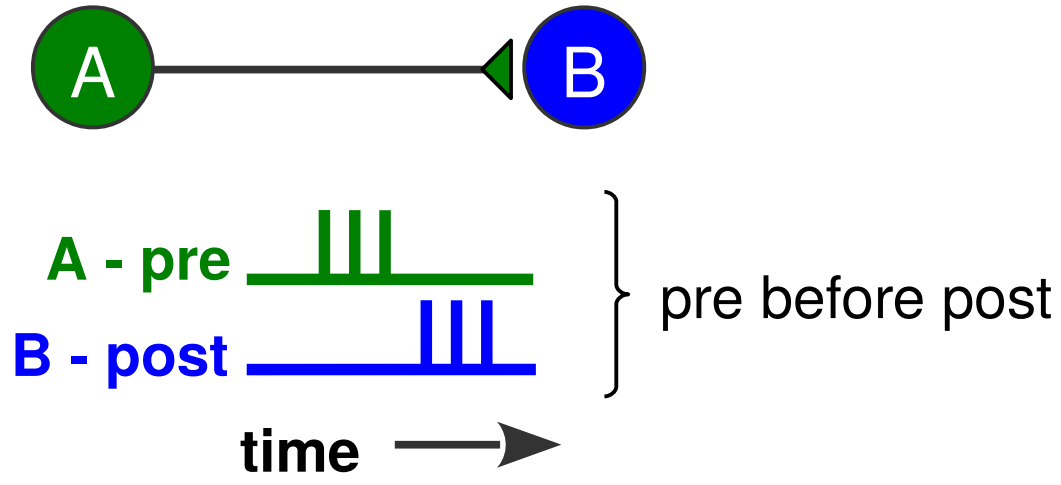
Spike timing : nomenclature



Spike timing : nomenclature



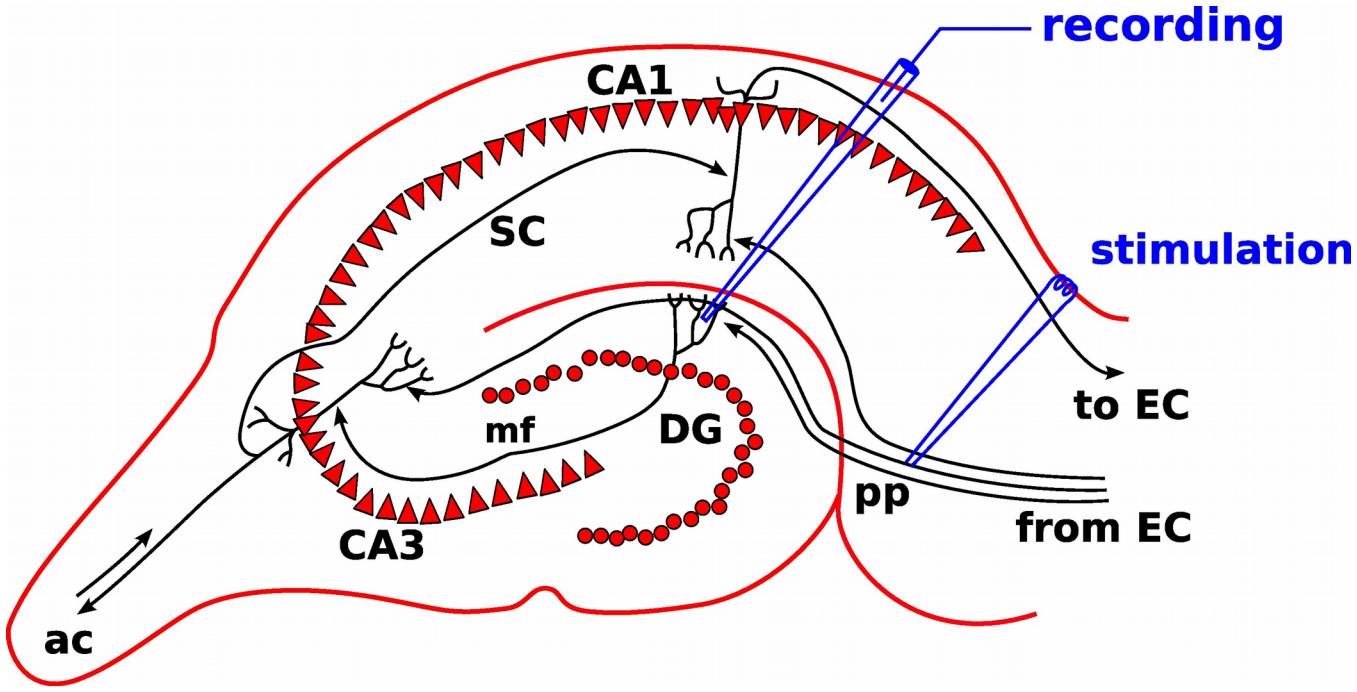
LTP induction: early conceptual work



"When an axon of cell A is near enough to excite a cell B and *repeatedly* and *persistently* takes part in firing it, some growth or metabolic changes take place in one or both cells such that A's efficiency, as one of the cells firing B, is *increased.*" [Hebb 1949; see also Konorski 1948]

Induction: first experimental work in hippocampus

hippocampus



EC	...	enthorhinal cortex
DG	...	dentate gyrus
CA3/1	...	cornu ammonis 3/1

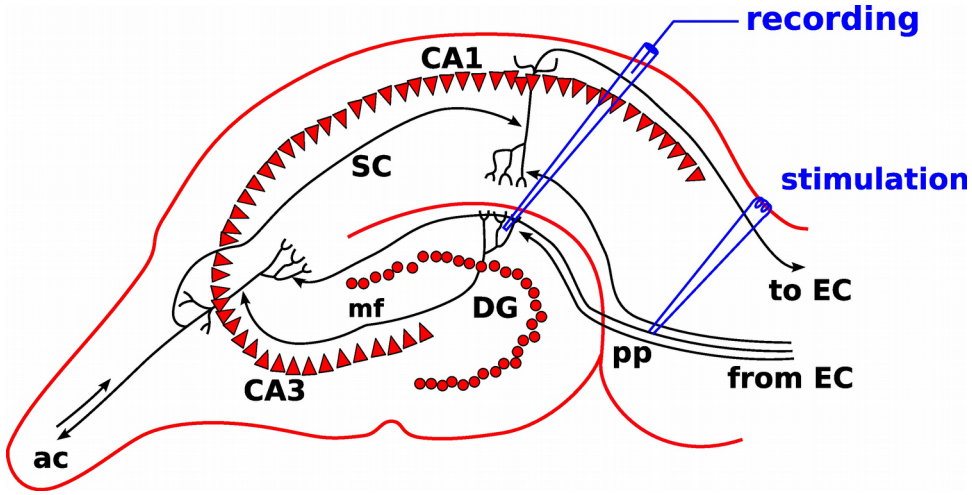
pp	...	perforant path
mf	...	mossy fibres
ac	...	associational commissural path
sc	...	Schaffer collateral

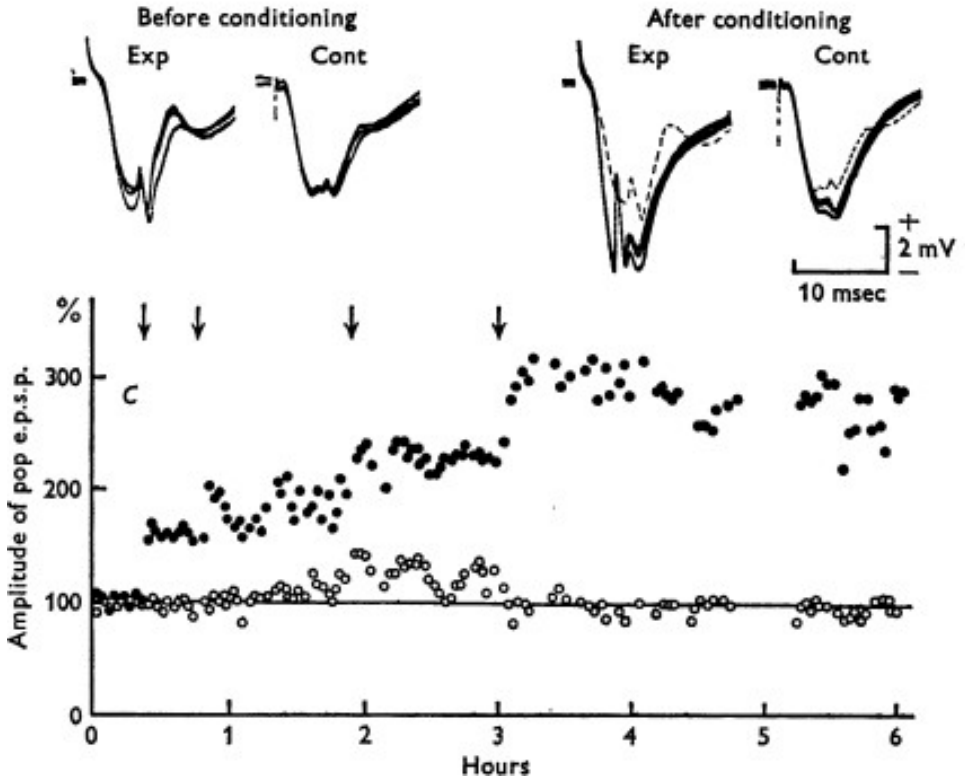
Induction: LTP through high frequency stimulation

hippocampus (*in vivo*)

pre 10-20 Hz for 10-15 sec

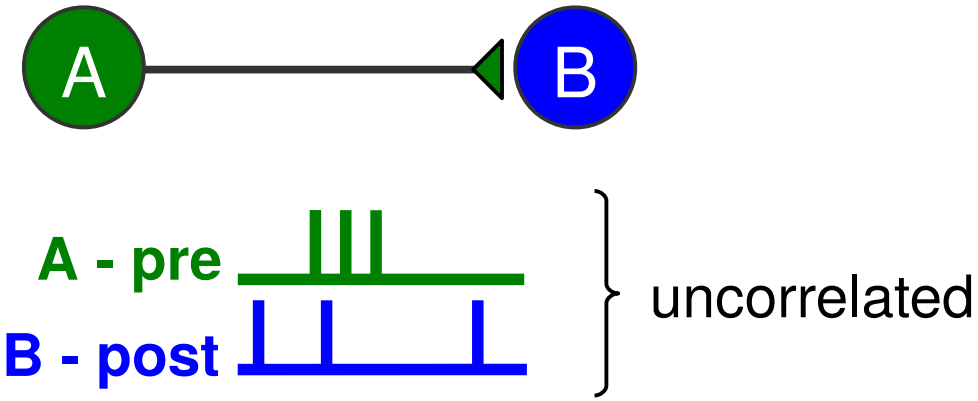
post or 100 Hz for 3-4 sec





[Bliss and Lømo 1973]

LTD induction: postulate of Stent

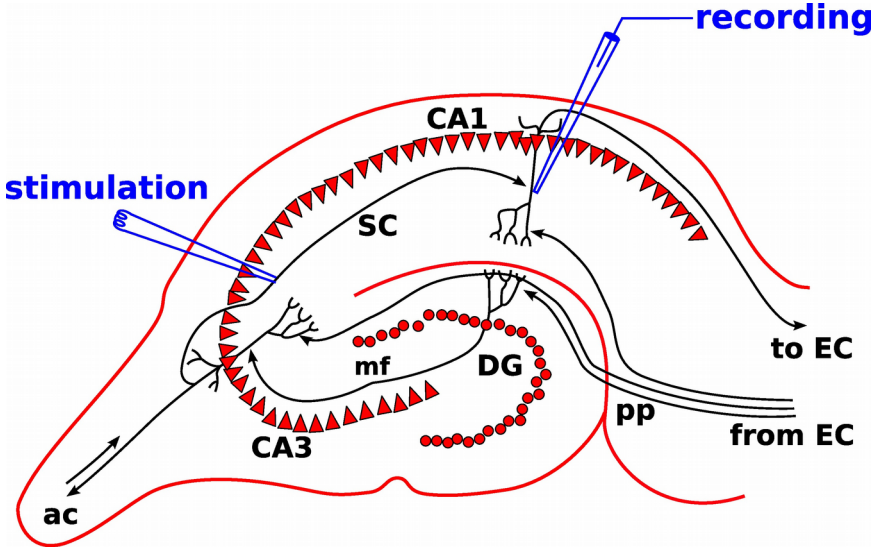


"When the presynaptic axon of cell A *repeatedly* and *persistently* fails to excite the postsynaptic cell B while cell B is firing under the influence of other presynaptic axons, metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is *decreased*."

[G. Stent 1973;
see also Sejnowski 1977, von der Malsburg 1973, Bienenstock et al. 1982]

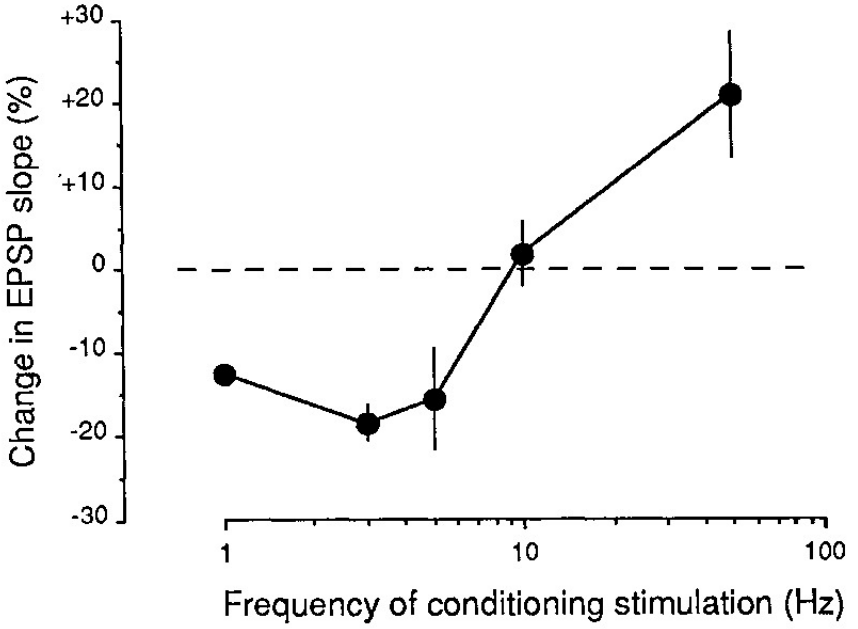
Plasticity induction: LTD obtained at low frequencies

hippocampus (slices)



pre
post

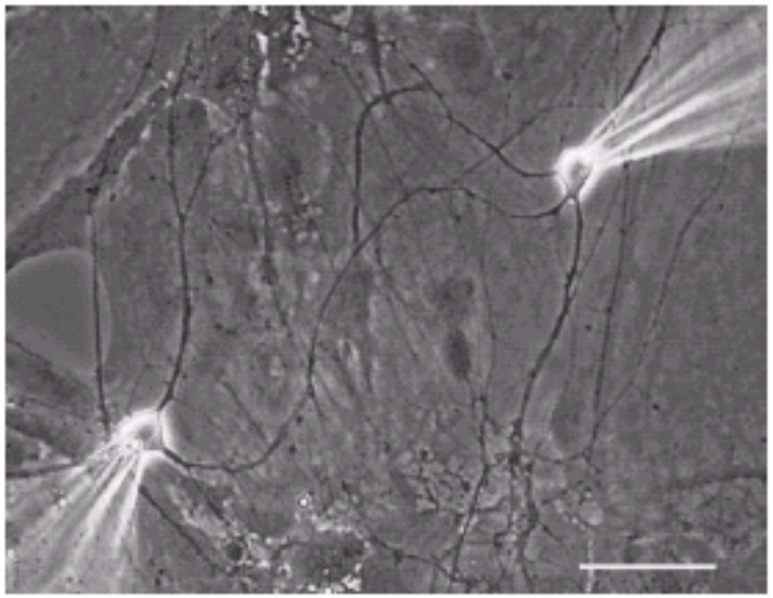
900 pulses at 1-50 Hz



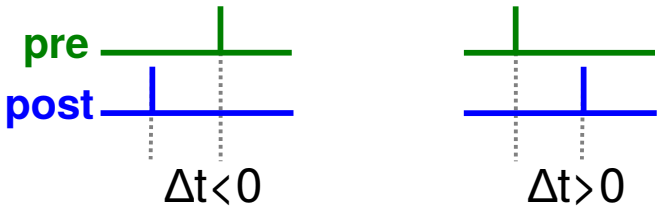
[Dudek and Bear 1992;
Dunwiddie and Lynch 1978]

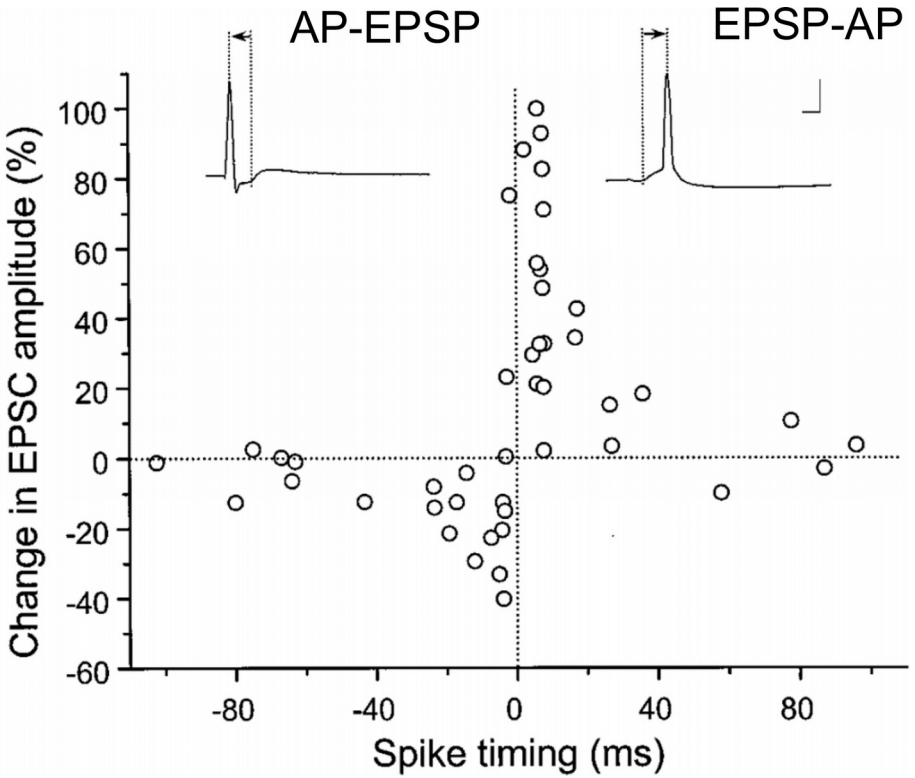
STDP : plasticity from single spike-pairs

hippocampal cultures



60 pairings @ 1 Hz



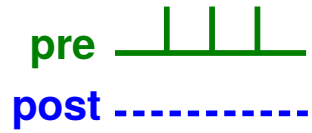


[Bi & Poo, J Neurosci 1998]

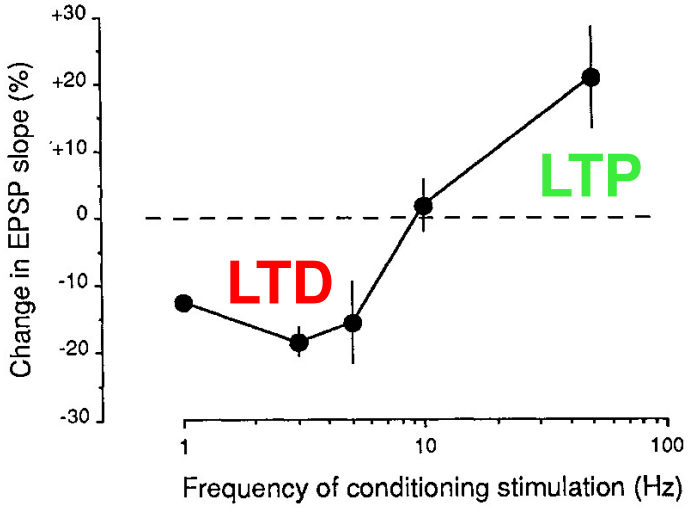
[Magee & Johnston 1997; Zhang et al. 1998; Markram et al. 1997; Sjöström et al. 2001; Feldman 200]

