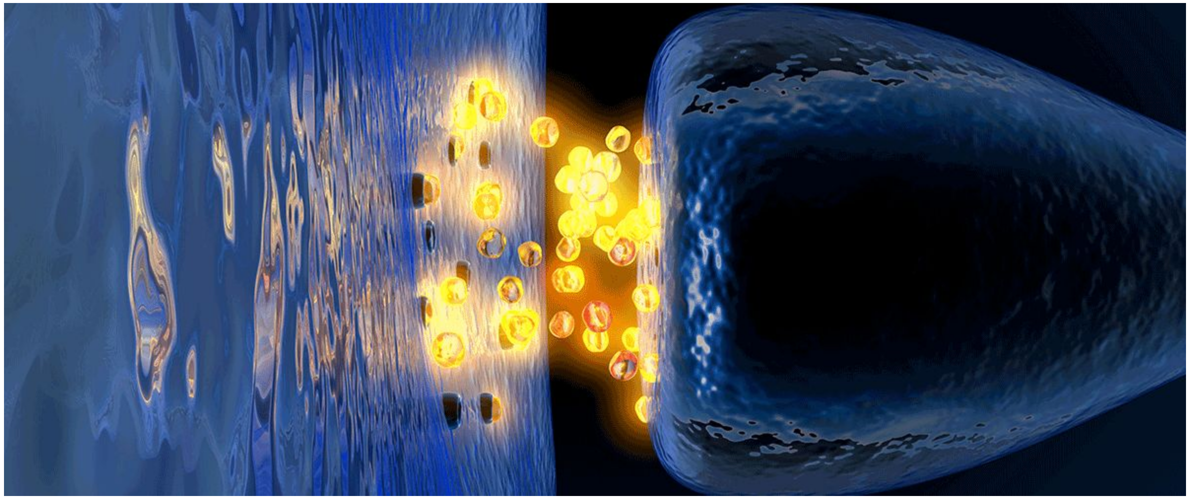
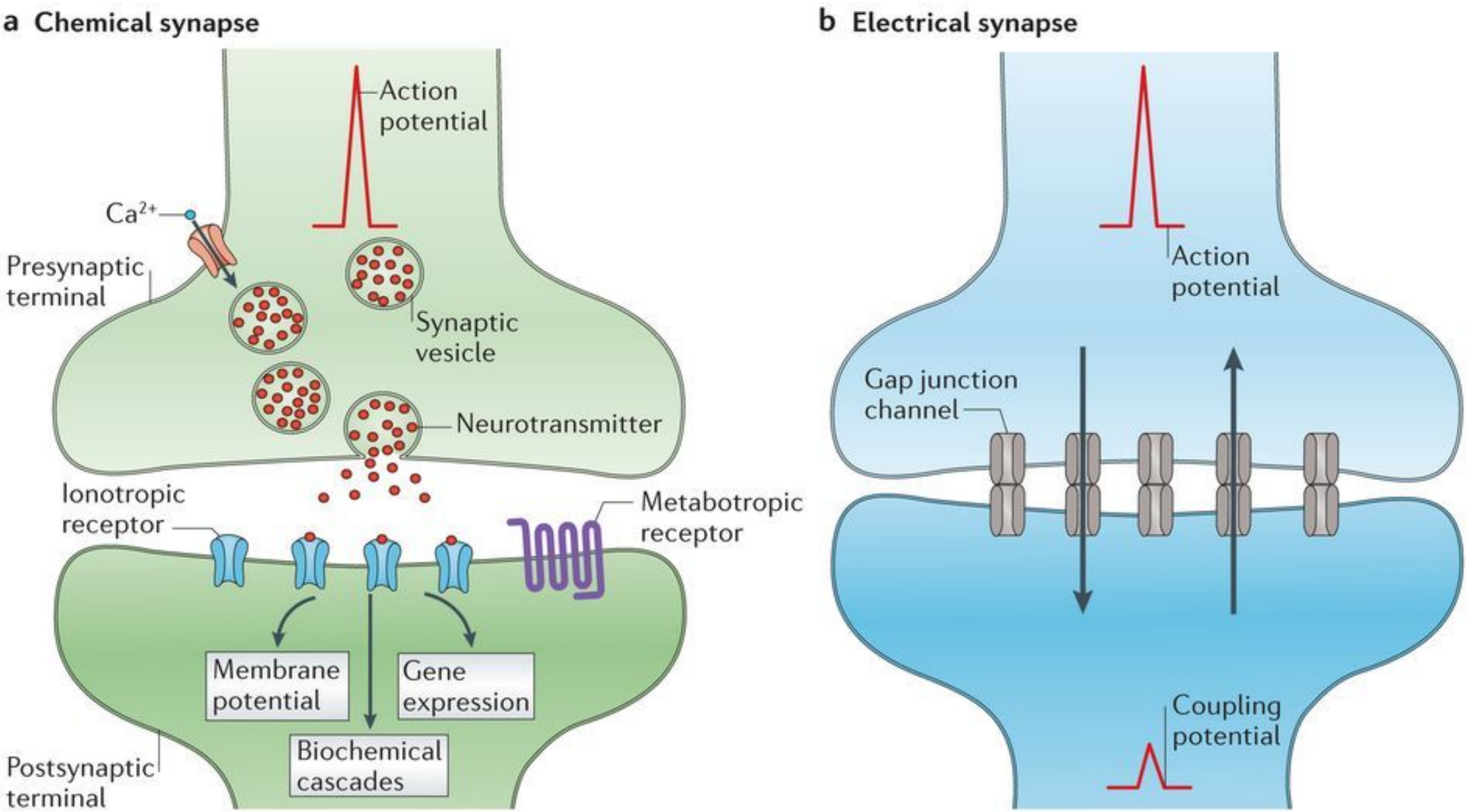
LASCON 2026