Frequency-dependent plasticity and STDP

frequency-dependent plasticity

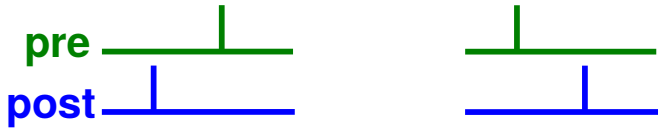


900 pulses at 1-100 Hz

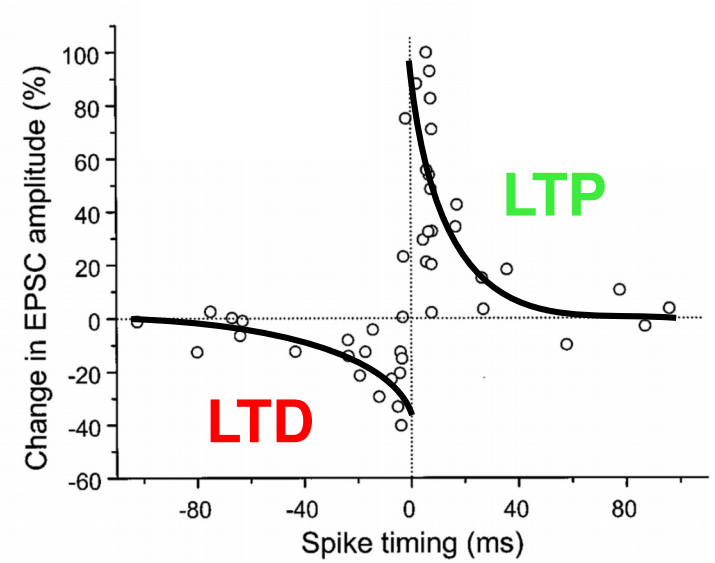


[Dudek and Bear 1992;
Dunwiddie and Lynch 1978]

spike timing-dependent plasticity



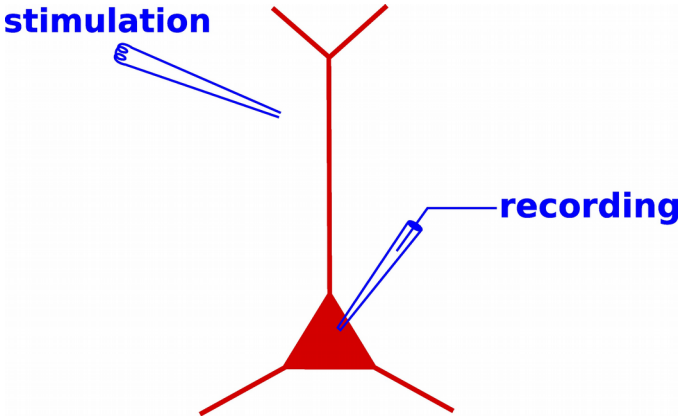
60 pairings @ 1 Hz

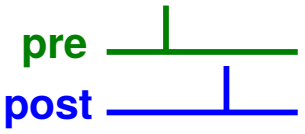


[Markram et al. 1997; Bi & Poo 1998;
Zhang et al. 1998]

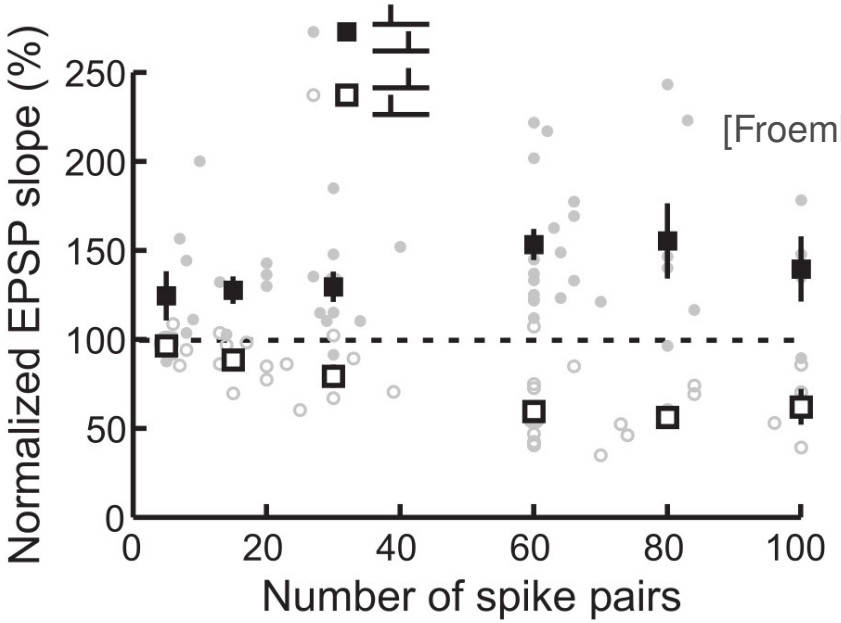
Outline

Number of pairing





XX pairings @ 0.2 Hz



[Froemke et al. 2006]

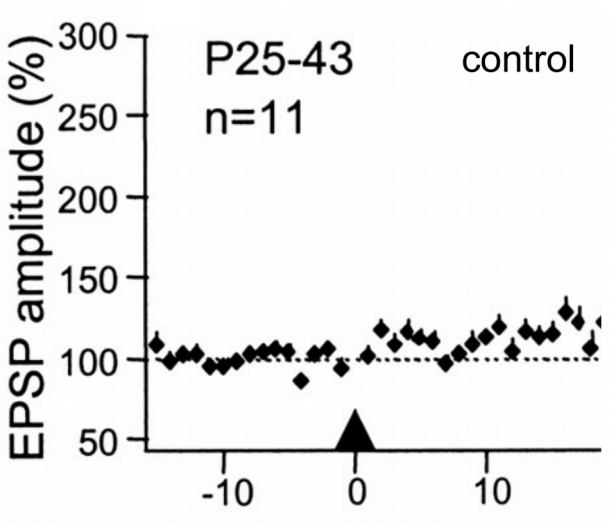
- generally : plasticity induction with spike-pairs requires the *repeated* presentation of the pre-post pair
- LTP induced with a few pairs
- LTD requires the presentation of ~20 stimulation pairs

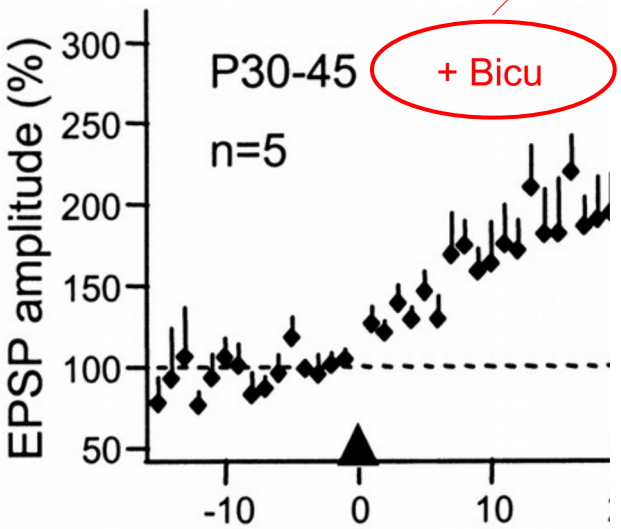
Role of synaptic inhibition

control
➔ no plasticity

inhibition blocked
➔ LTP

Δt = +10 ms



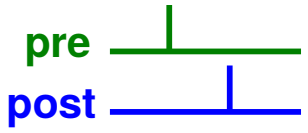


Bicuculline is a competitive antagonist of $GABA_A$ receptors.

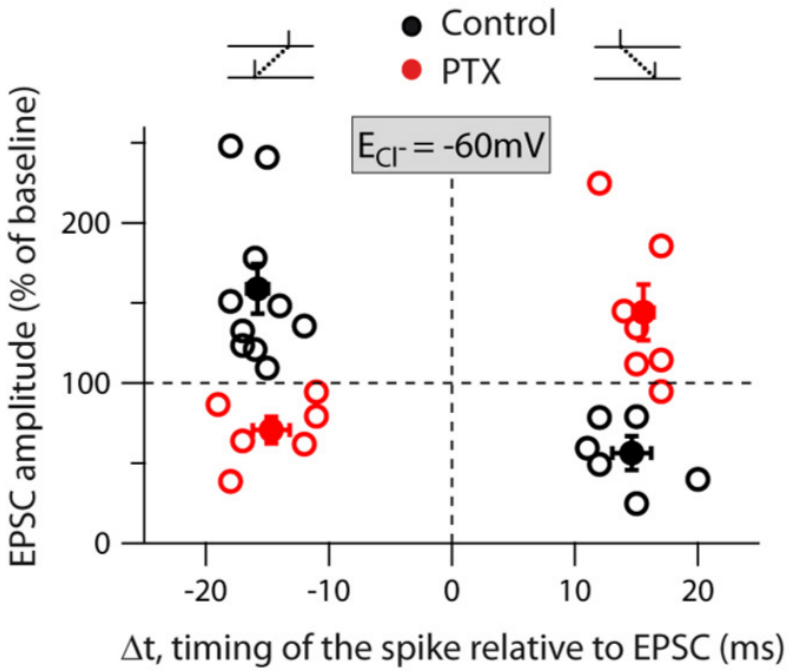
[Mederith et al. *J Neuroci* 2003]

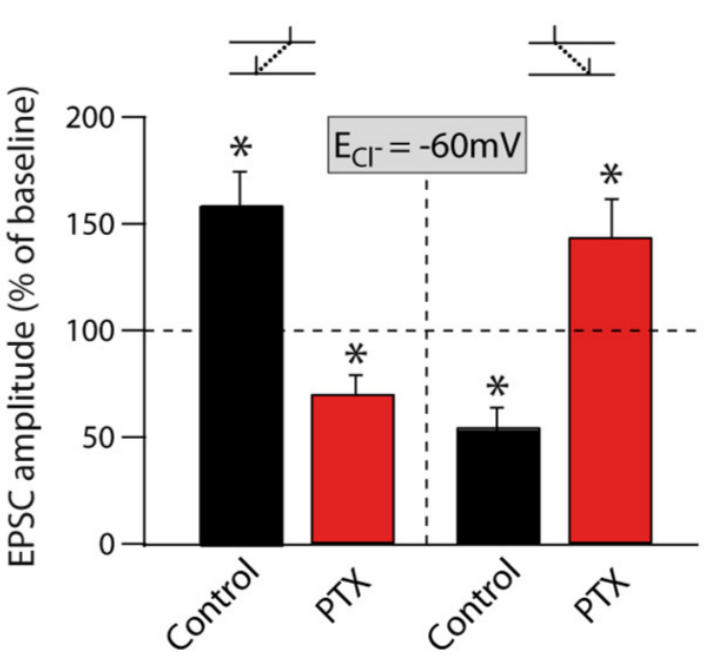
- Attention : inhibition is blocked in many (in particular classical) plasticity studies
- synaptic inhibition can prevent plasticity induction

Role of synaptic inhibition



100-150 pairings @ 1 Hz



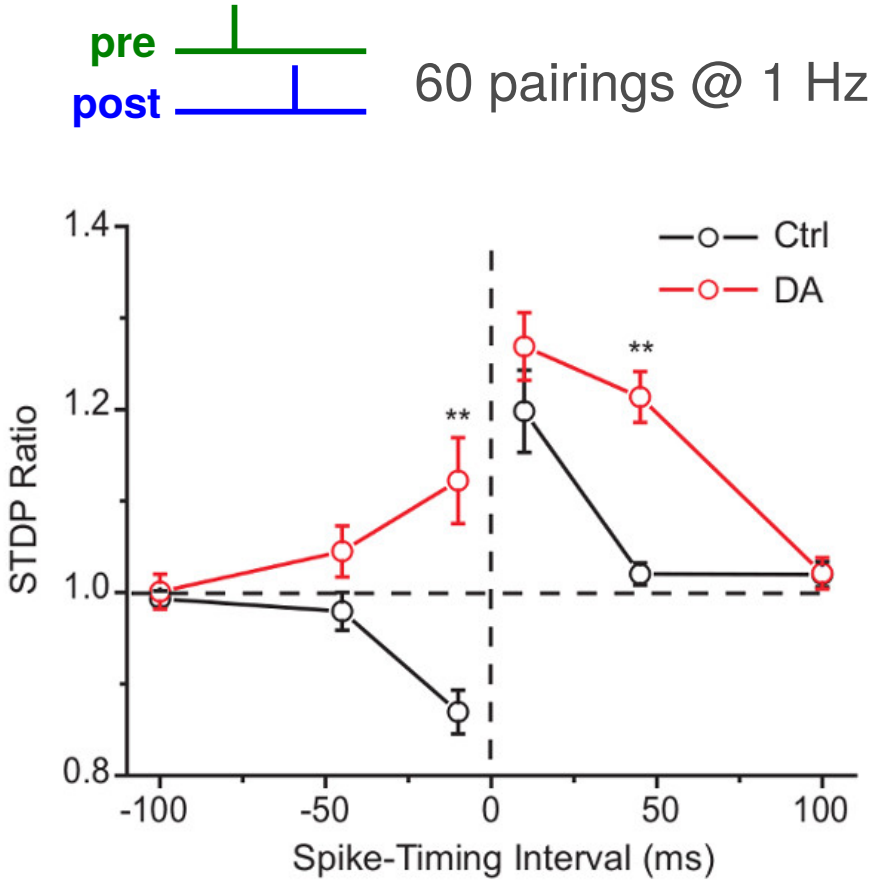


[Paille et al. *J Neurosci* 2013]

Picrotoxin is a noncompetitive antagonist at $GABA_A$ receptors

- at the corticostriatal synapse : inhibition inverts the STDP curve

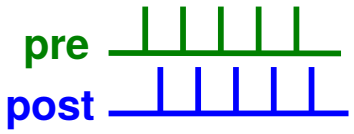
Role of neuromodulation - Dopamine



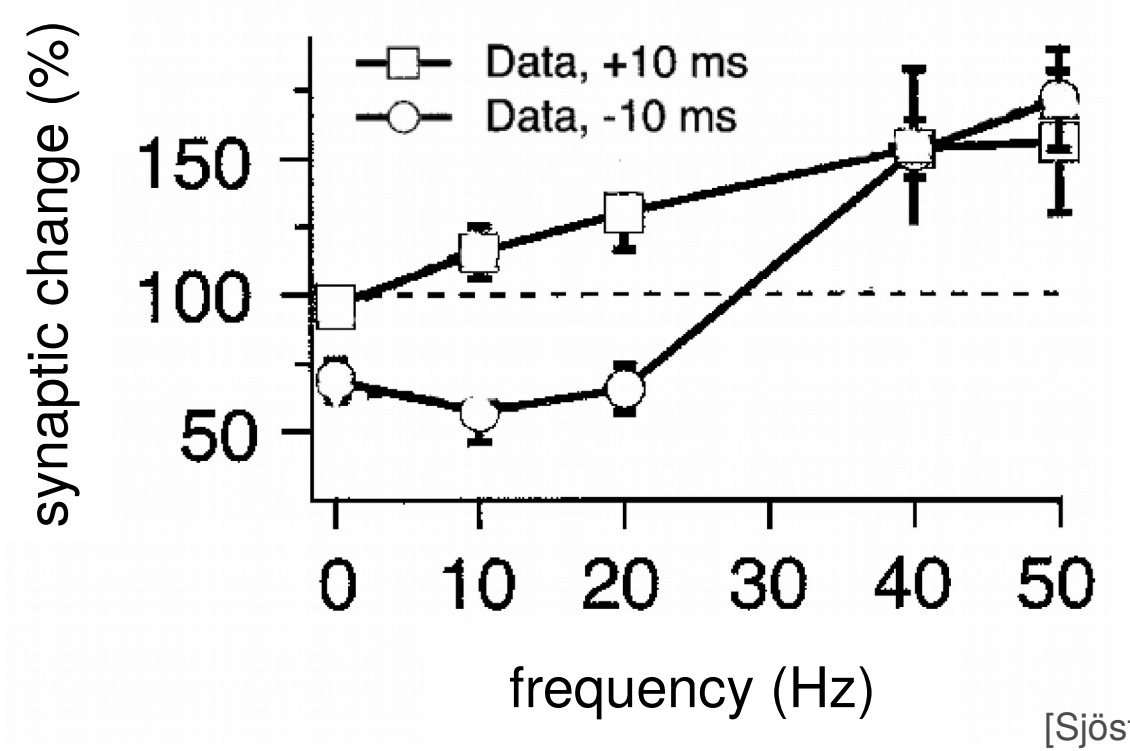
[Zhang et al. *PNAS* 2009]

- many neurotransmitter have been shown to shape synaptic plasticity
- e.g. : dopamine controls sign and magnitude of plasticity

STDP depends on frequency of spike-pairs



5 pairings, 15x @ 0.1 Hz

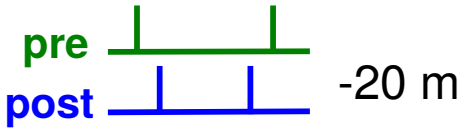


[Sjöström et al. *Neuron* 2001]

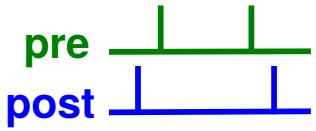
- in the first studies of STDP, spike-pairs were presented at low frequencies
- pre-post pairing induce no plasticity at low and LTP at high frequencies
- post-pre pairings induce LTD at low- and LTP at high frequencies

Non-linearity in STDP induction protocols

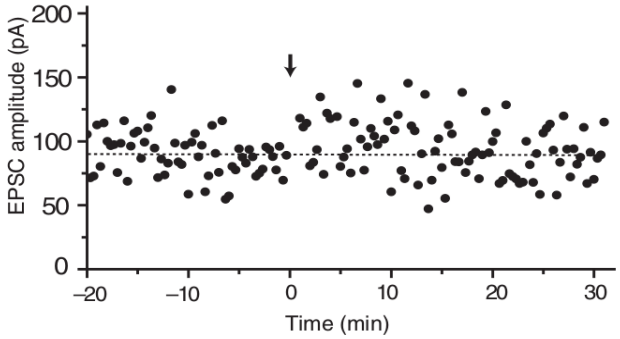
+5/-5 ms, 60 pairings @ 1 Hz

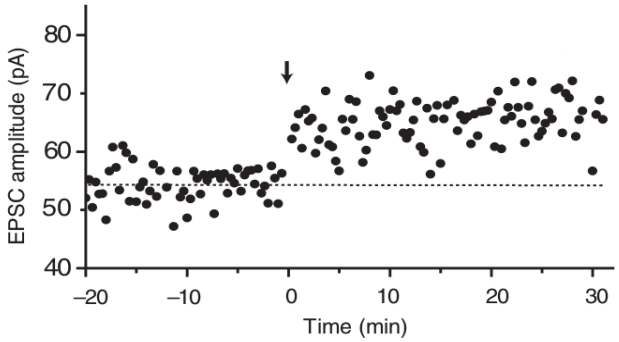


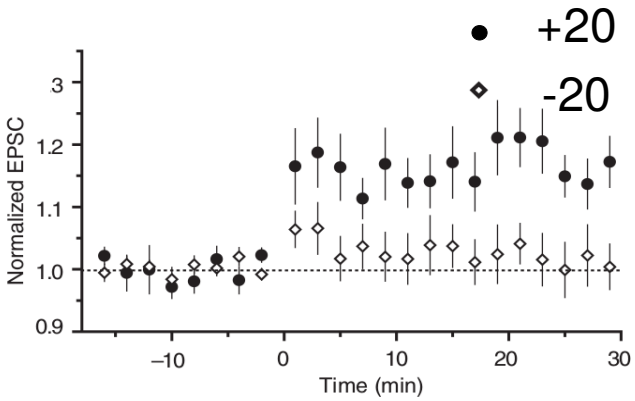
-20 ms



+20 ms



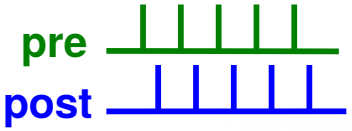




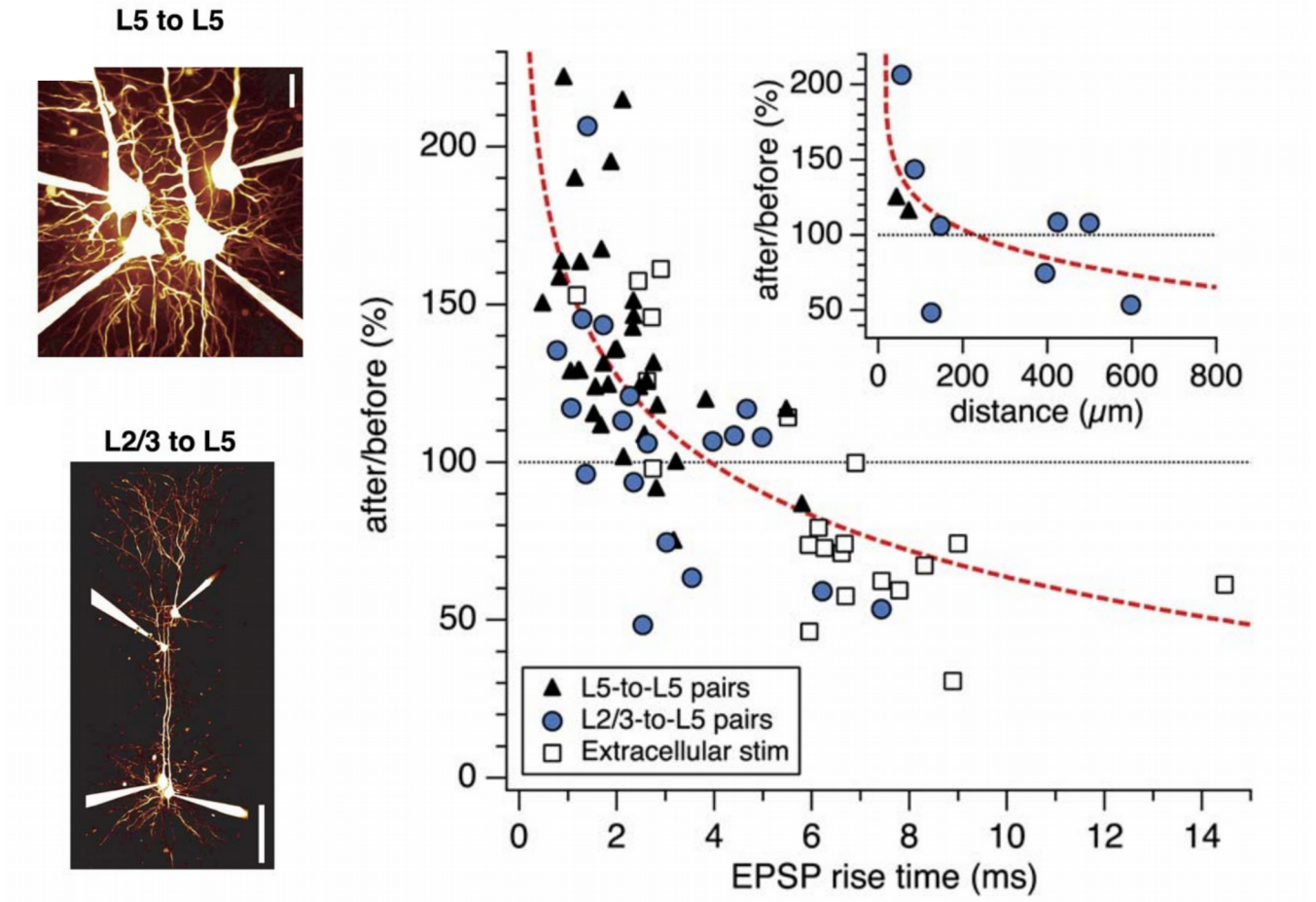
[Wang et al. *Nat Neurosci* 2005]

- order of pre-post, post-pre pairs in quadruplet stimulation determines plasticity outcome
  - pre-post post-pre quadruplet -> no plasticity
  - post-pre pre-post quadruplet -> LTP

STDP depends on synaptic location



Δt=+10 ms, 5 pairings, 50 Hz, 15x @ 0.1 Hz

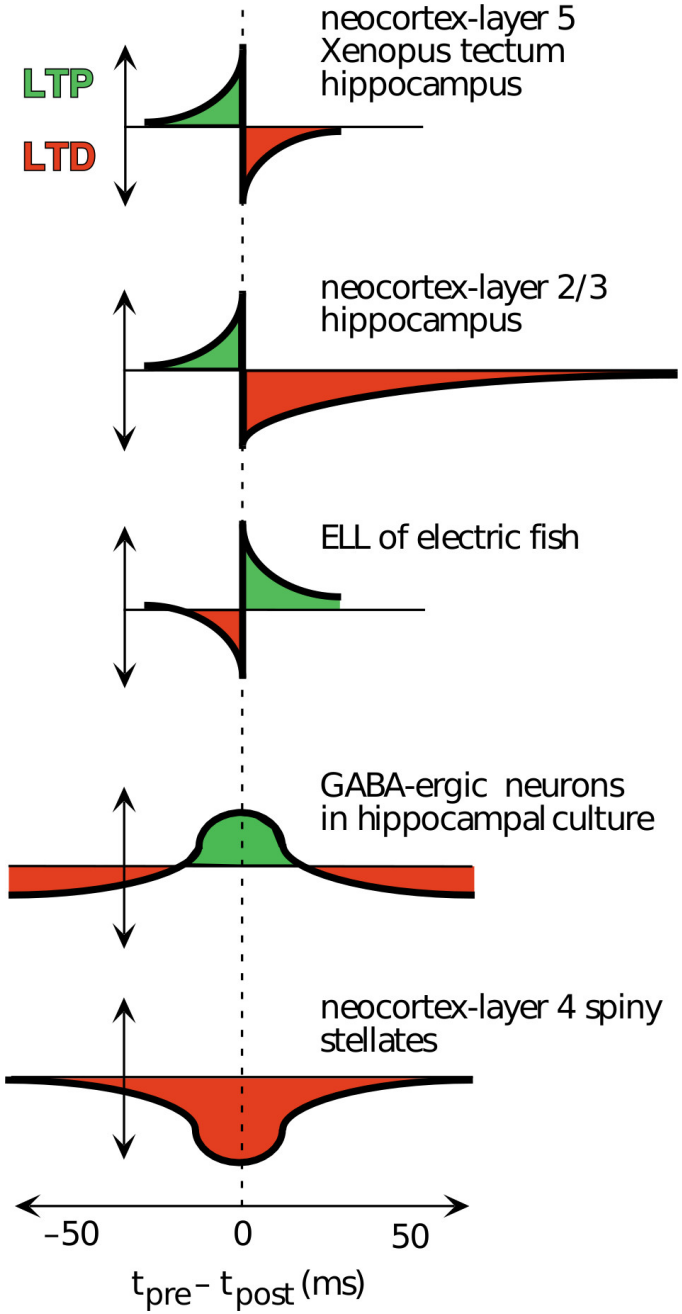


[Sjöström & Hausser, *Neuron* 2006]

[Froemke et al. *Nature,* 2005; Letzkus et al. *J Neurosci* 2006]

- Proximal synapse : LTP
- Distal synapse : LTD

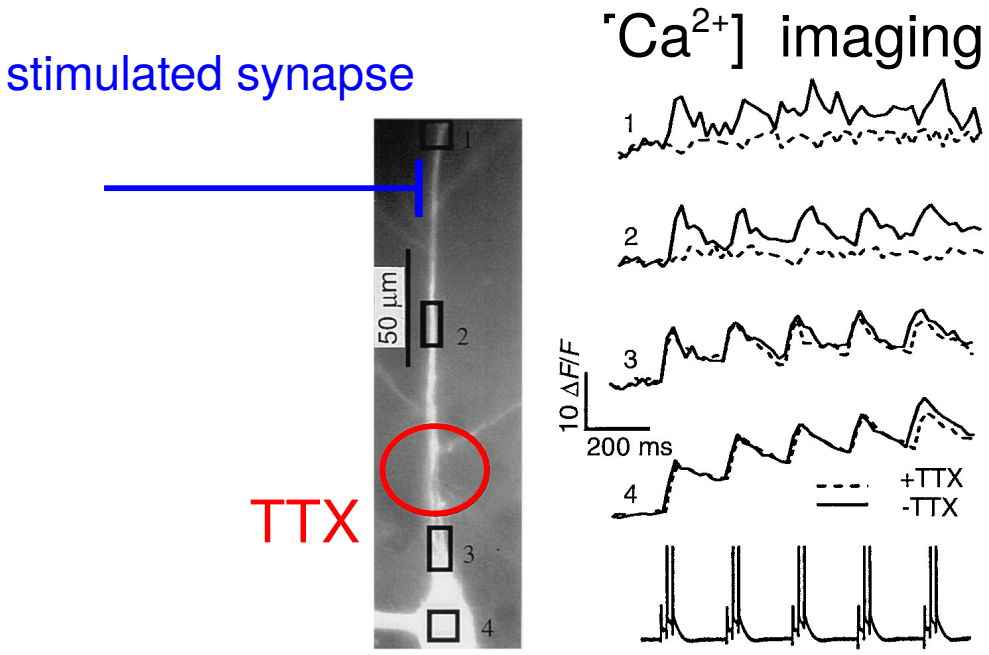
STDP windows depends on brain structure, synapse type



[Abbott & Nelson *Nat Neurosci* 2000]

Outline

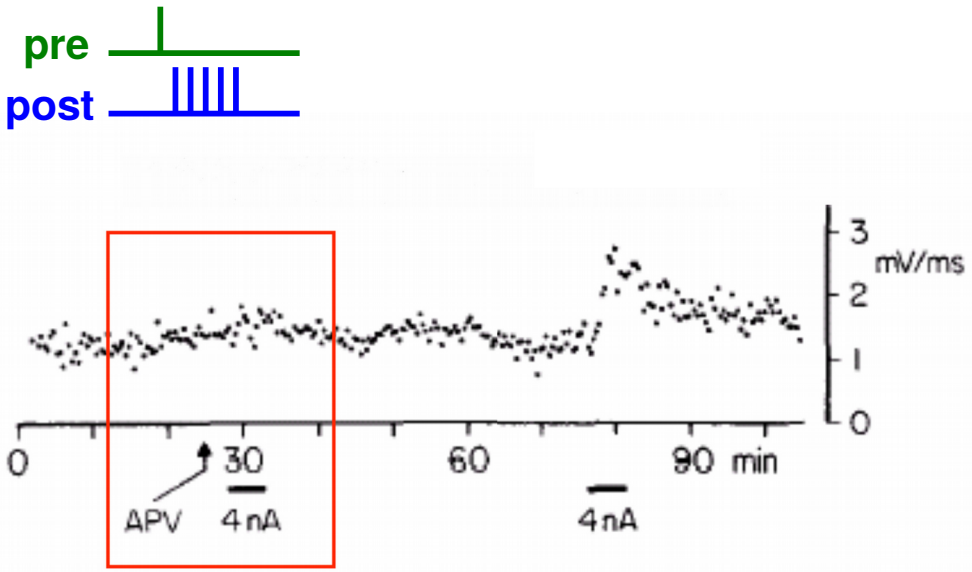
Backpropagating action potential required for STDP



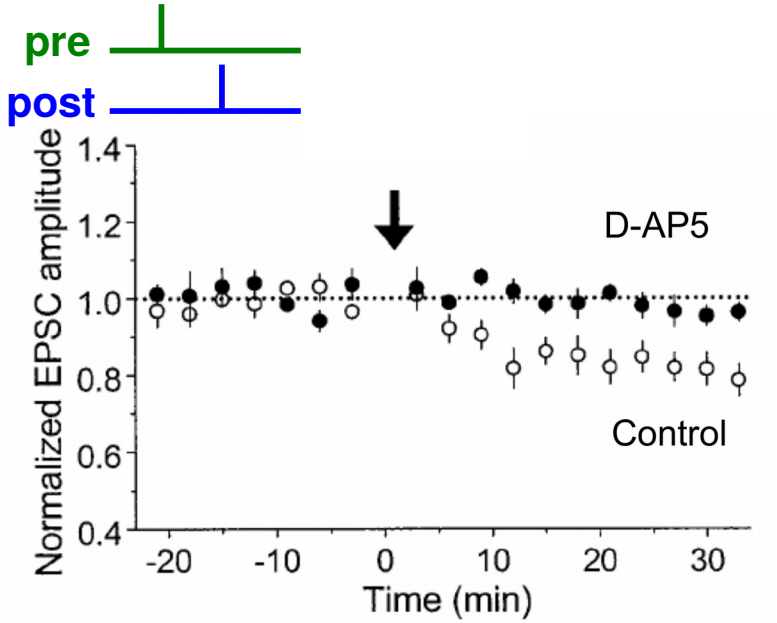
[Magee & Johnston *Science* 1997]

- Backpropagating action potential provides postsynaptic depolarization required for STDP

STDP requires NMDA receptor activation



[Gustafsson et al. *J Neurosci* 1987]

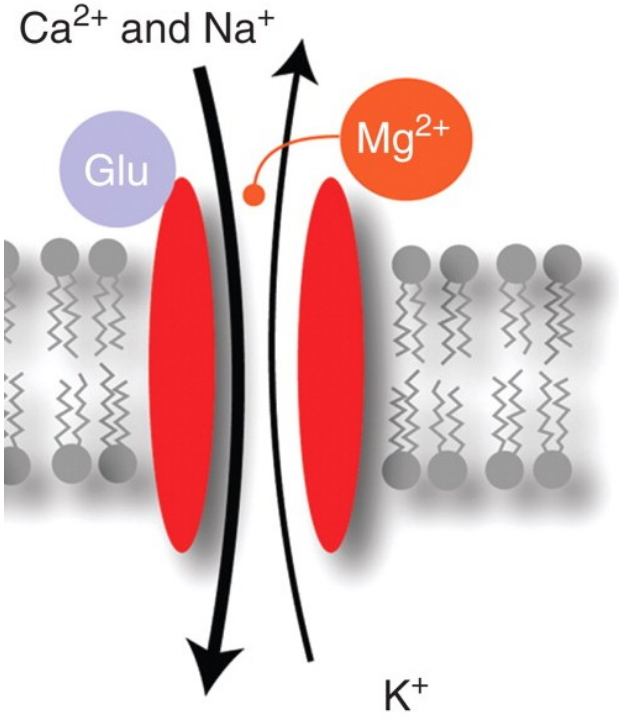


[Bi & Poo *J Neurosci* 1998]

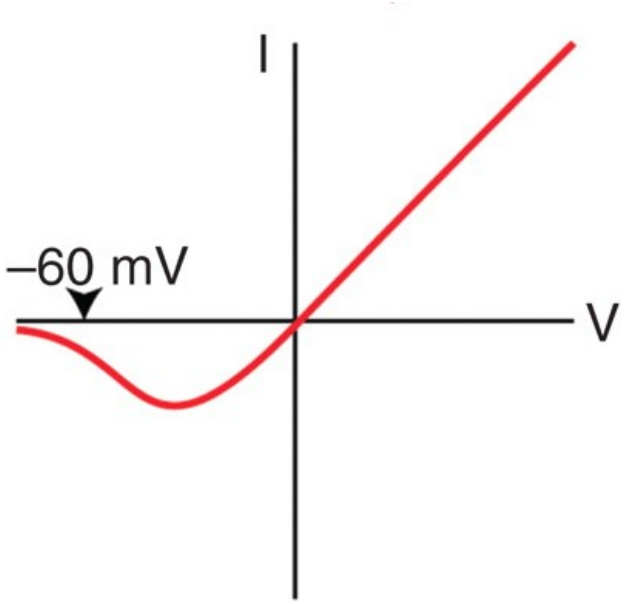
- NMDAR antagonist blocks STDP induction

  (D-AP5 or APV is a selective NMDA receptor antagonist)

Postsynaptic NMDA receptor



current-voltage relationship



- coincidence detector :

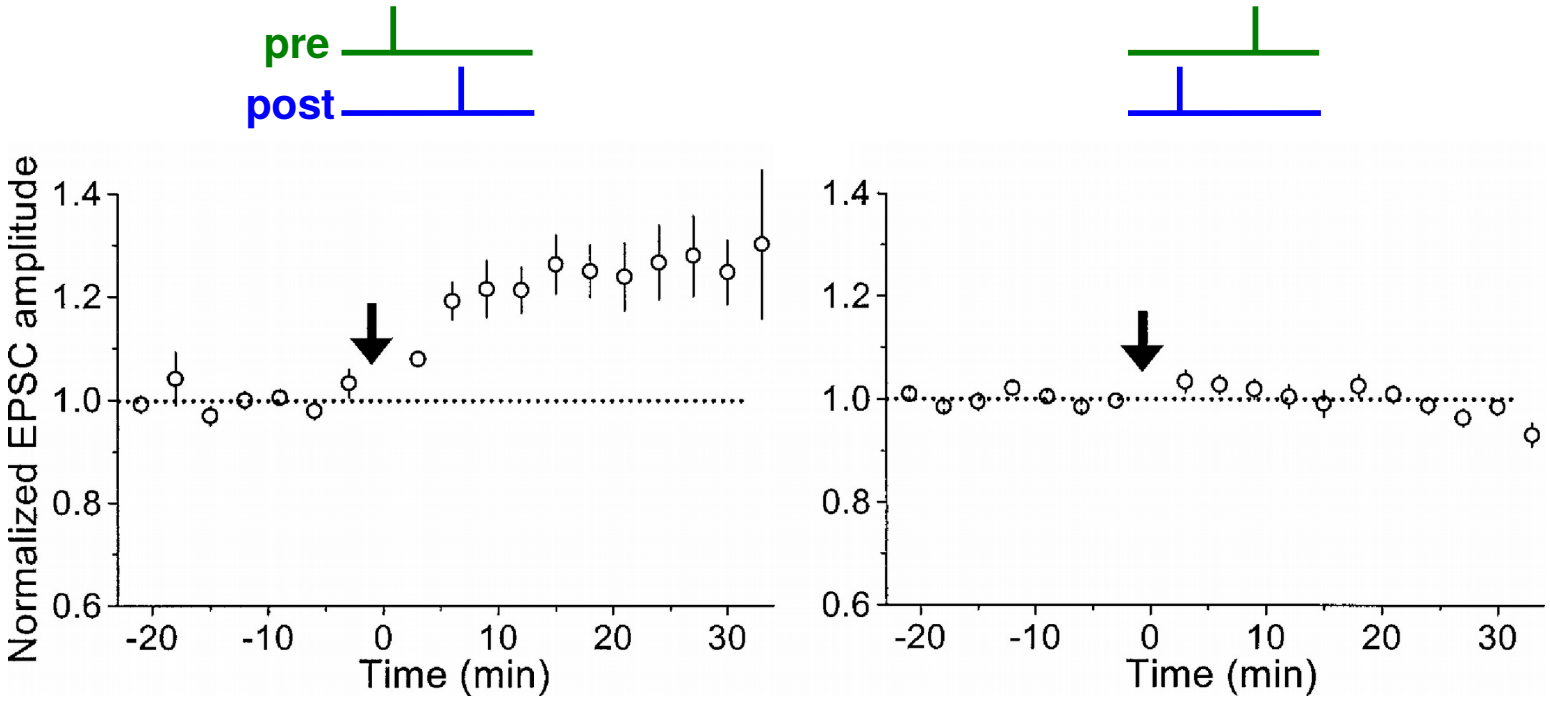
  presynaptic action potential → glutamate (Glu)

  postsynaptic depolarization → Mg^{2+} block is expelled

- calcium permeable

Voltage-dependent Ca channels required for LTD

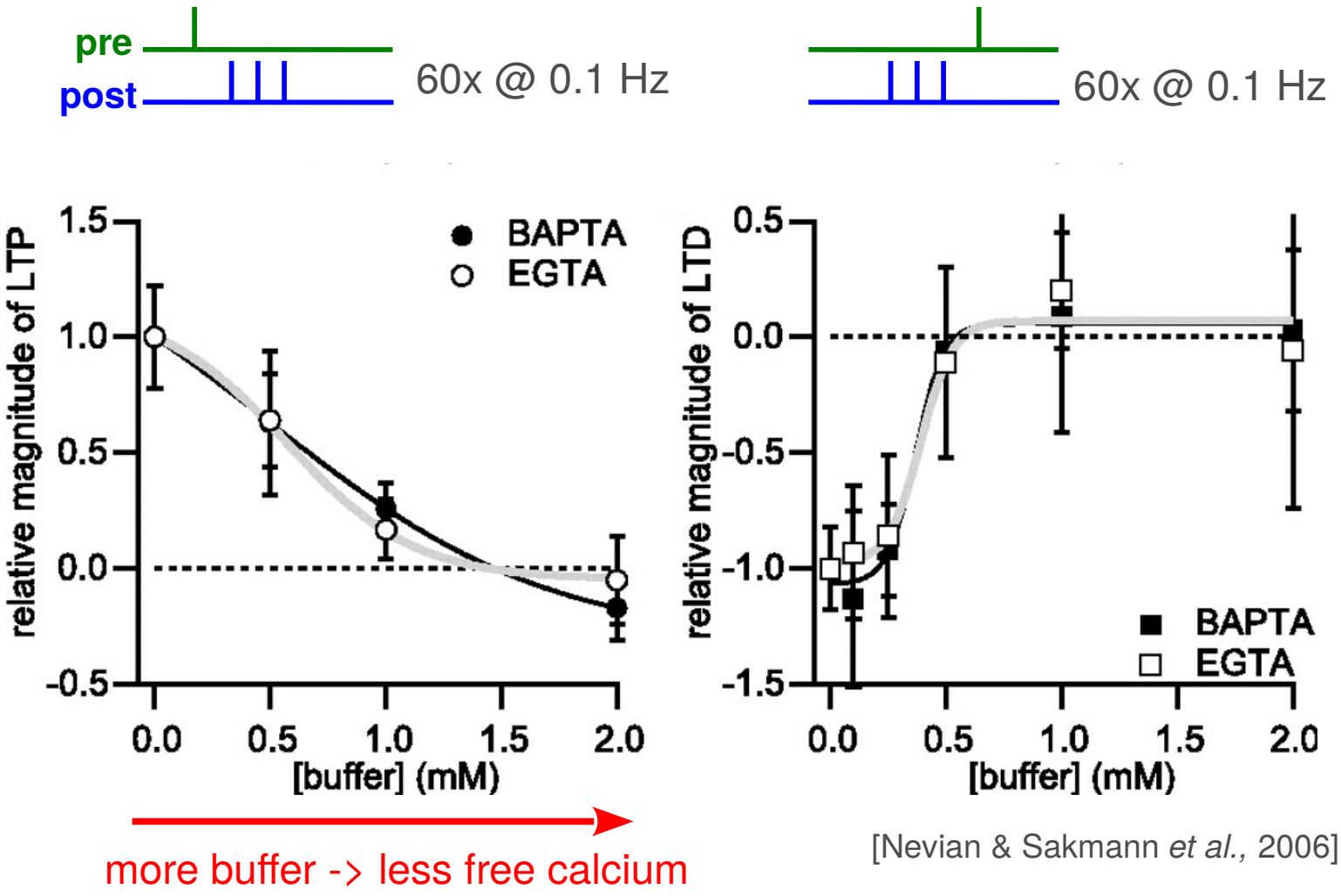
+ nimodipine (L-type calcium channel blocker)