Tutorial: Modeling Synapses and Networks



Arnd Roth and Valery Bragin

Types of Synapses

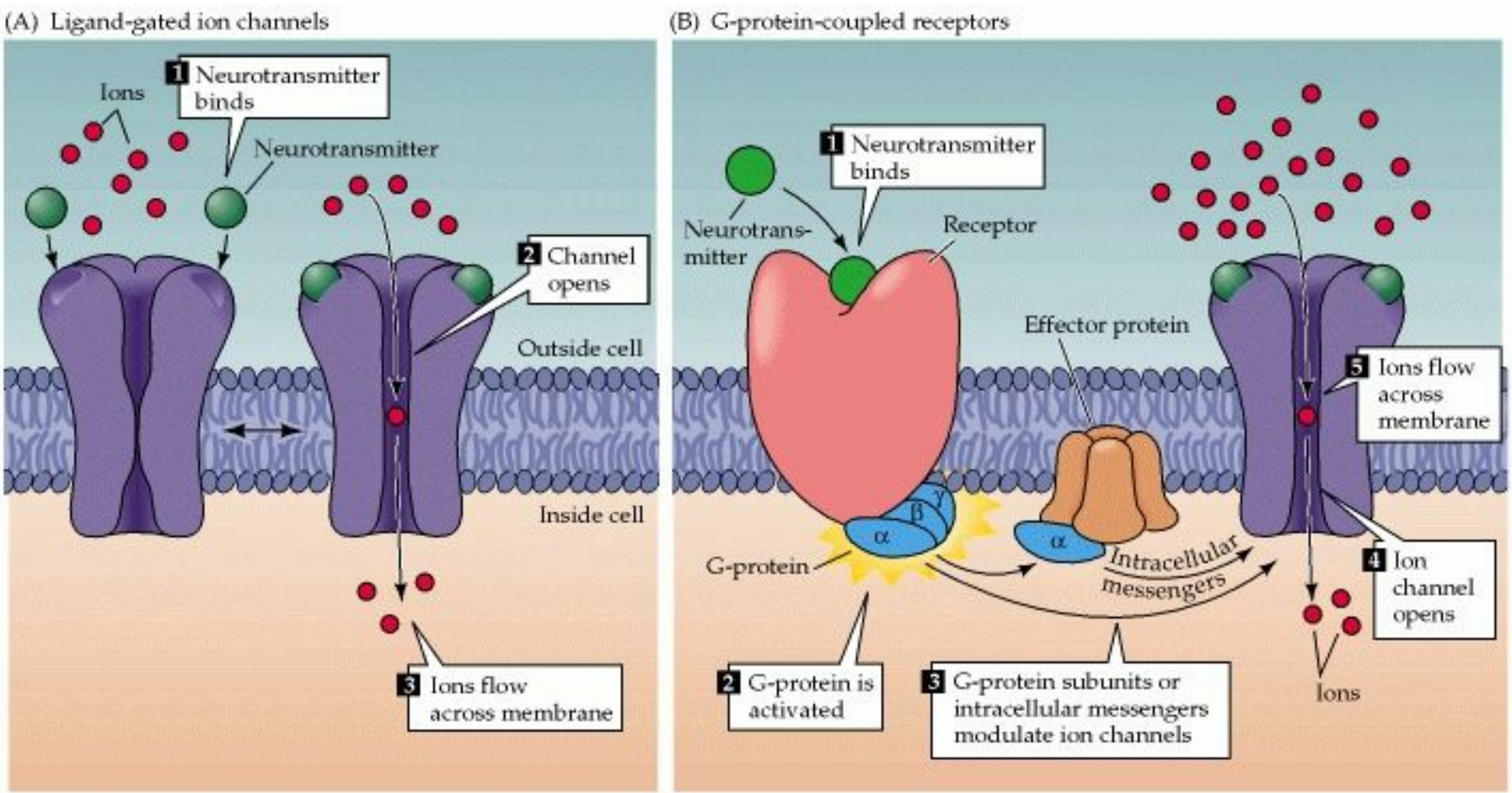


Nature Reviews | Neuroscience

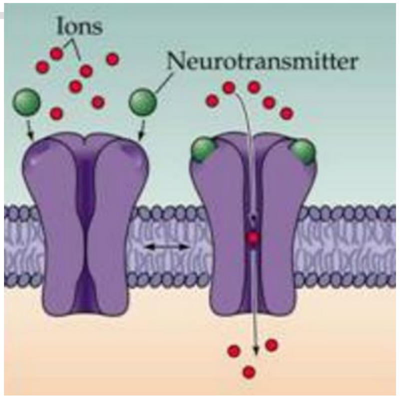
Types of Chemical Synapses

Ionotropic

Metabotropic



NEURON Synapse



- NEURON synapses correspond to the postsynaptic receptor
- Requires input event (presynaptic spike) to get activated
- If input event, modifies channel conductance (g) based on *weight:*
  $g = g + weight$
- Synapse generates current based on equilibrium potential (e):
  $i_{syn} = g \cdot (v - e)$
- Synaptic current generates a post-synaptic potential:
  - if $e > V_{rest}$ $\rightarrow$ excitatory synapse (EPSP)
  - if $e < V_{rest}$ $\rightarrow$ inhibitory synapse (IPSP)

NEURON Synapses

- ExpSyn
  - eg. ***syn = h.ExpSyn(dend(0.5))***
  - Connected to presynaptic cell via NetCon (requires event=spike to activate)
  - Parameters:
    - *e*: synapse equilibrium potential (mV). , eg. *syn.e = 0 or syn.e = -80*
    - *tau*: time constant of exponential decay, eg. *syn.tau = 1*

  https://github.com/neuronsimulator/nrn/blob/master/src/nrnoc/expsyn.mod

```
INITIAL {
    g=0
}

BREAKPOINT {
    SOLVE state METHOD cnexp
    i = g*(v - e)
}

DERIVATIVE state {
    g' = -g/tau
}

NET_RECEIVE(weight (uS)) {
    g = g + weight
}
```

- Exp2Syn
  - features tau_rise and tau_decay

- More complex synapse models that use eg. Ca^{2+} concentrations

Postsynaptic potentials

- Binding of neurotransmitters to the post synaptic membrane can either be:
- **Excitatory (produces EPSP)**
  - Depolarizes membrane potential
- **Inhibitory (produces IPSP)**
  - Hyperpolarizes membrane potential

Both types of PSPs are *graded potentials* (as opposed to action potentials)

NEURON Netcons

Syntax:
con = h.NetCon(source voltage, target, sec = source section)

eg. *con = h.NetCon(soma(0.5)._ref_v,* ***syn****, sec=soma)*
con.weight = 0.1
con.delay = 1
con.threshold = 10

Description:
Network Connection object that defines a synaptic connection between a source and target.
When the source variable passes *threshold,* the target will receive an event at time t+*delay* along with weight information.

Source:
Normally a reference to a *membrane potential (v)* which is watched during simulation for v > threshold.

Target:
Must be a POINT_PROCESS (eg. synapse)

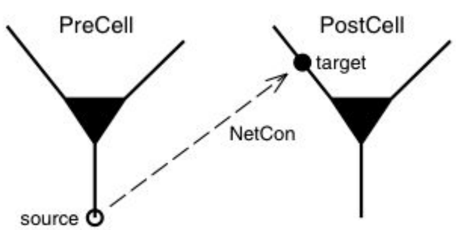


Figure 2.1. A NetCon attached to the presynaptic neuron PreCell detects spikes at the location labeled source, and delivers events to the synapse target which is attached to the postsynaptic neuron PostCell.

Netcons

Parameters:

- *delay*: time between action potential reaching axon terminal and
- *weight:* change of conductance in synaptic ionic channels (open/close channels)
  ~= amount of neurotransmitter binding to receptors * num receptors
  ~= amount of Ca^{2+} channels, concentration of Ca^{2+} ions