[Bi & Poo *J Neurosci* 1998]

- LTD but not LTP involves the activation of L-type calcium channels

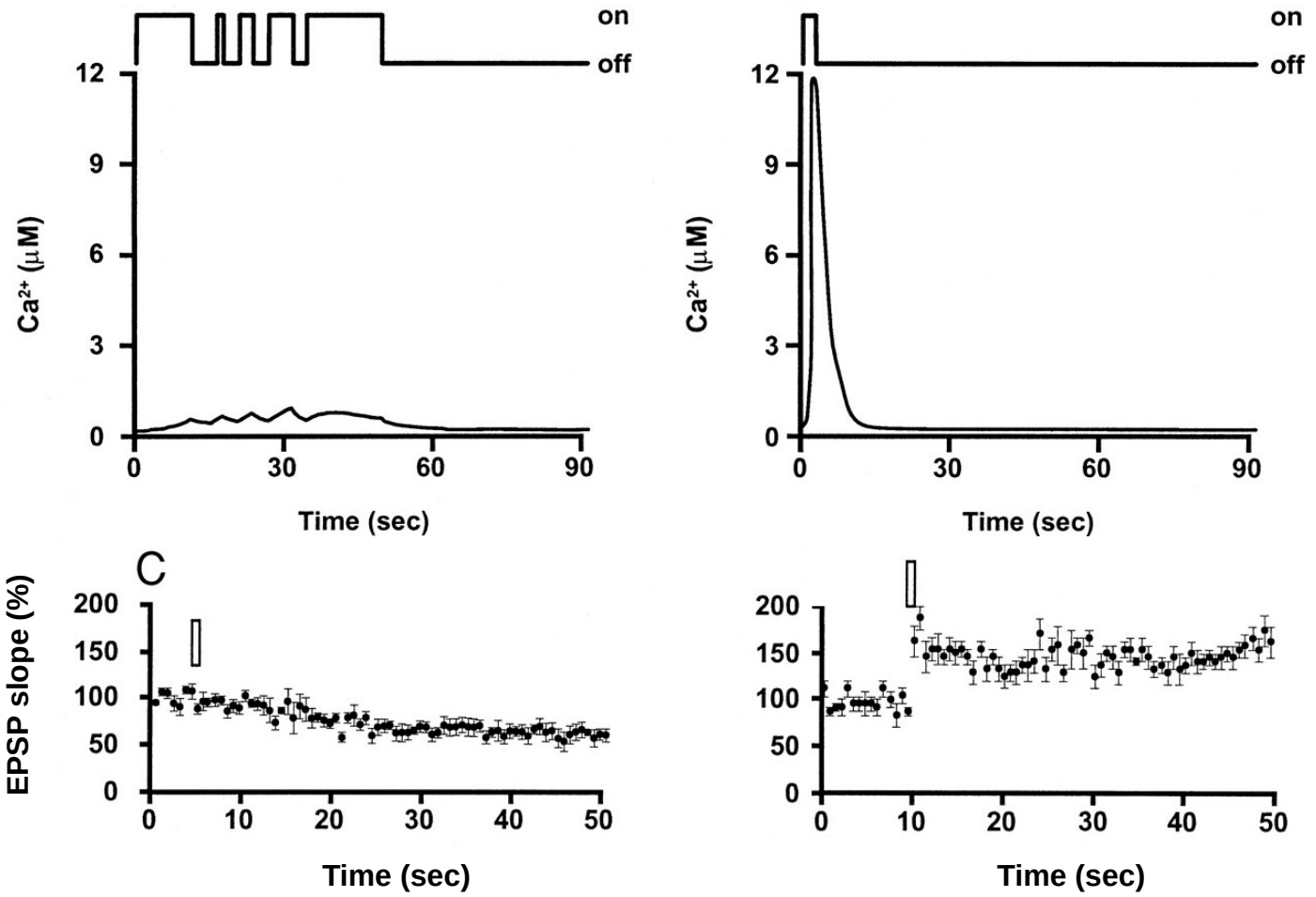
Postsynaptic calcium *required* for plasticity



[Nevian & Sakmann *et al.*, 2006]

- LTP/LTD equally sensitive to fast and slow [Ca^{2+}] buffers

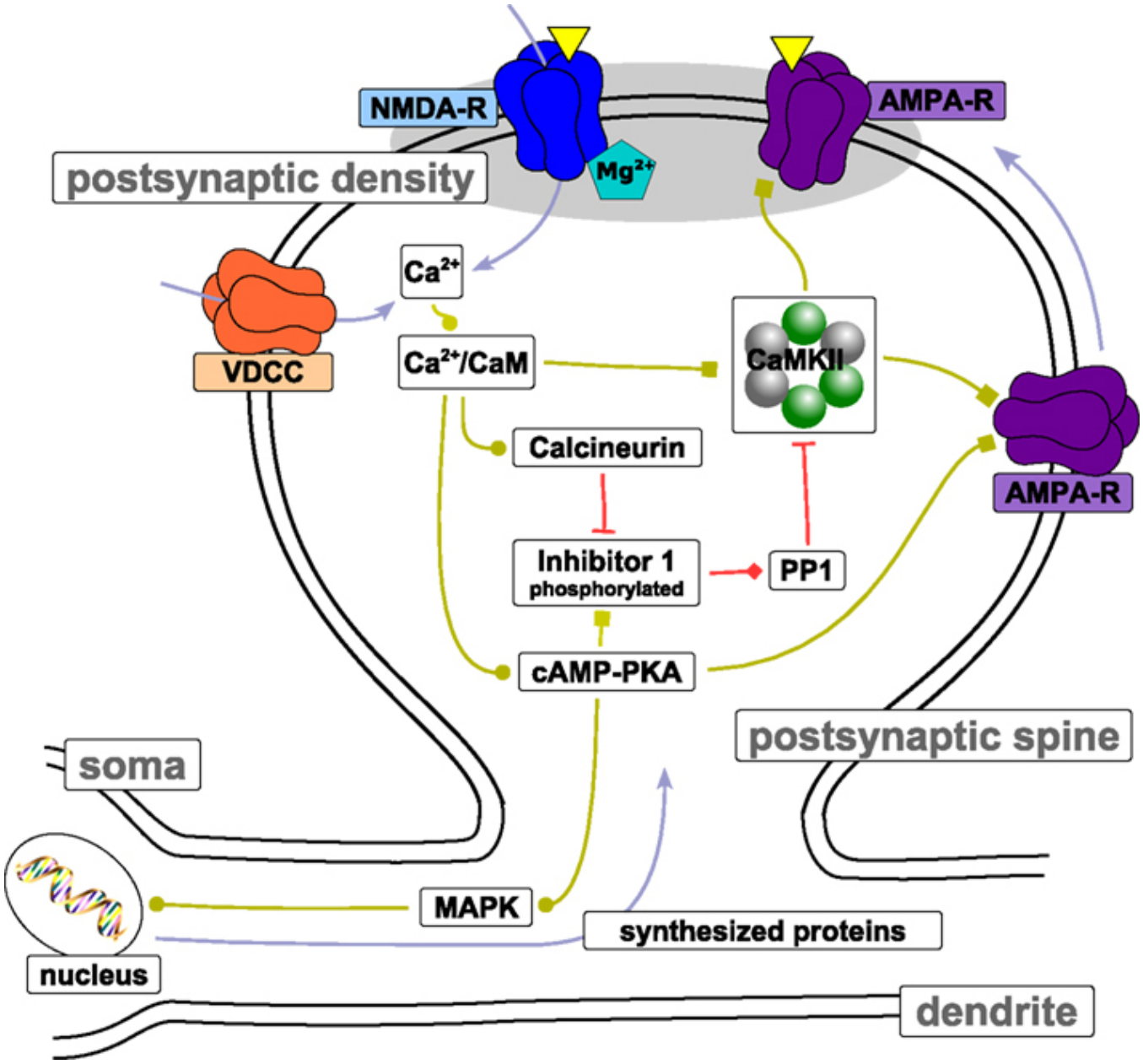
Postsynaptic calcium *sufficient* for plasticity



[Malenka *et al. Science* 1988; Yang *et al., J Neurophysiol* 1999]

- LTP induced by brief, large amplitude [Ca^{2+}] increases
- prolonged, modest rise in [Ca^{2+}] elicits LTD

Signal pathways downstream of Calcium



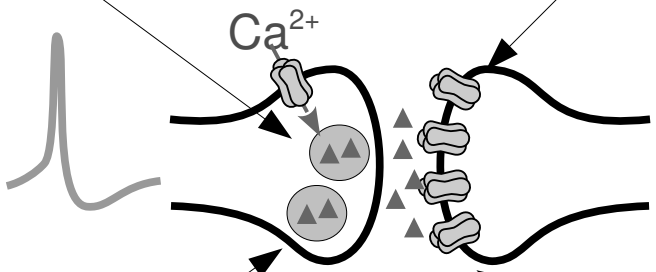
Expression of long-term changes

presynaptic

postsynaptic

neurotransmitter vesicle number

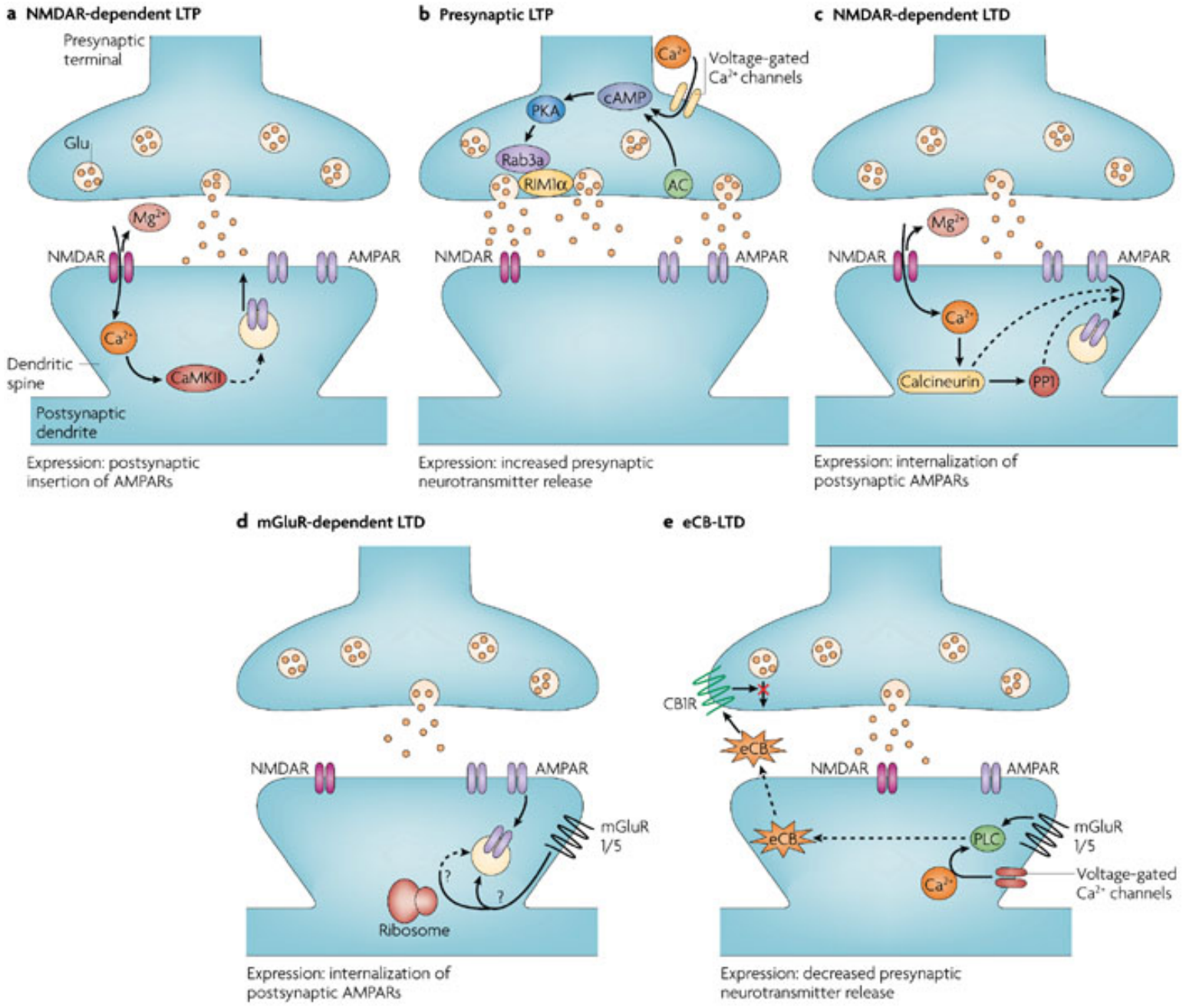
number of AMPA receptors



probability of vesicle release

conductance of AMPA receptors

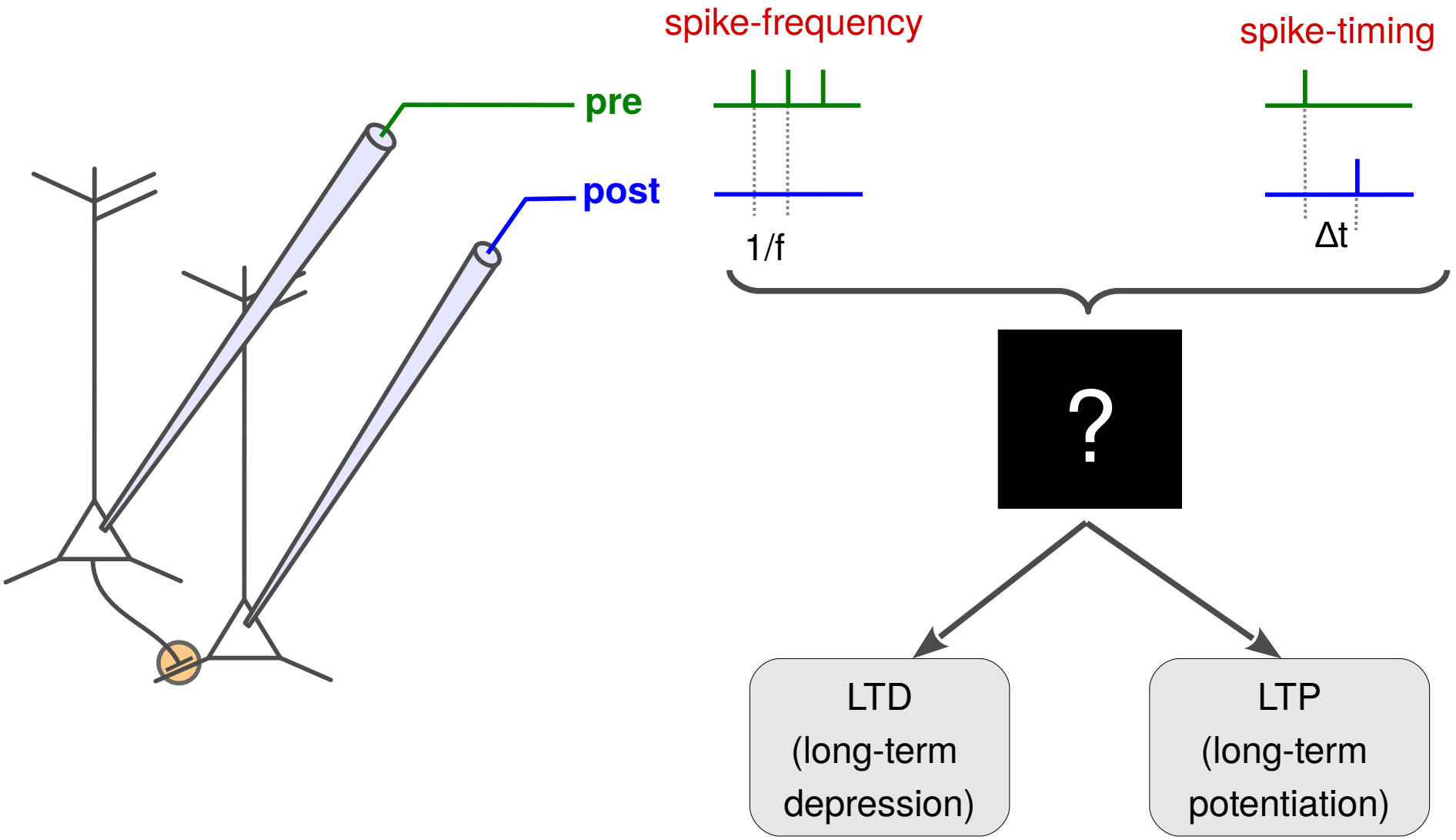
Diversity of induction and expression pathways



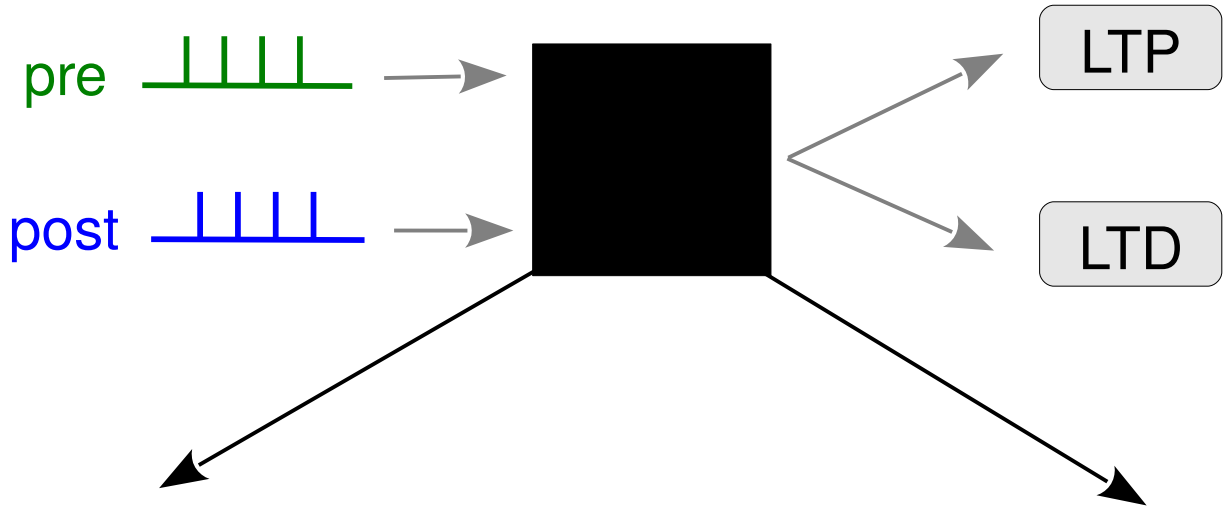
[Kauer, Malenka. *Nat Rev Neurosci* 2010]

Outline

Modeling : translation from spikes to plasticity results



Modeling approaches : phenomenological vs. biophysical



phenomenological models of LTP/LTD

- use pre- and postsynaptic spike times or rate to calculate change in synaptic strength
- conversion can involve arbitrarily complex mathematical models

biophysical models of LTP/LTD

- resolve *parts* of the underlying biological machinery involved in the induction of plasticity
- degree of biological detail varies largely

Modeling studies : phenomenological vs. biophysical

phenomenological models of LTP/LTD

- rate-based plasticity models
  [Hebb, 1949; Bienenstock *et al.*, 1982; Oja, 1982]
- spike-timing based models
  [Gerstner *et al.*, 1996; van Rossum *et al*. 2000; Song, 2000; Pfister & Gerstner, 2006]

biophysical models of LTP/LTD

- Ca^{2+} – dynamics based models
  [Karmarkar *et al*., 2002; Shouval *et al.*, 2002; Rubin *et al*., 2005; Graupner & Brunel 2012]
- CaMKII kinase-phosphatase system
  [Crick 1984; Lisman, 1985; Okamoto & Ichikawa, 2000; Zhabotinsky, 2000; Graupner & Brunel, 2007; Urakubo *et al.*, 2008]
- extensive protein networks
  [Bhalla & Iyengar, 1999; Hayer & Bhalla, 2005]
- local clustering of receptors
  [Shouval, 2005]

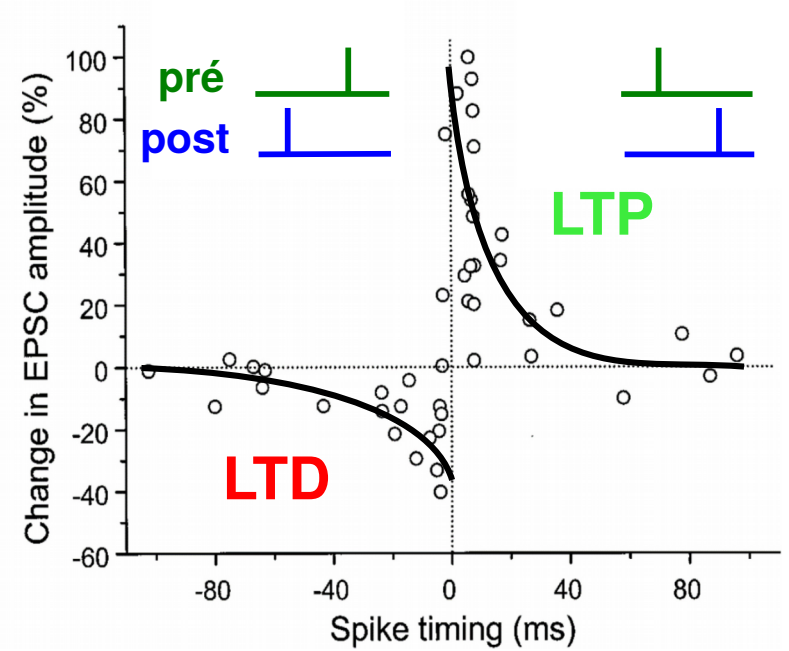
“Standard” STDP model

- spike-timing based rules : $\Delta w_{ij} = f\left(\{t_{ik}\},\{t_{jk}\}\right)$