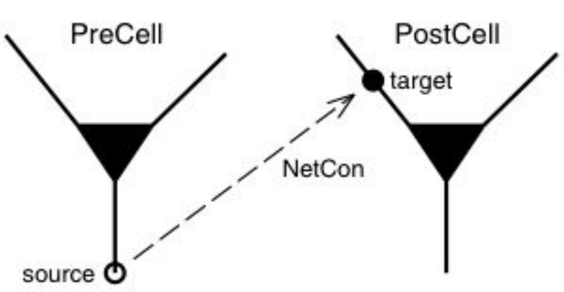
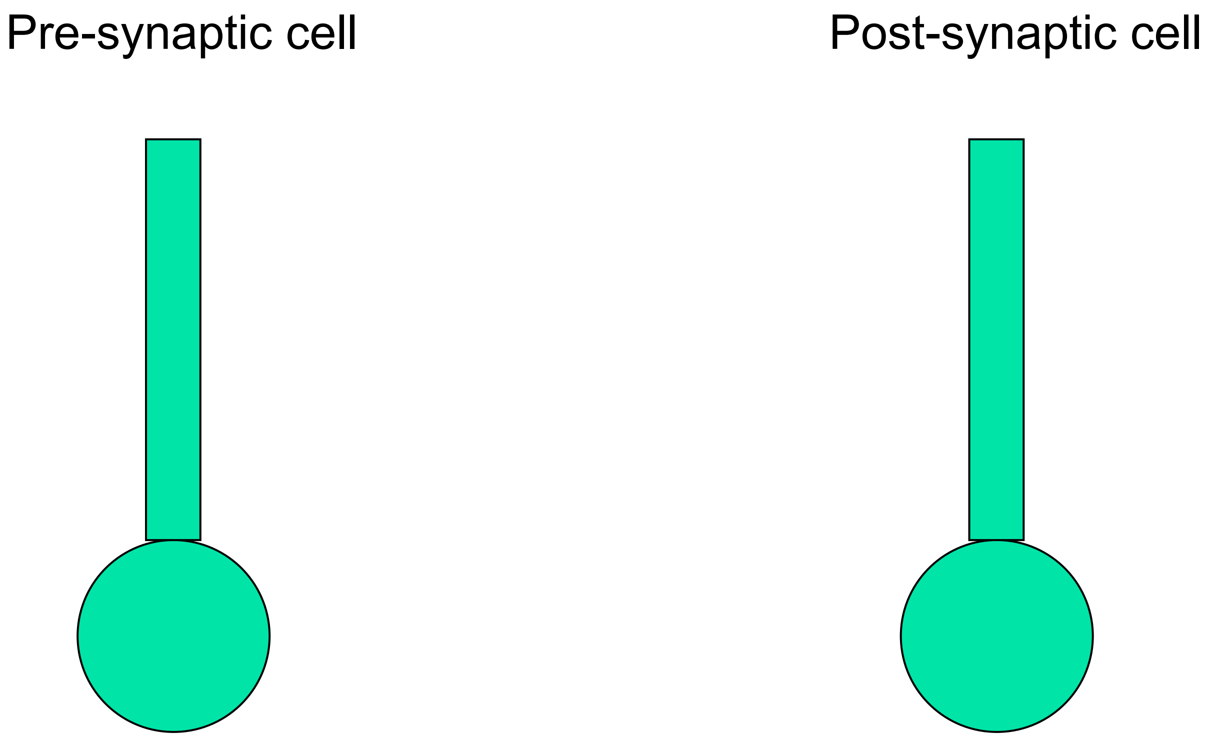


Figure 2.1. A NetCon attached to the presynaptic neuron PreCell detects spikes at the location labeled source, and delivers events to the synapse target which is attached to the postsynaptic neuron PostCell.

Synaptic connection model



Synaptic connection model

Pre-synaptic cell

Post-synaptic cell

NEURON Synapse
(Ionotropic receptor)

Params:

- *e*: equilibrium potential (mV)
- *tau*: time constant (ms)

Function:
Changes channel conductance (g) when event received (presyn spike).

Generates current that moves V towards e :

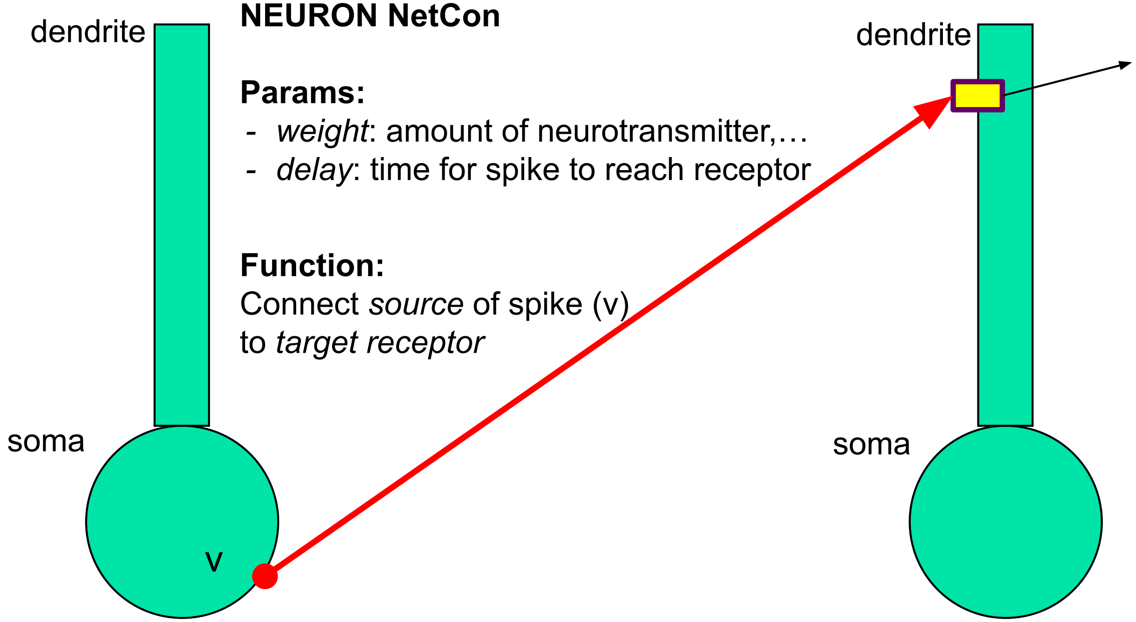
- if $e > V_{rest}$ → excitatory synapse (depolarizing)

- if $e < V_{rest}$ → inhibitory potential (hyperpolarizing)

Synaptic connection model

Pre-synaptic cell

Post-synaptic cell



NEURON NetCon

Params:
- *weight*: amount of neurotransmitter,…
- *delay*: time for spike to reach receptor

Function:
Connect *source* of spike (v)
to *target receptor*

NEURON Synapse
(Ionotropic receptor)

Params:
- *e*: equilibrium potential (mV)
- *tau*: time constant (ms)

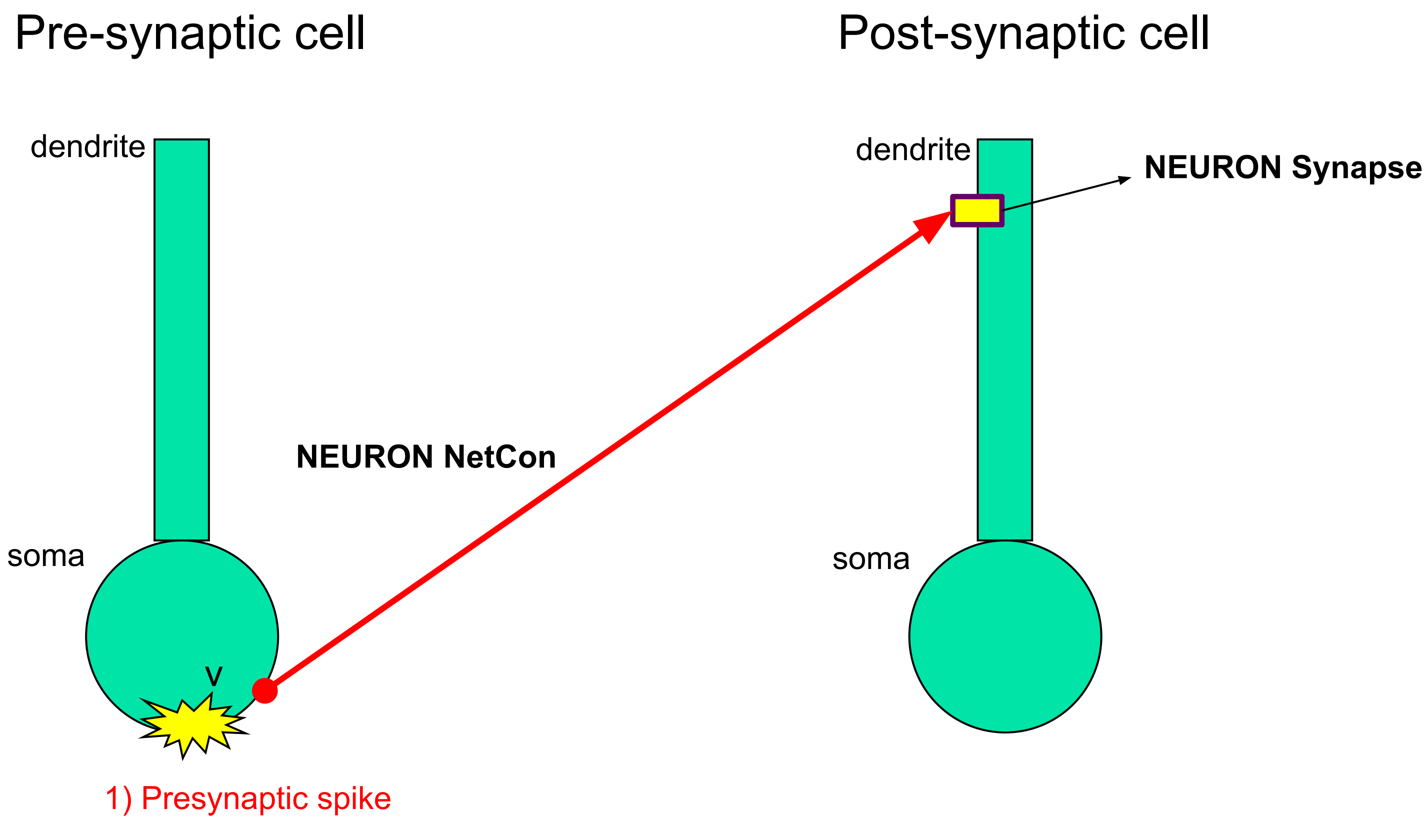
Function:
Changes channel conductance (*g*)
when event received (presyn spike).