- “standard” STDP :

$$f\left(\{t_{ik}\},\{t_{jk}\}\right) = \sum_{k,k'} F\left(t_{ik} - t_{jk'}\right)$$

$$F(\Delta t) = \begin{cases} A_+ \exp\left(-\Delta t/\tau_+\right) & \Delta t > 0 \\ A_- \exp\left(-\Delta t/\tau_-\right) & \Delta t < 0 \end{cases}$$



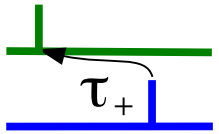
- Variations of the rule :
  * additive/multiplicative
  * All-to-all spike pairings / nearest neighbors

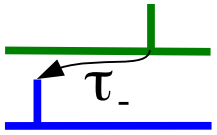
- **Problems :** does not depenend on firing rate
  does not resolve the nonlinearities of plasticity

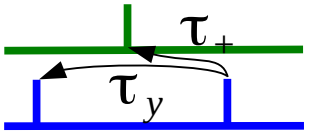
More recent plasticity models

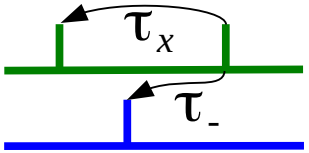
Triplet-based model

[Pfister & Gerstner, 2006; Clopath et al., 2010]

LTP : A_2^+ 

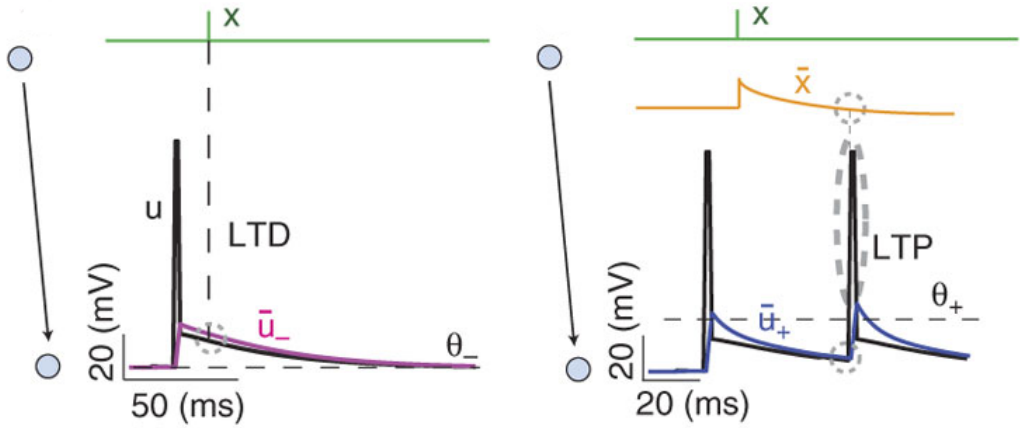
LTD : A_2^- 

LTP : A_3^+ 

LTD : A_3^- 

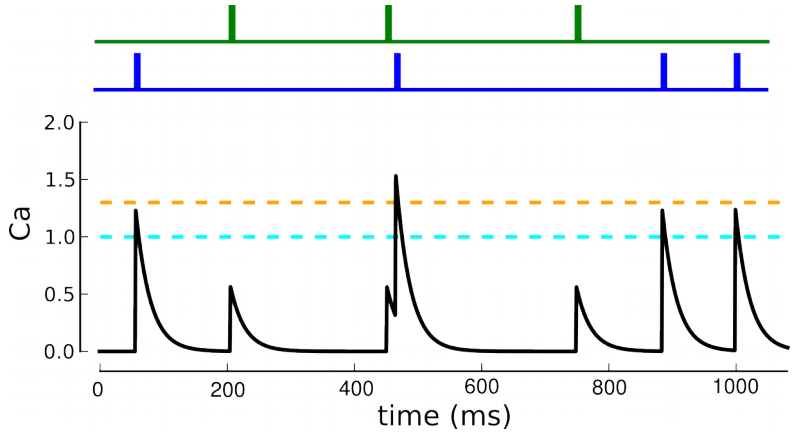
Model based on postsynaptic potential

[Clopath *et al.*, 2010]



Calcium-based model

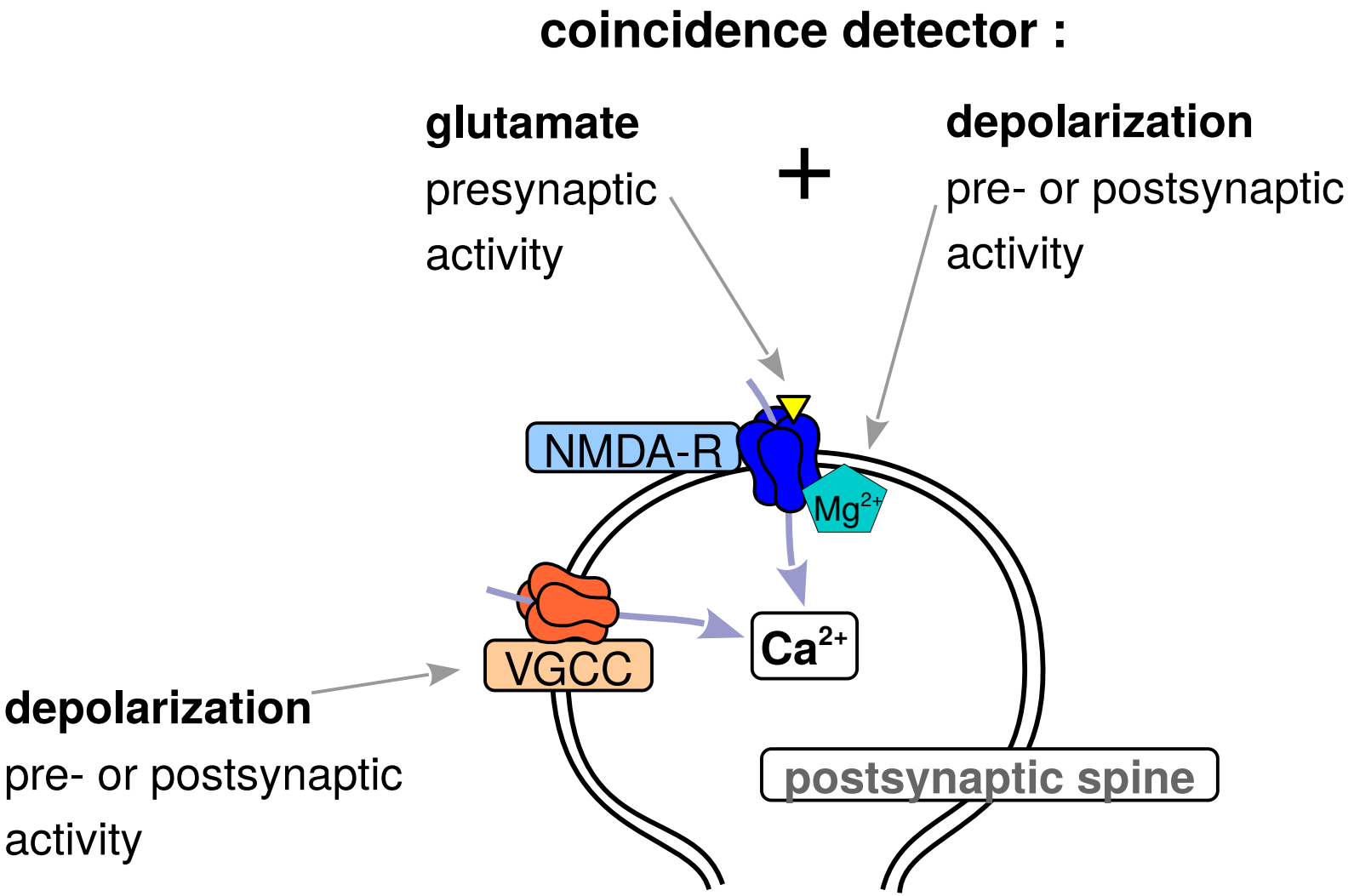
[Shouval *et al.* 2002,Graupner &Brunel 2012]



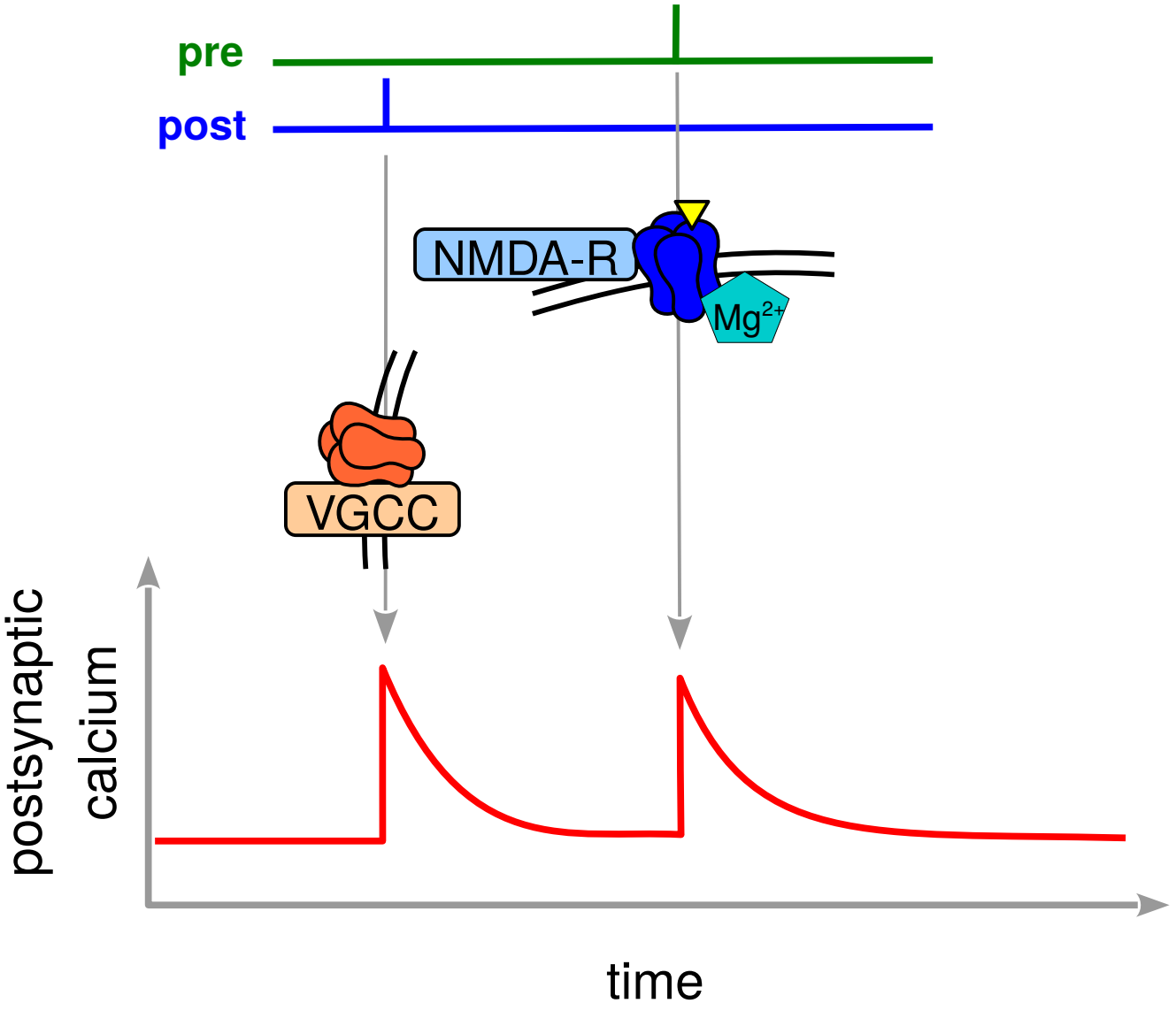
potentiation

depression

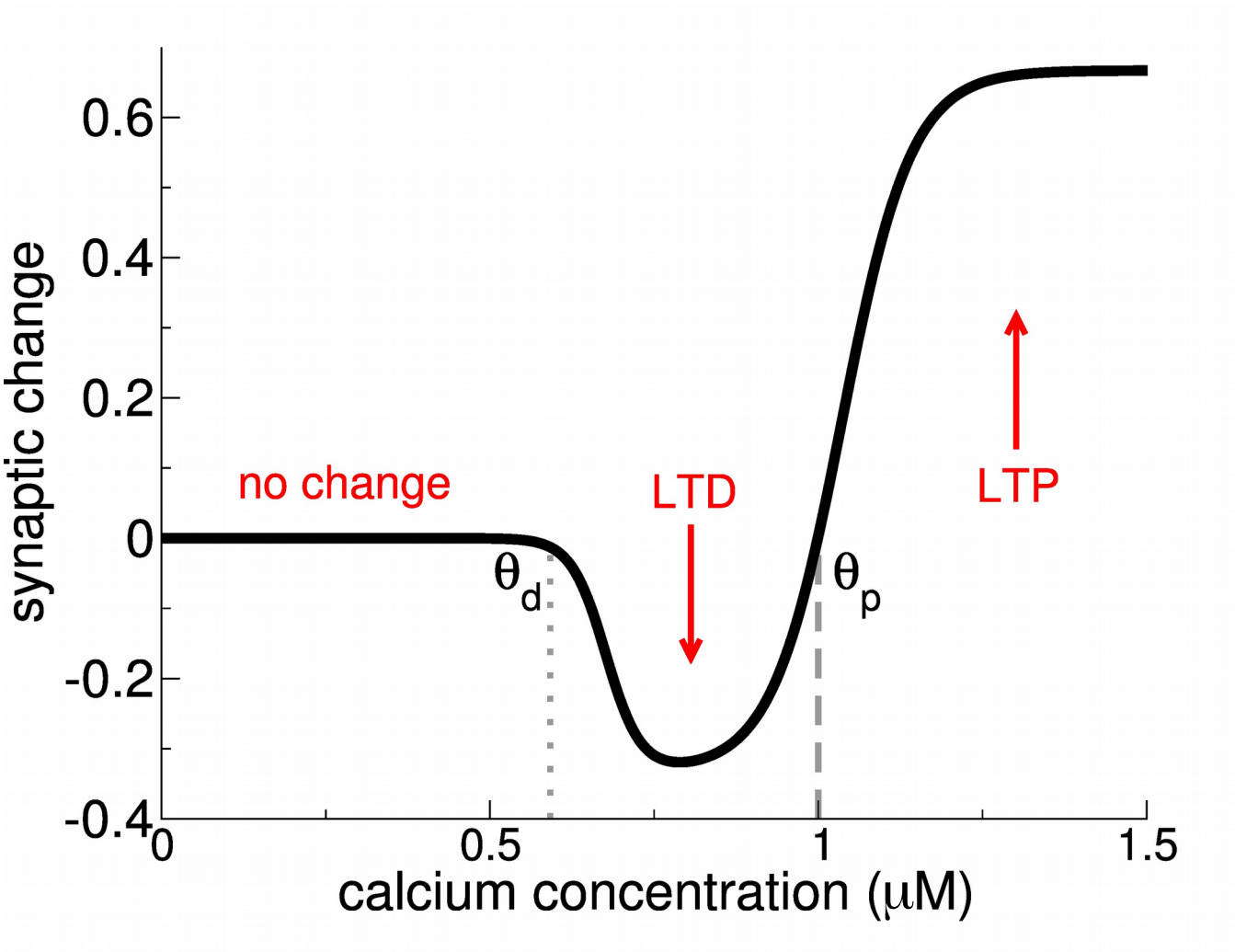
Calcium influx



Calcium transients from spike-pair stimulation



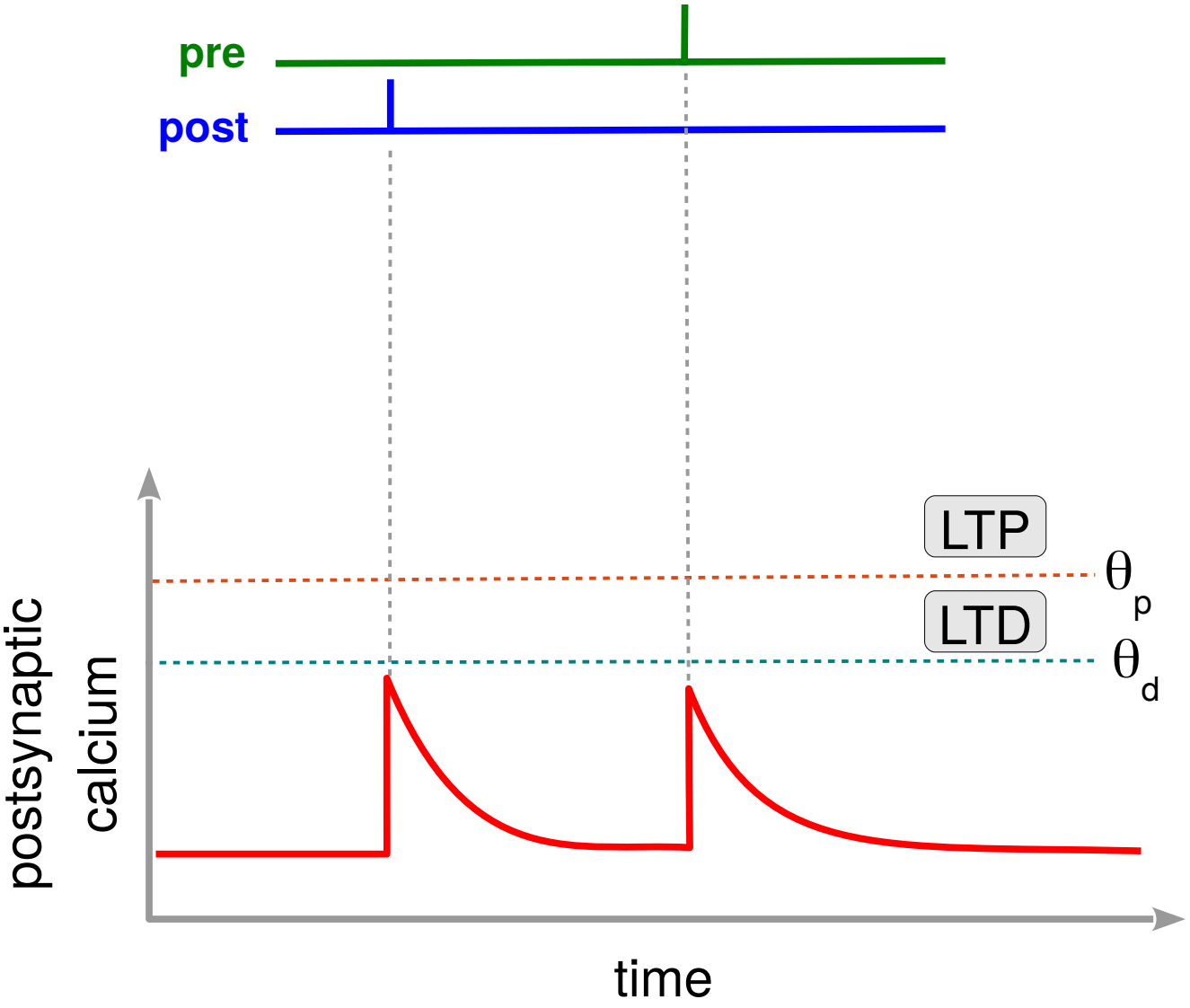
Calcium control hypothesis



[Shouval *et al.*, *PNAS* 2002]

- the calcium control hypothesis posits that the level of postsynaptic calcium concentration controls amplitude and the sign of plasticity