Generates current that moves *V* towards *e* :

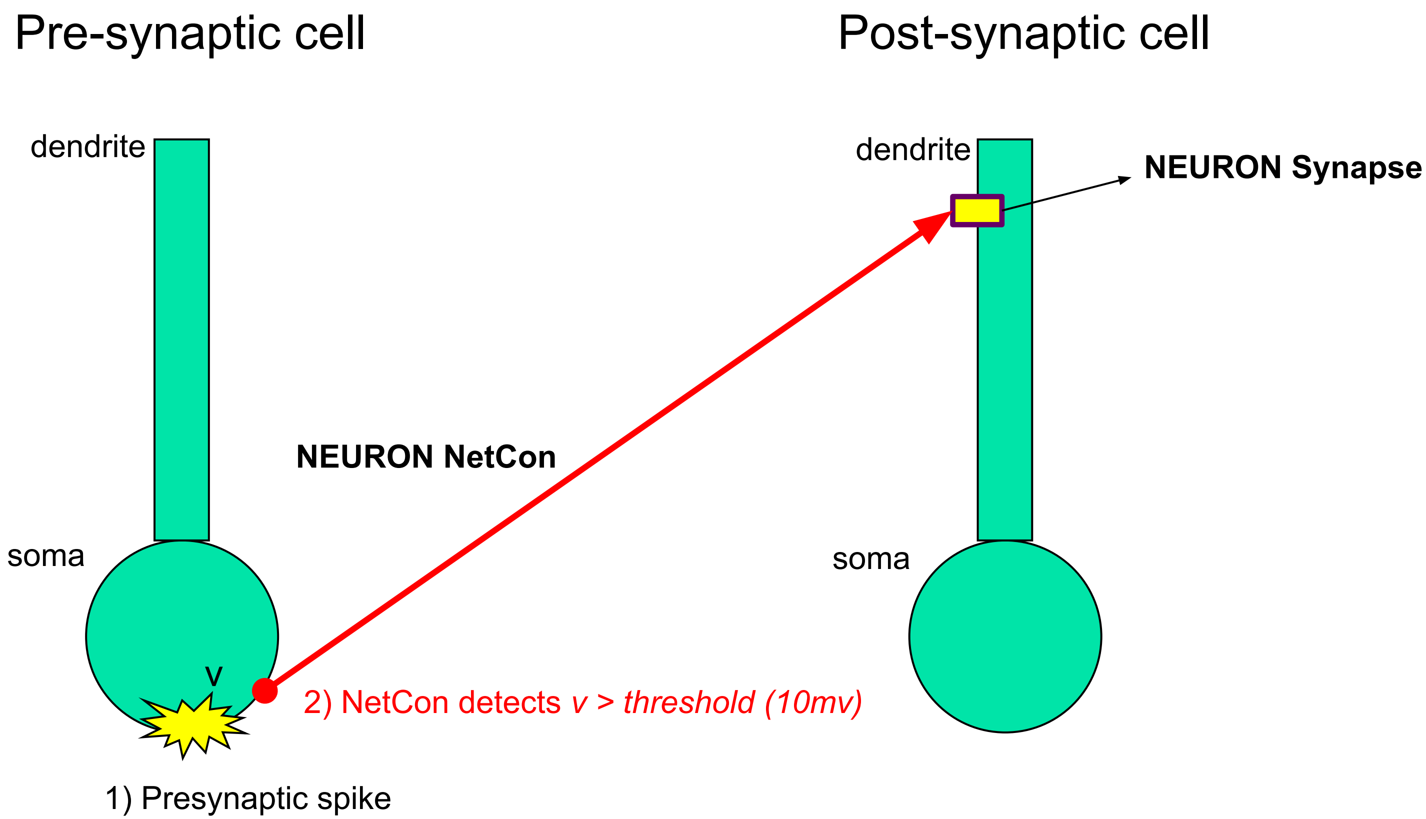
- if $e > V_{rest}$ → excitatory synapse (depolarizing)

- if $e < V_{rest}$ → inhibitory synapse (hyperpolarizing)

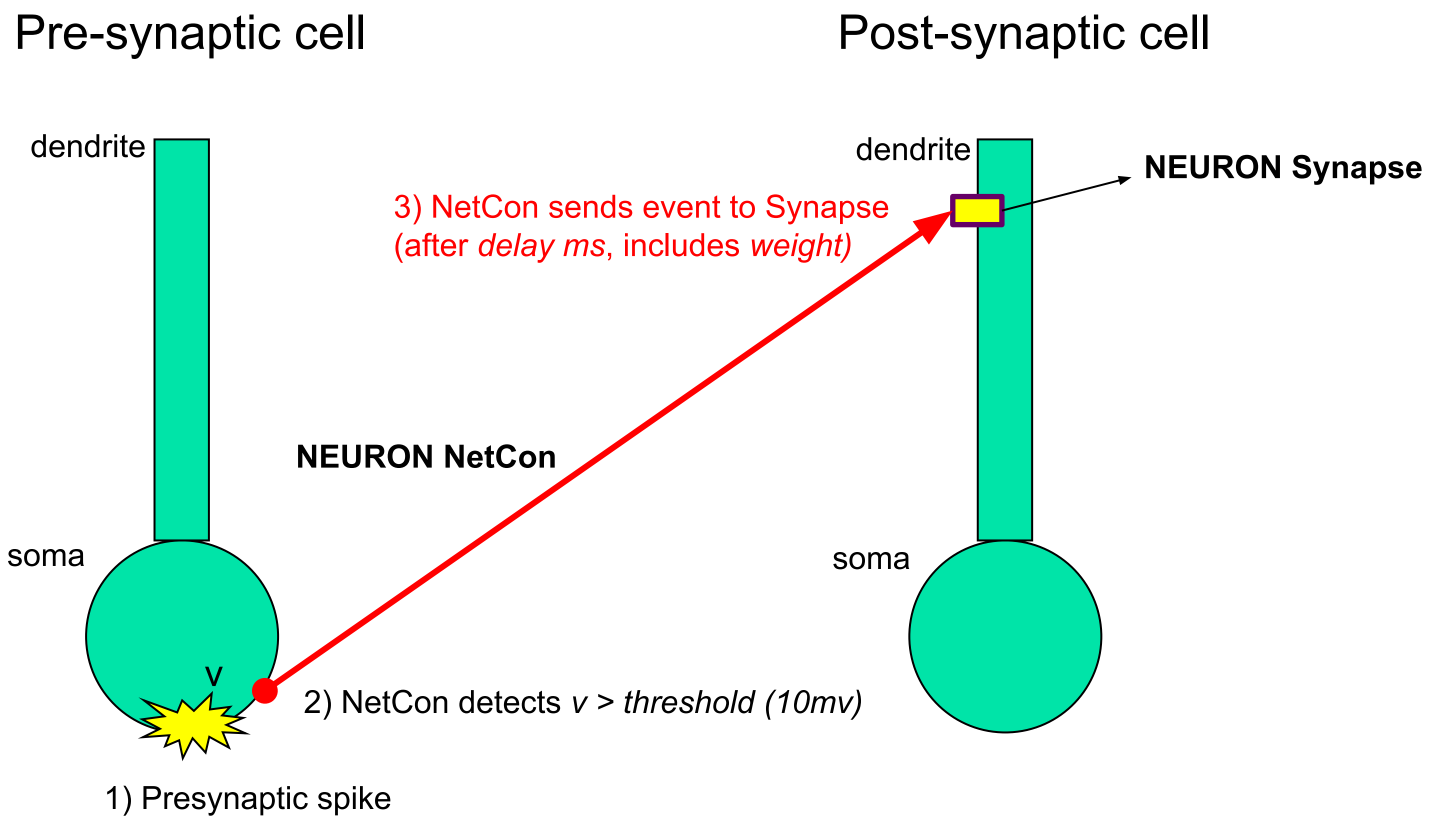
Synaptic connection model



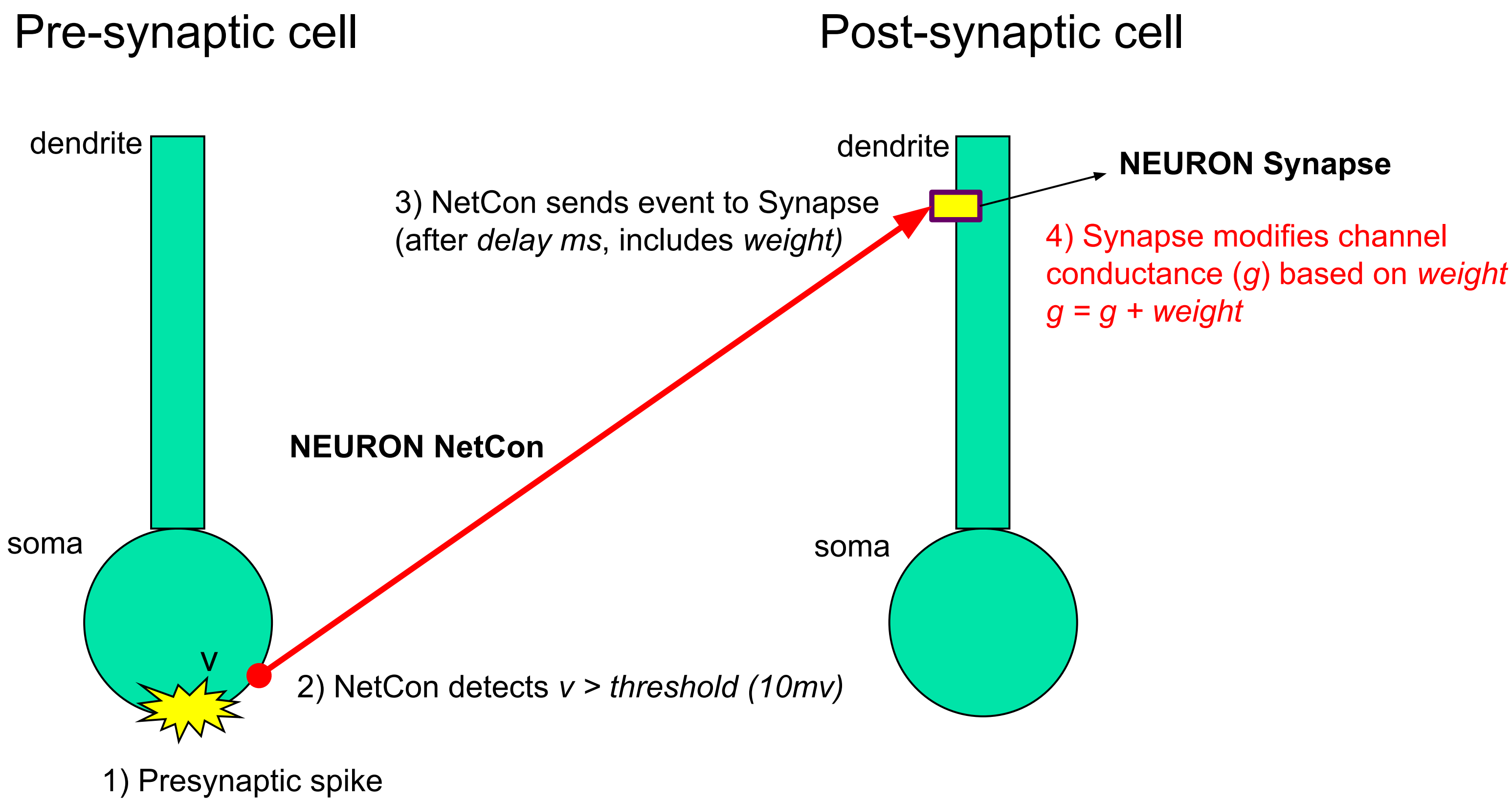