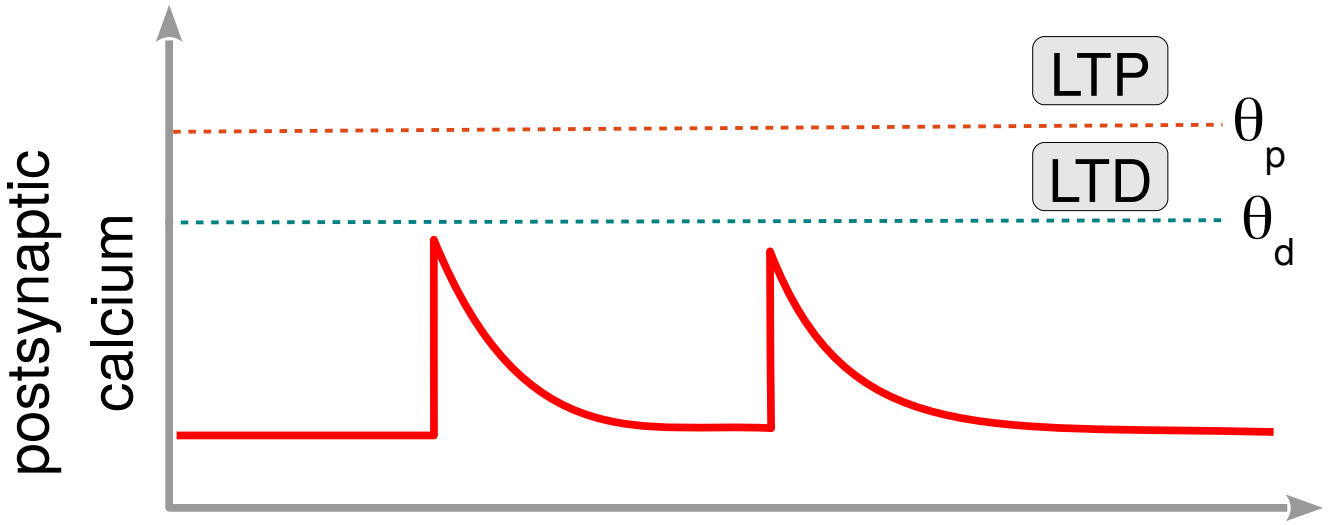
Calcium control hypothesis introduces LTD/LTP thresholds



Question : role of calcium in shaping STDP

I. **Can the dynamics of the postsynaptic calcium account for synaptic plasticity induced by spike-pairs ?**

II. **To which extent can the STDP phenomenology be explained by calcium ?**



Calcium amplitudes determine shape of STDP curve

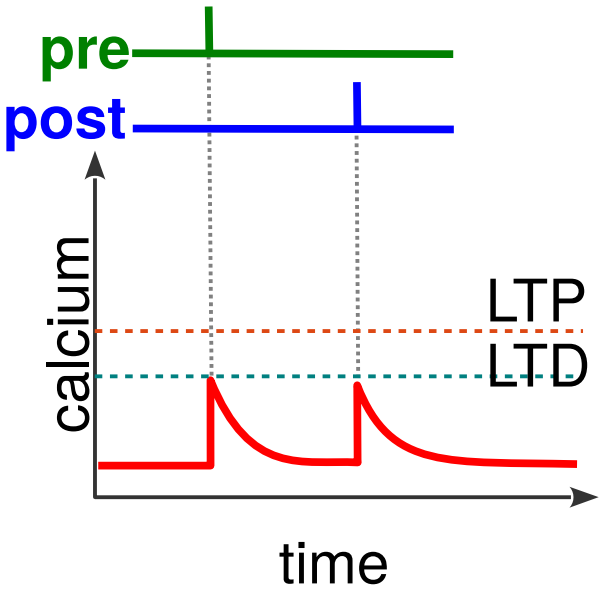
simulation I

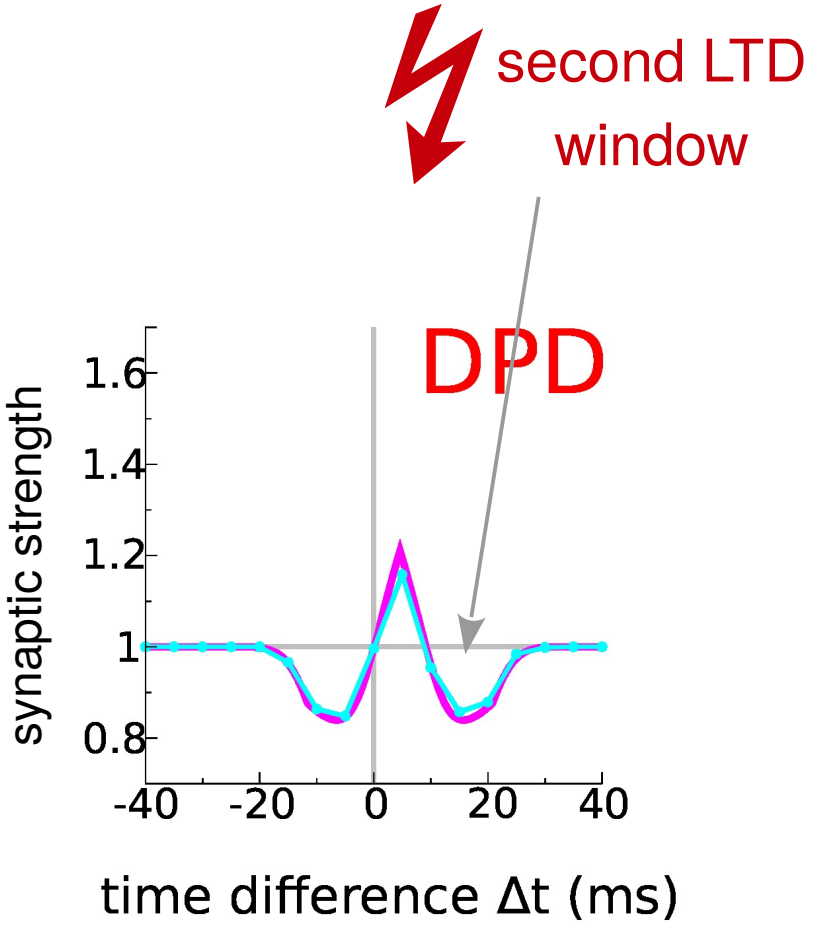
Calcium amplitudes determine shape of STDP curve

[Shouval *et al.*, 2002]

$C_{pre} < \theta_d$

$C_{post} < \theta_d$





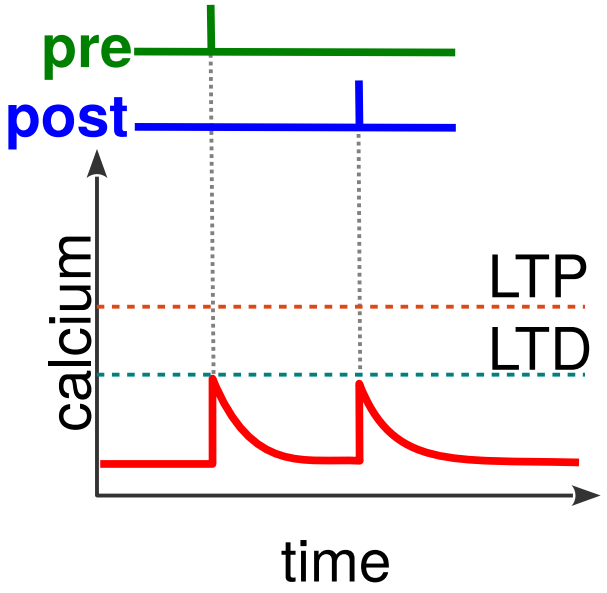
Calcium amplitudes determine shape of STDP curve

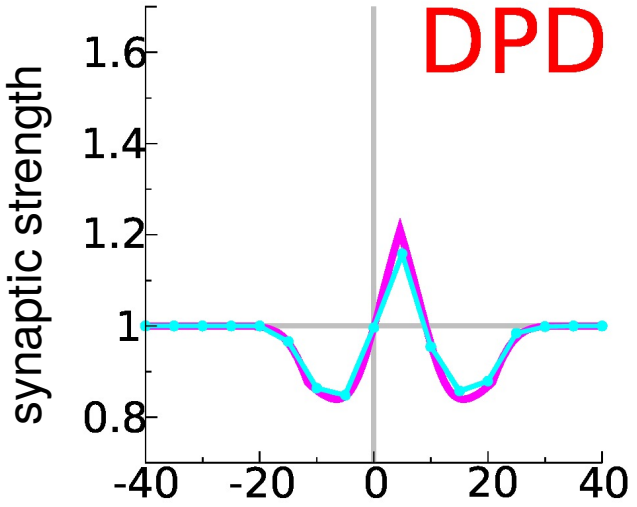
simulation II

Calcium amplitudes determine shape of STDP curve

$C_{pre} < \theta_d$

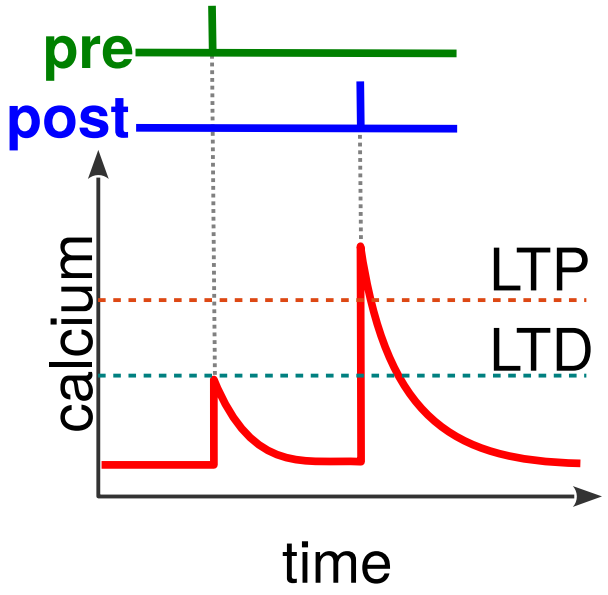
$C_{post} < \theta_d$

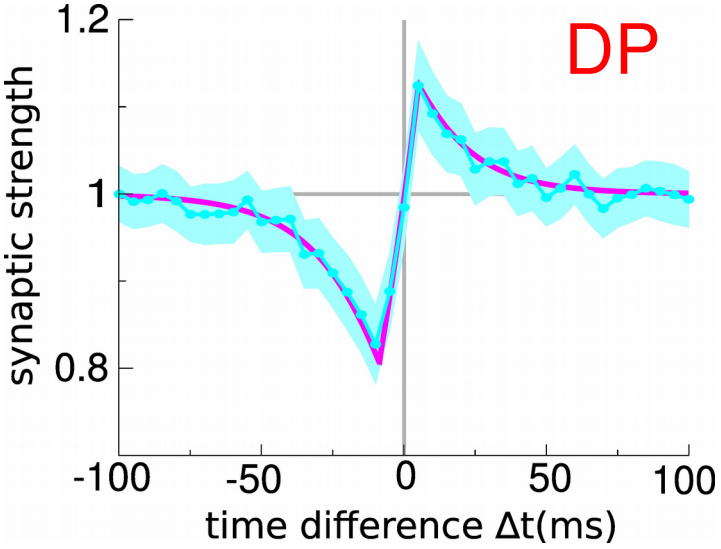




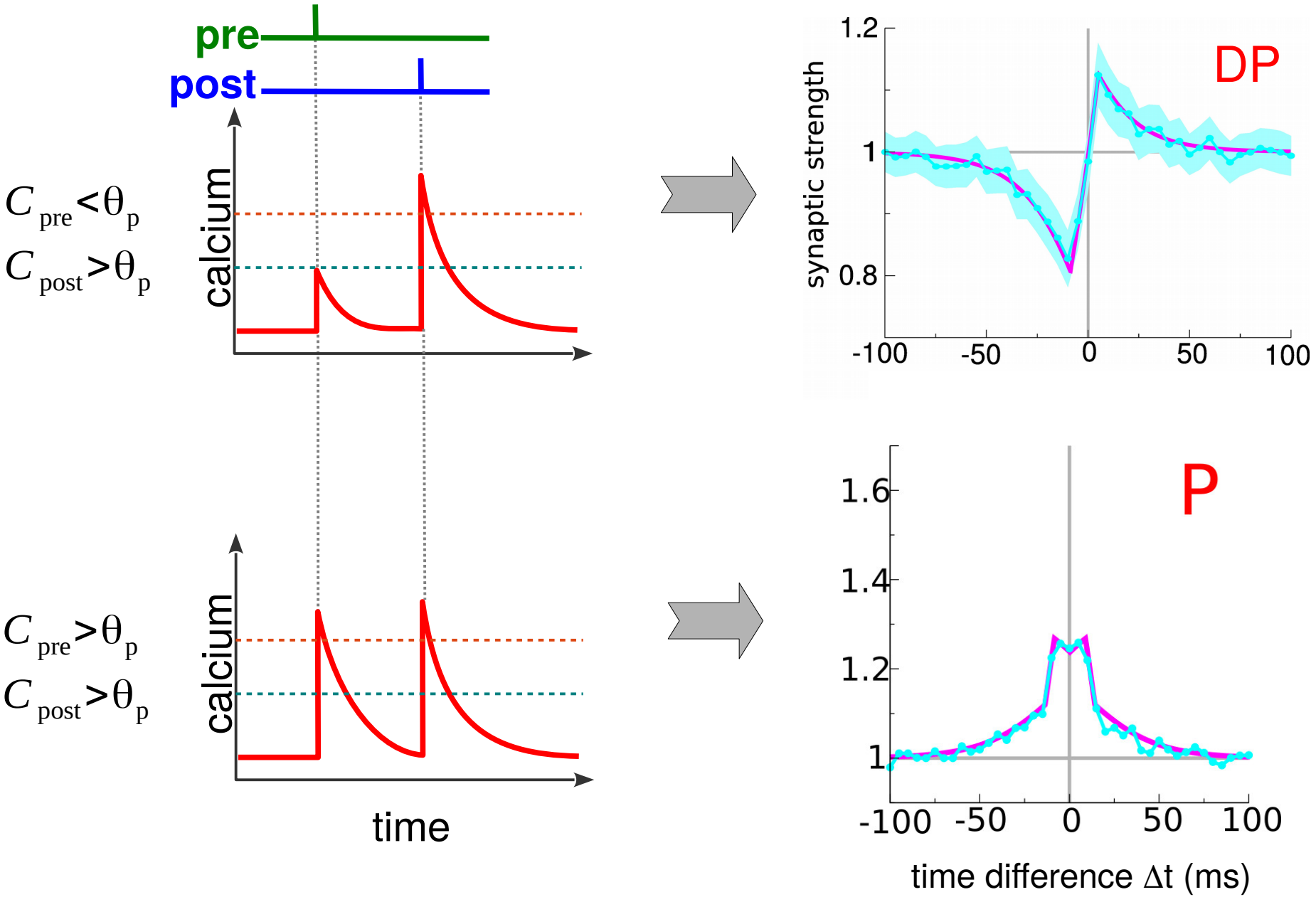
$C_{pre} < \theta_p$

$C_{post} > \theta_p$

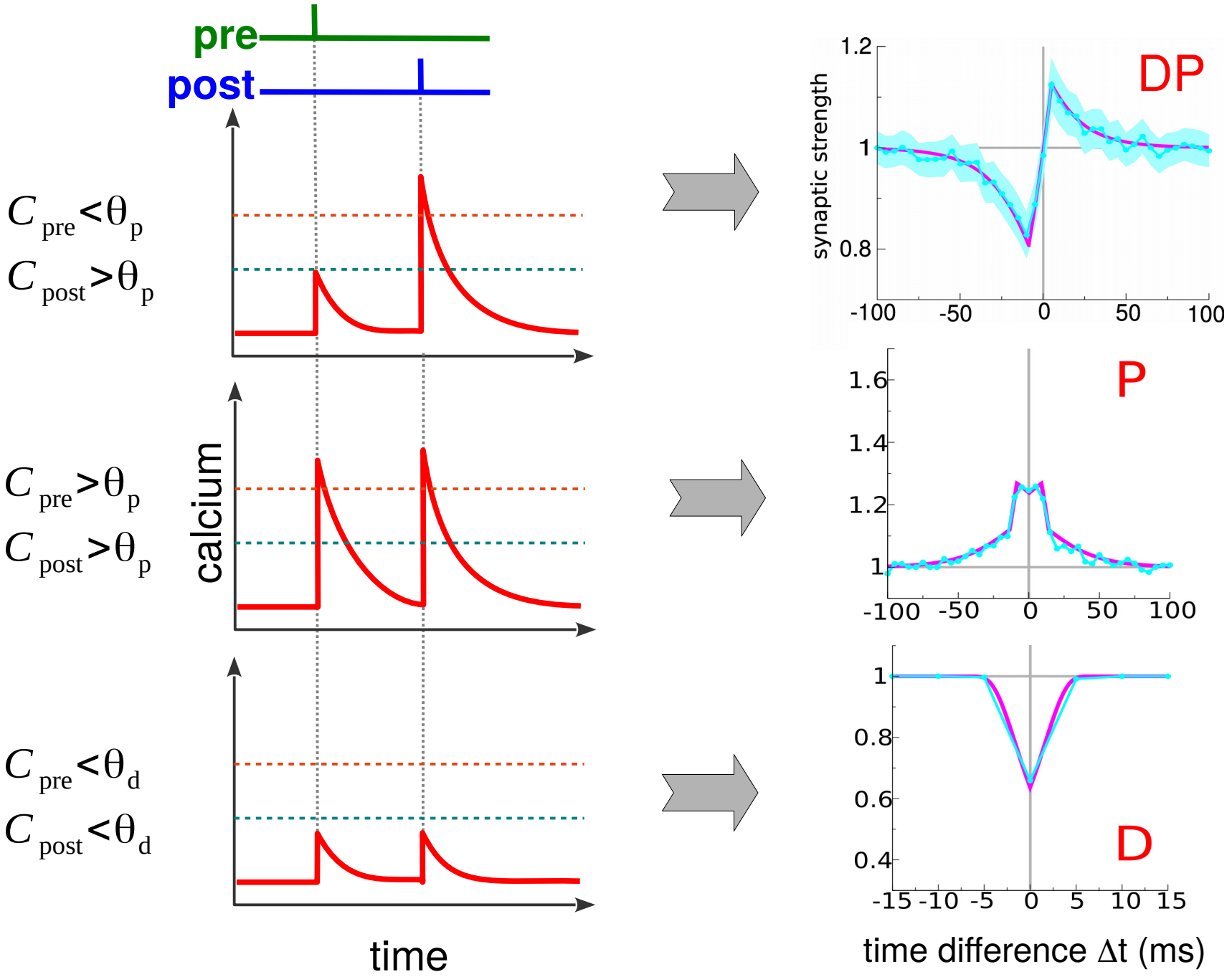




Calcium amplitudes determine shape of STDP curve

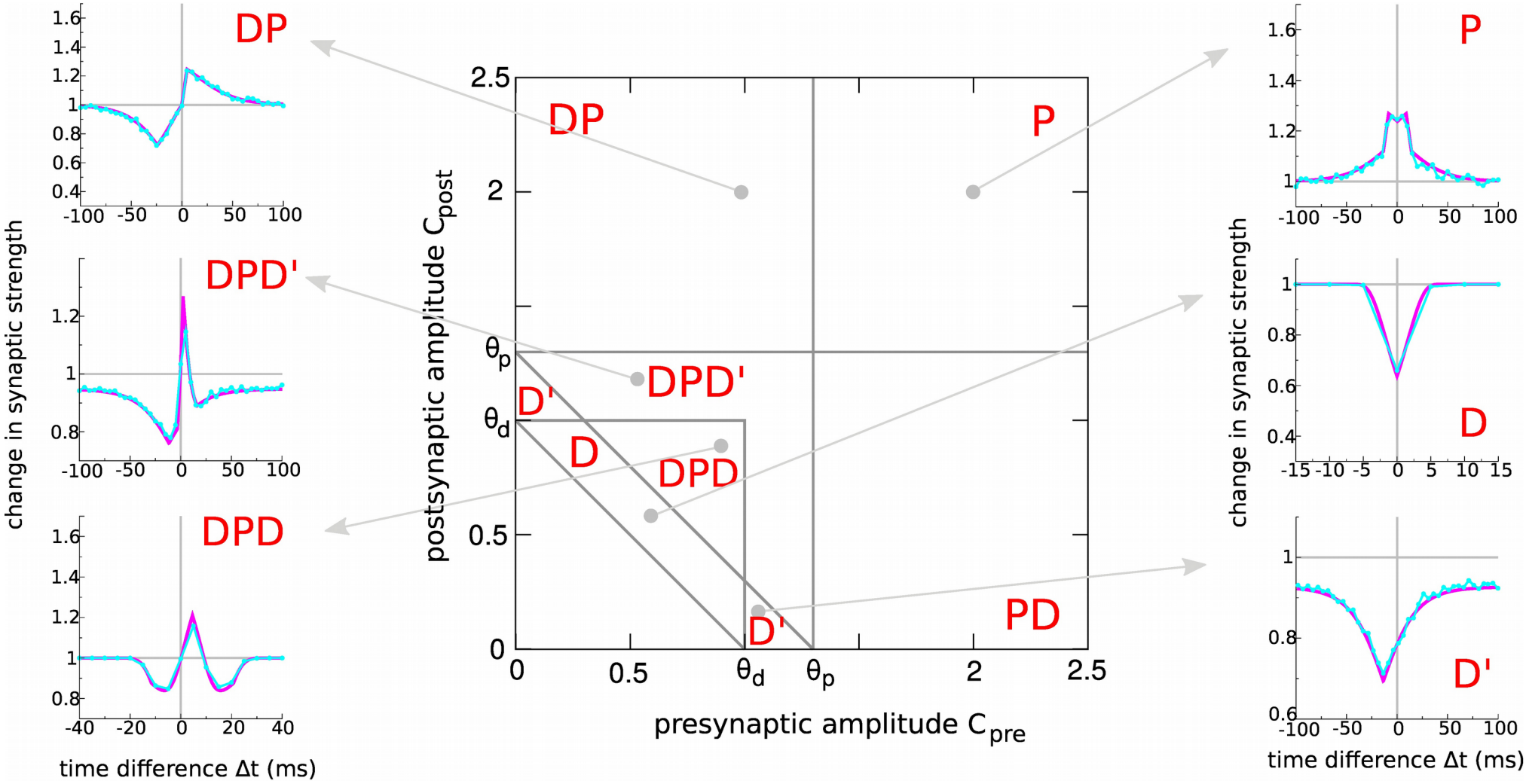


Calcium amplitudes determine shape of STDP curve



Diversity of STDP curves : spike-pair stimulation

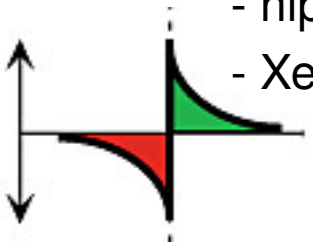
D ... depression , P ... potentiation



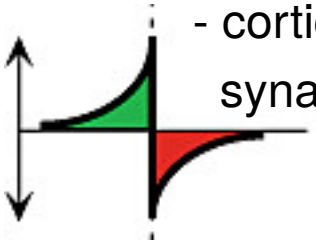
[Graupner & Brunel, *PNAS* 2012]

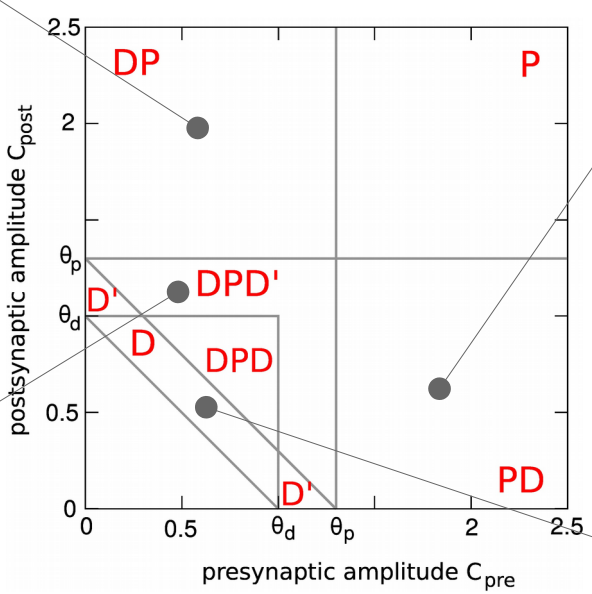
Diversity of STDP curves : experimental results

- neocortex-layer V
- hippocampus
- Xenopus tectum



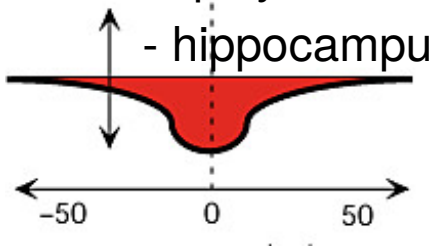
- ELL of electric fish
- corticostriatal synapse





- GABA-ergic neurons in hippocampal cultures

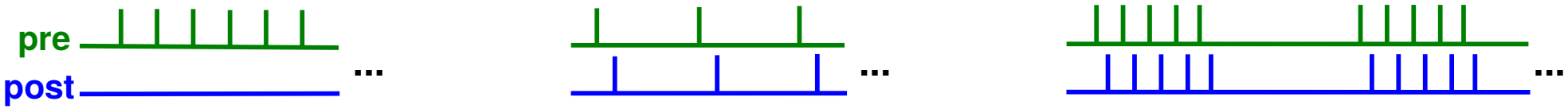
- neocortex-layer IV spiny stellates
- hippocampus



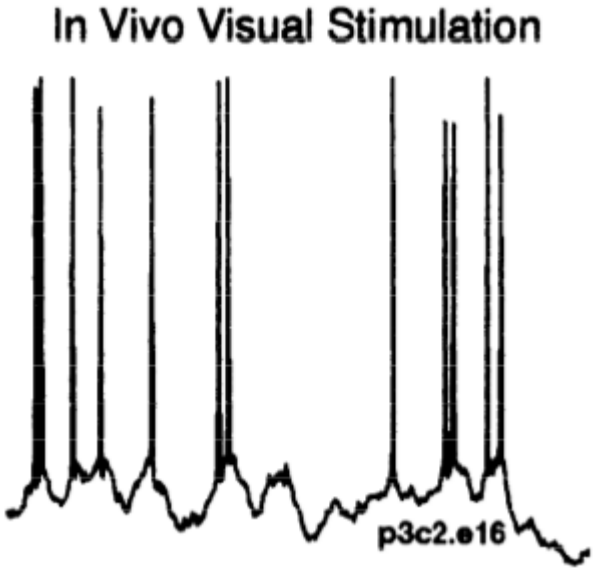
Outline

Firing patterns : Realistic firing is highly irregular

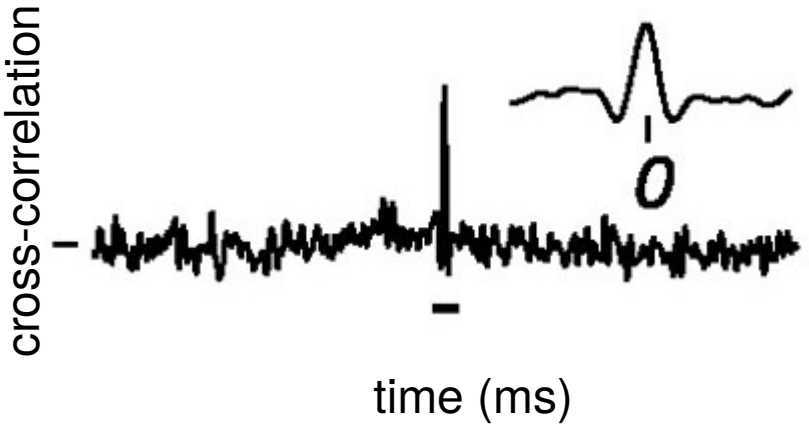
- stimulation protocols used to induce plasticity



- *in vivo* firing patterns

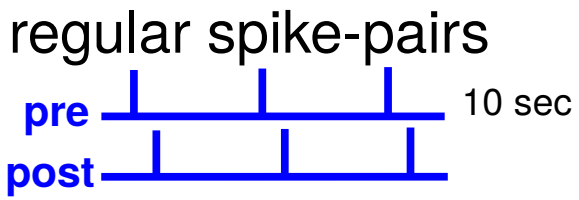


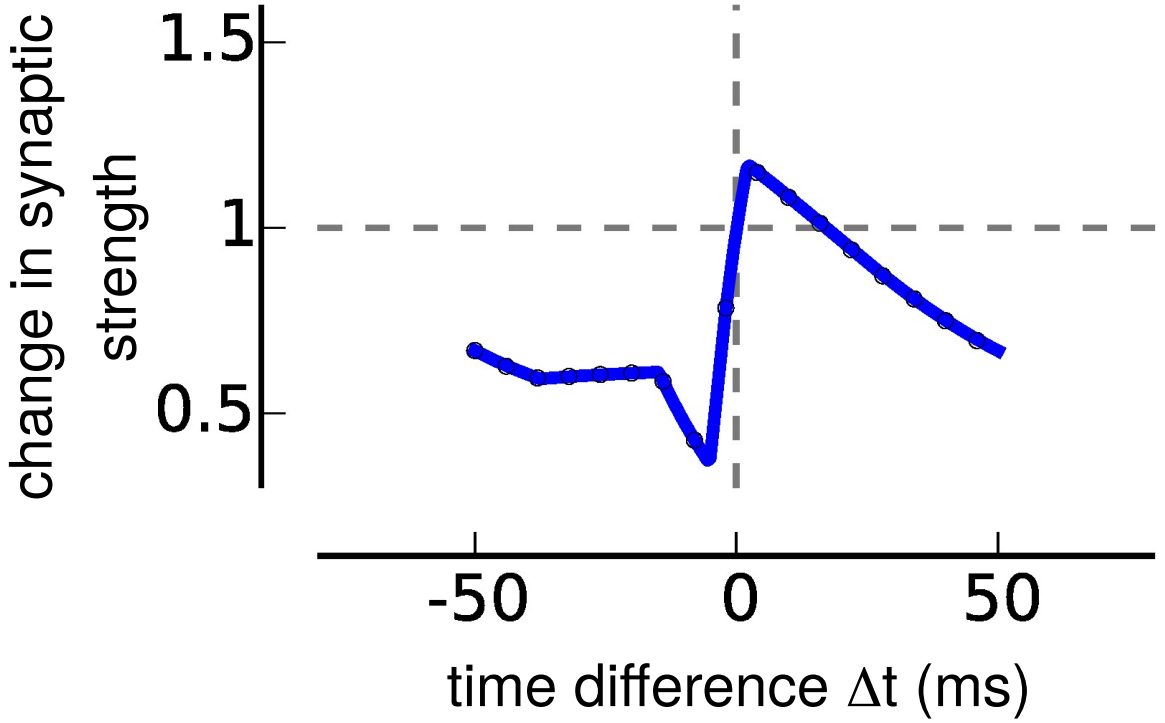
[Holt *et al.,* 1996]



[Kohn and Smith, 2005]

Regular vs. irregular spike-pairs

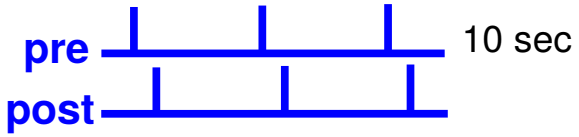




$\nu_{pre} = \nu_{post} = 10\ \mathrm{Hz}$

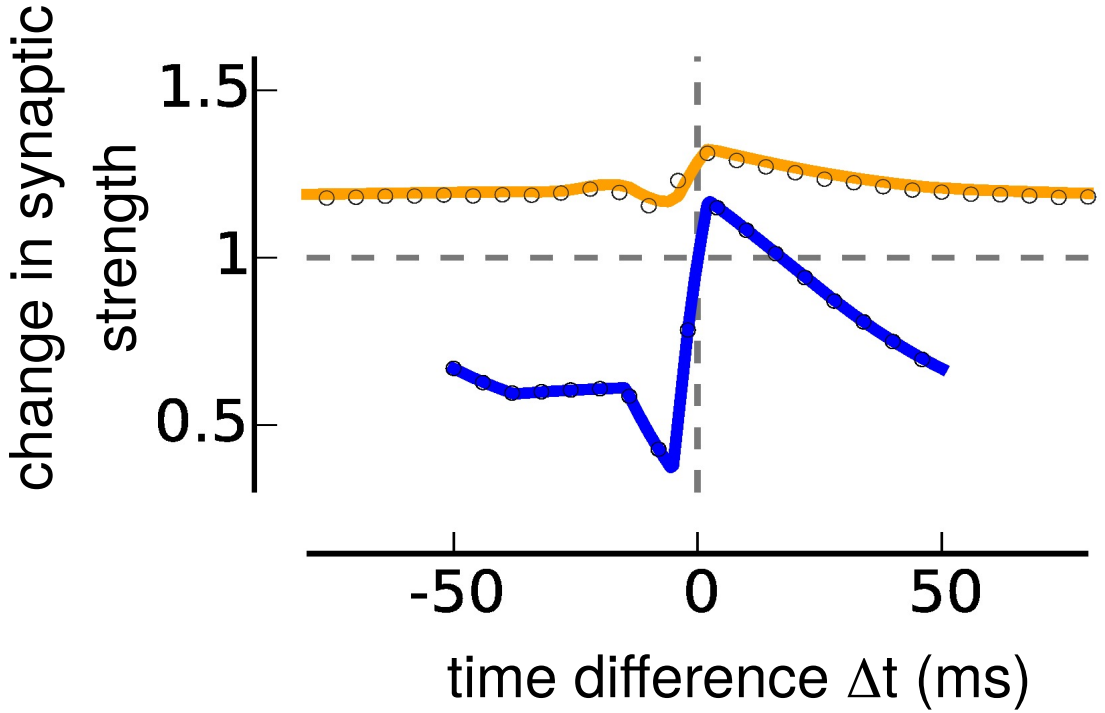
Regular vs. irregular spike-pairs

regular spike-pairs

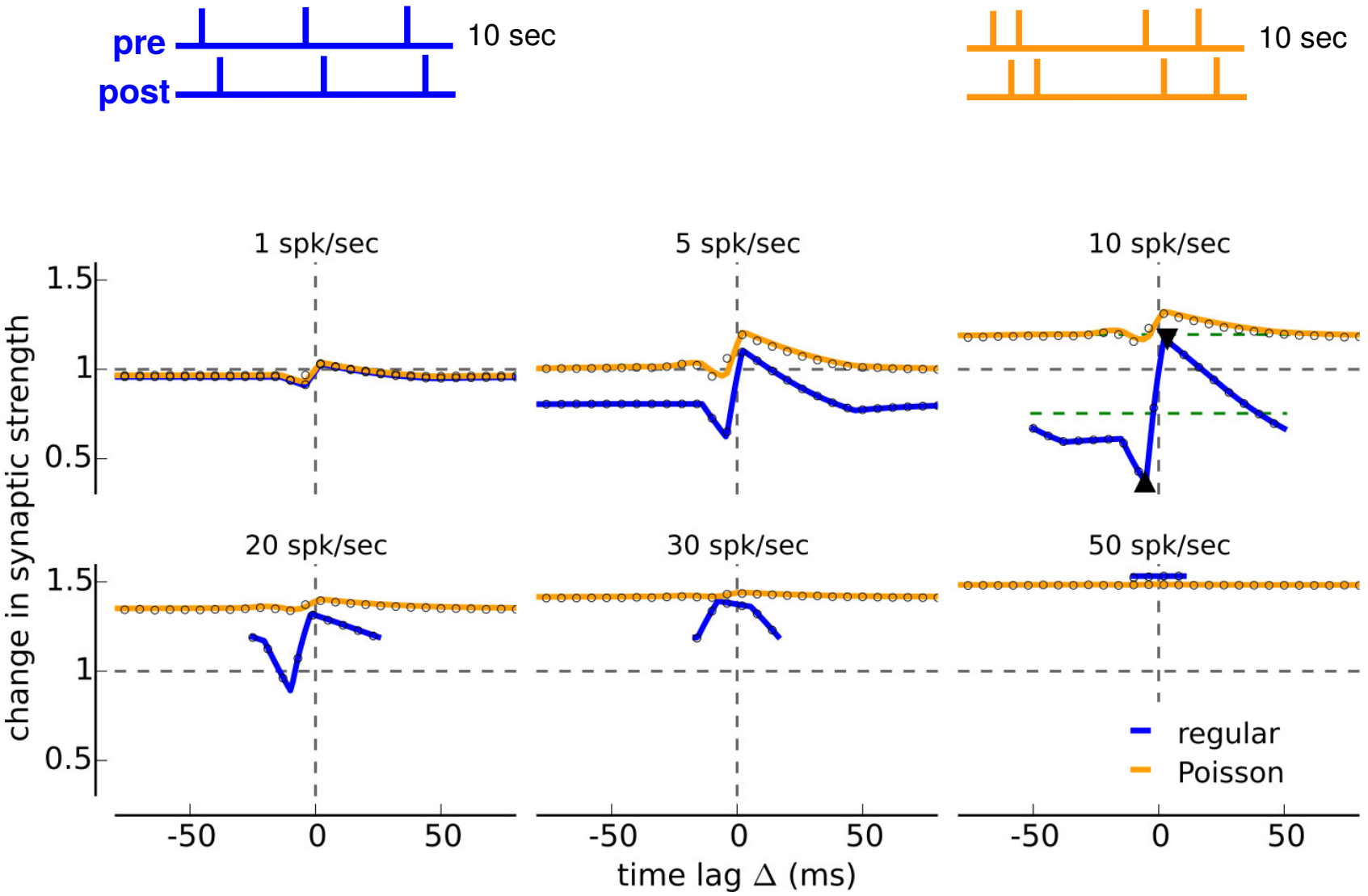


Poisson distributed spike-pairs

$\nu_{pre} = \nu_{post} = 10\,\text{spk/sec}$



Irregular spike-pairs flatten STDP curve

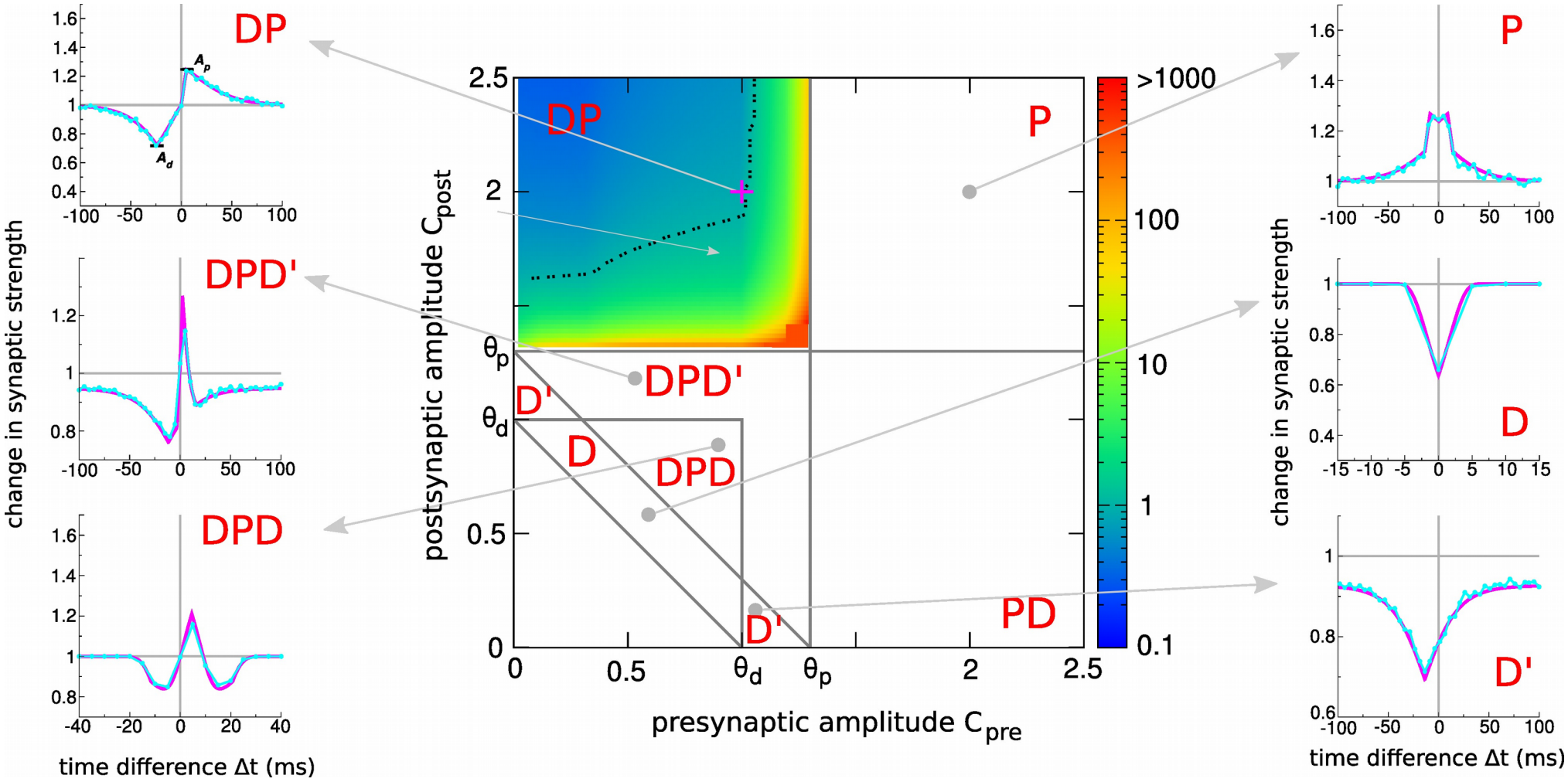


[Graupner, Wallisch & Ostojic. *J Neurosci* in press]

Conclusions

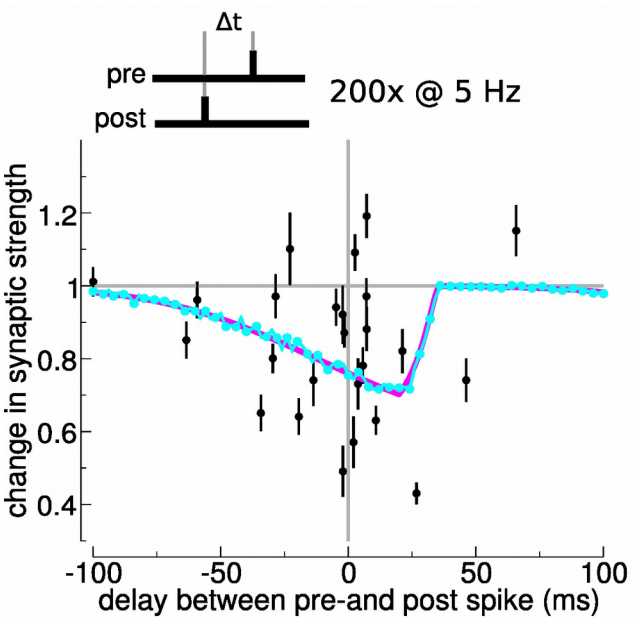
- STDP : temporally asymmetric form of synaptic plasticity induced by tight temporal correlations between the spikes of pre- and postsynaptic neurons
- induction: coincident pre- and postsynaptic activity lead to calcium influx through NMDA receptors, triggering intracellular signaling cascades
- biophysical model resolve various aspects of the synaptic machinery involved in plasticity induction, most commonly the postsynaptic calcium dynamics
- the role of STDP for learning in the living animal remains elusive

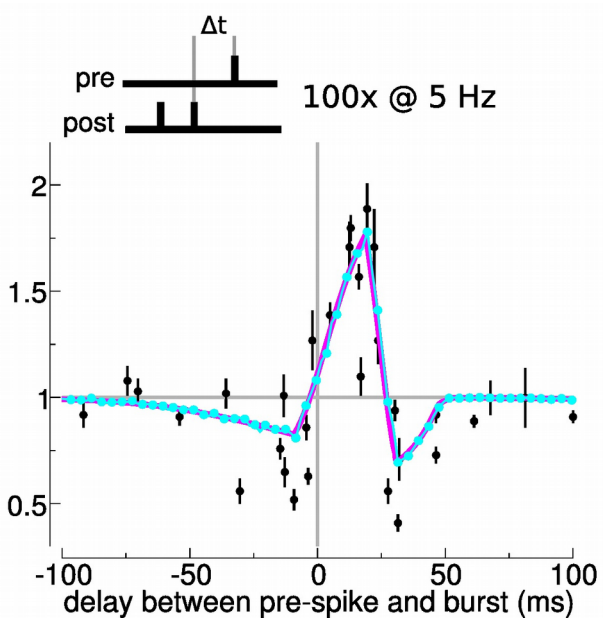
Diversity of STDP curves : spike-pair stimulation

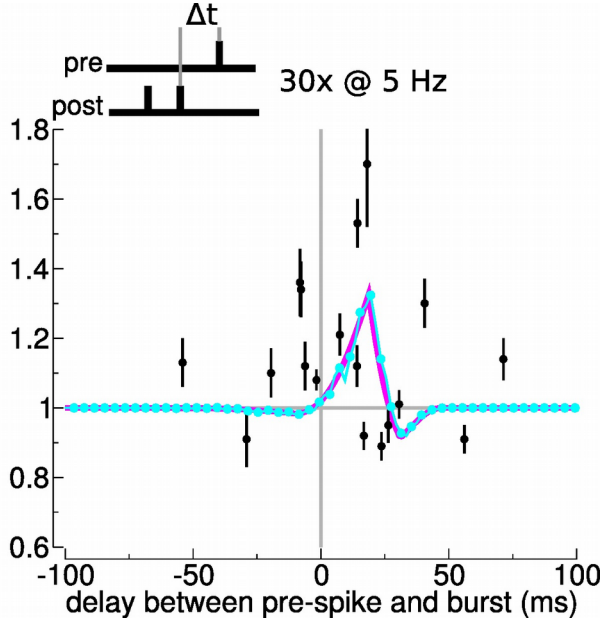


[Graupner & Brunel, 2012]

Malleability of hippocampal STDP explained by Ca^{2+}

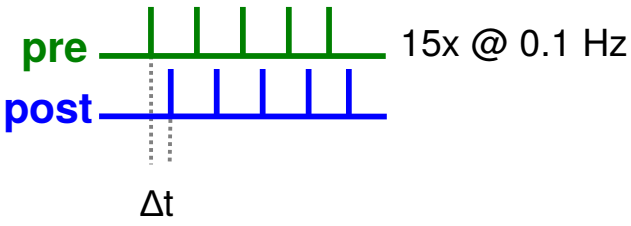


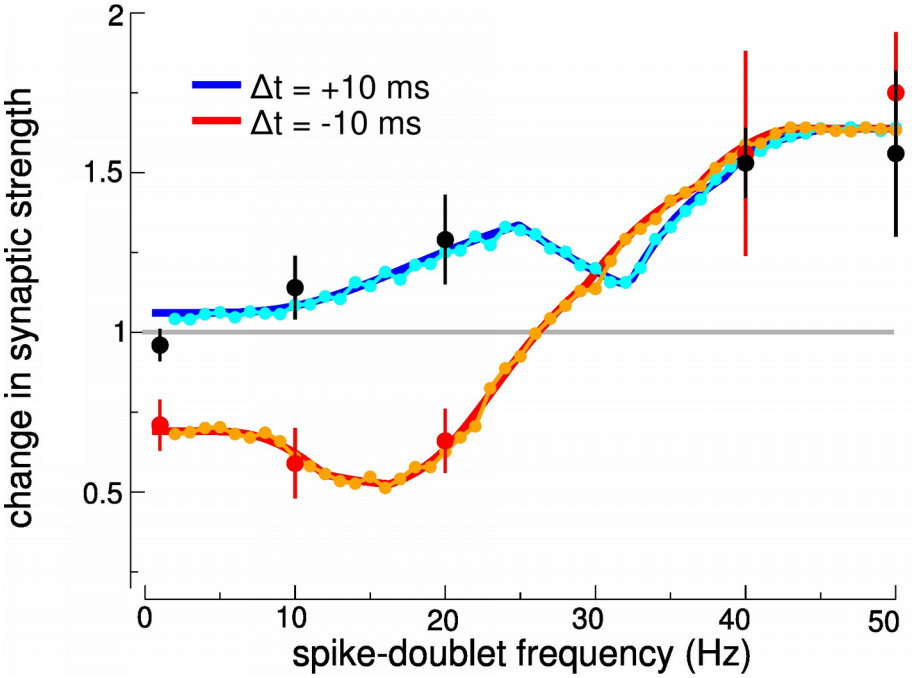


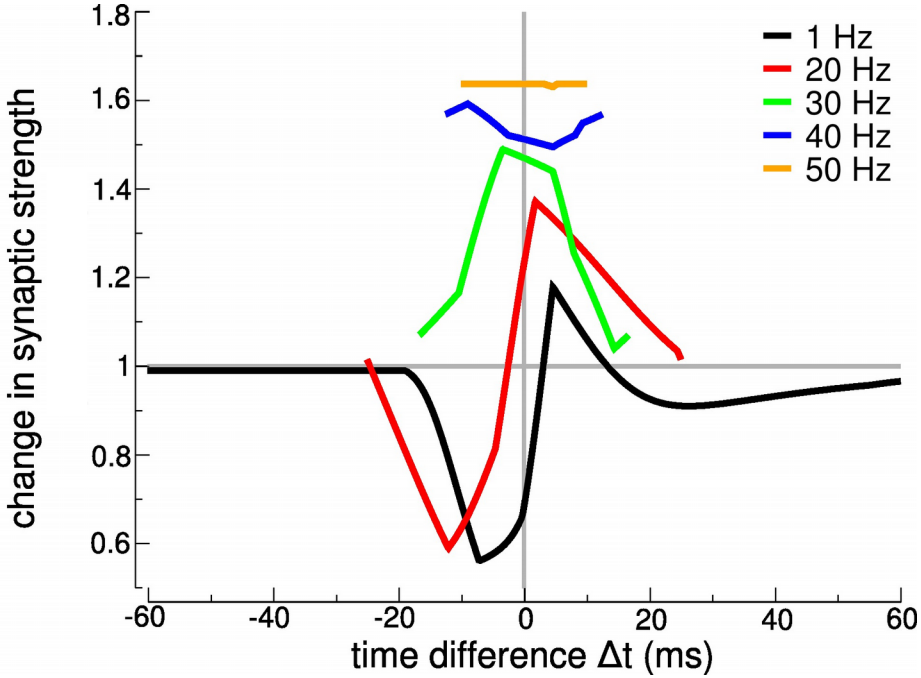


[Wittenberg & Wang, 2006]

Firing rate dependence in cortical slices

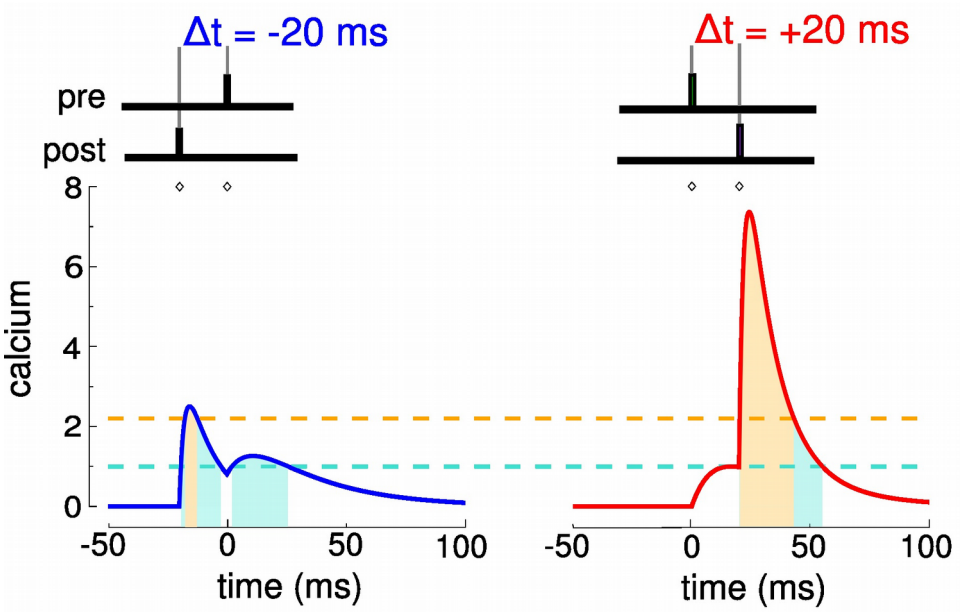


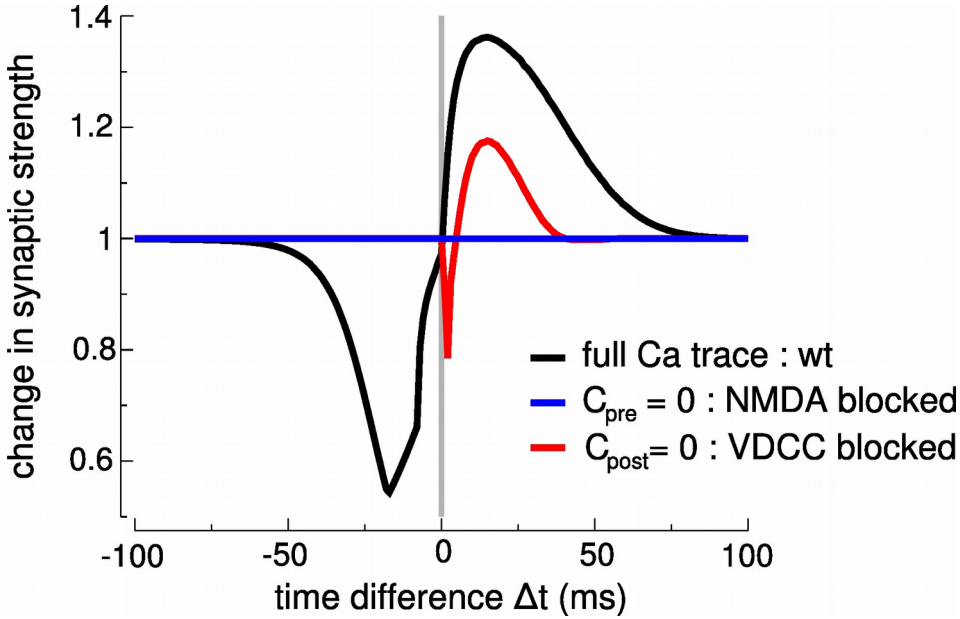




[Sjöström *et al*., 2001]

Pharmacological manipulations explained by Ca^{2+}

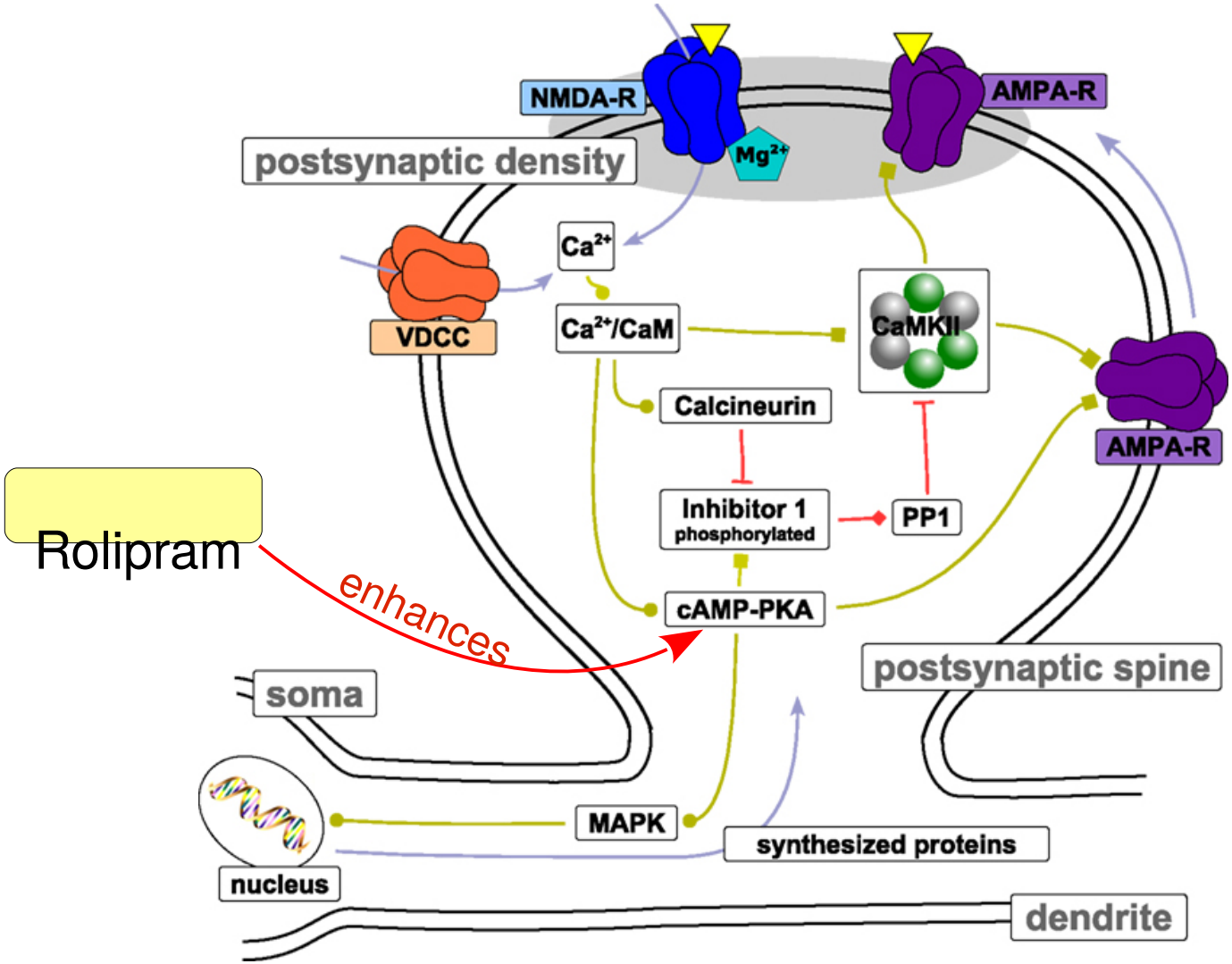




[Bi & Poo, 1998; Nevian & Sakmann, 2006]

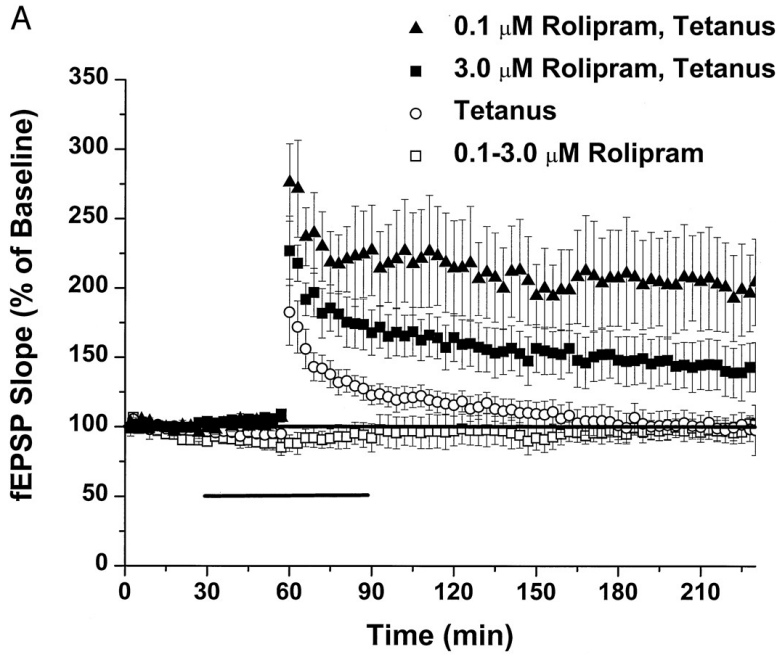
- nonlinear, finite rise time calcium transients necessary to reproduced pharmacological block experiments

Study the effect of nootropic drugs (memory enhancer)



Rolipram … selective phosphodiesterase-4 inhibitor

Study the effect of nootropic drugs

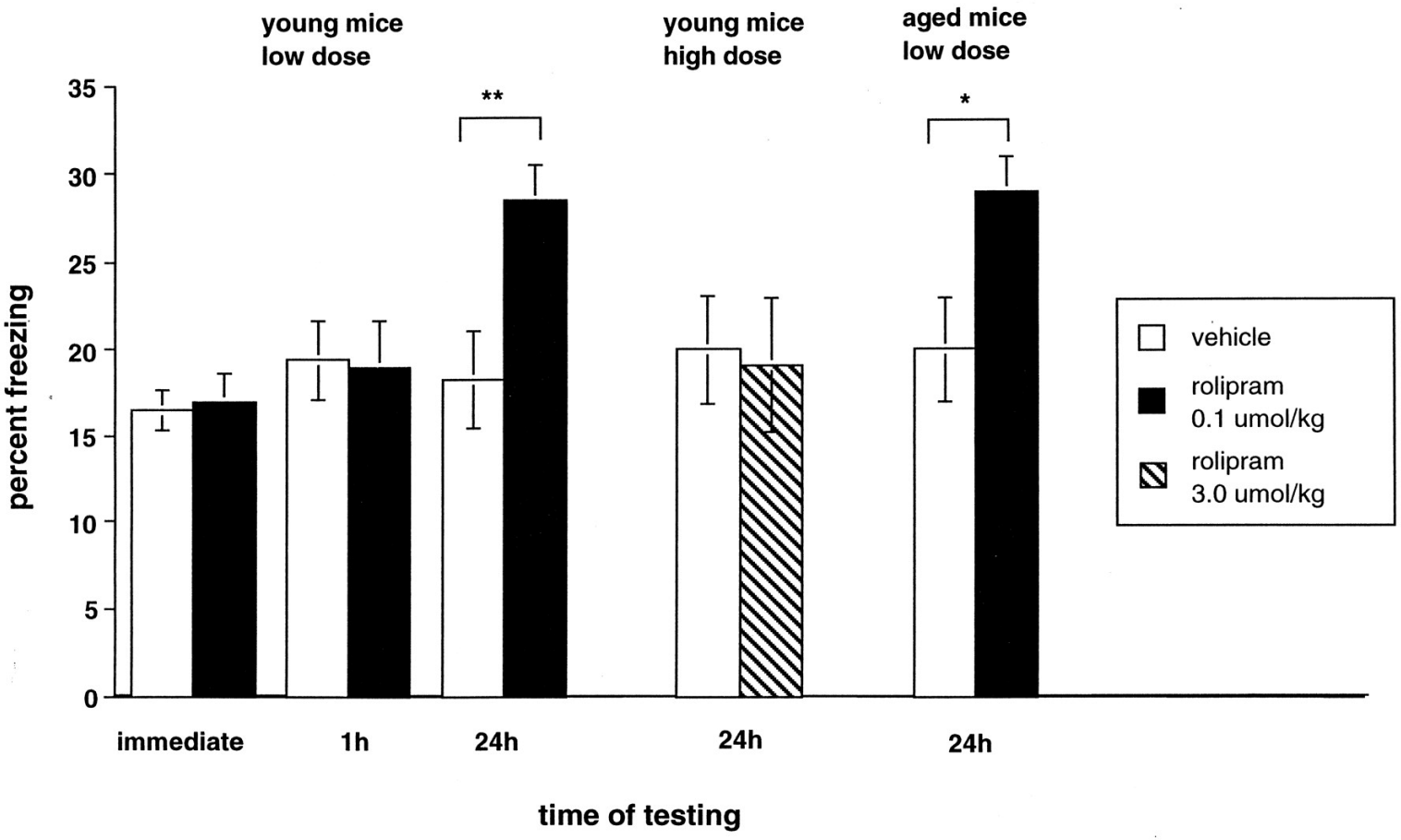


- boosting of cAMP *during* stimulation increases LTP

[Barath *et al.*, 1998]

Study the outcome of nootropic drugs

- Rolipram enhances memory



[Barath *et al.*, 1998]