Synaptic connection model



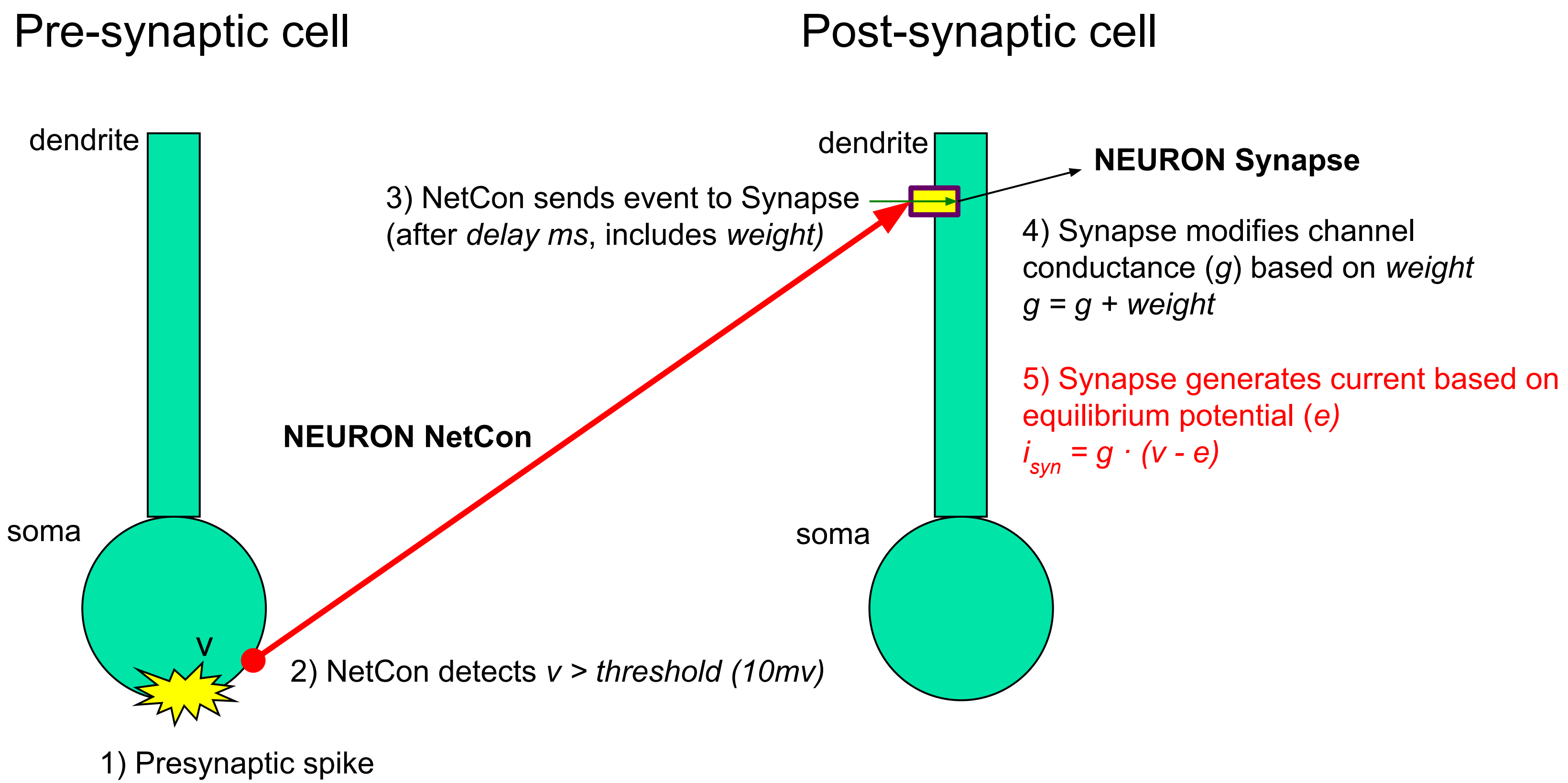
Synaptic connection model



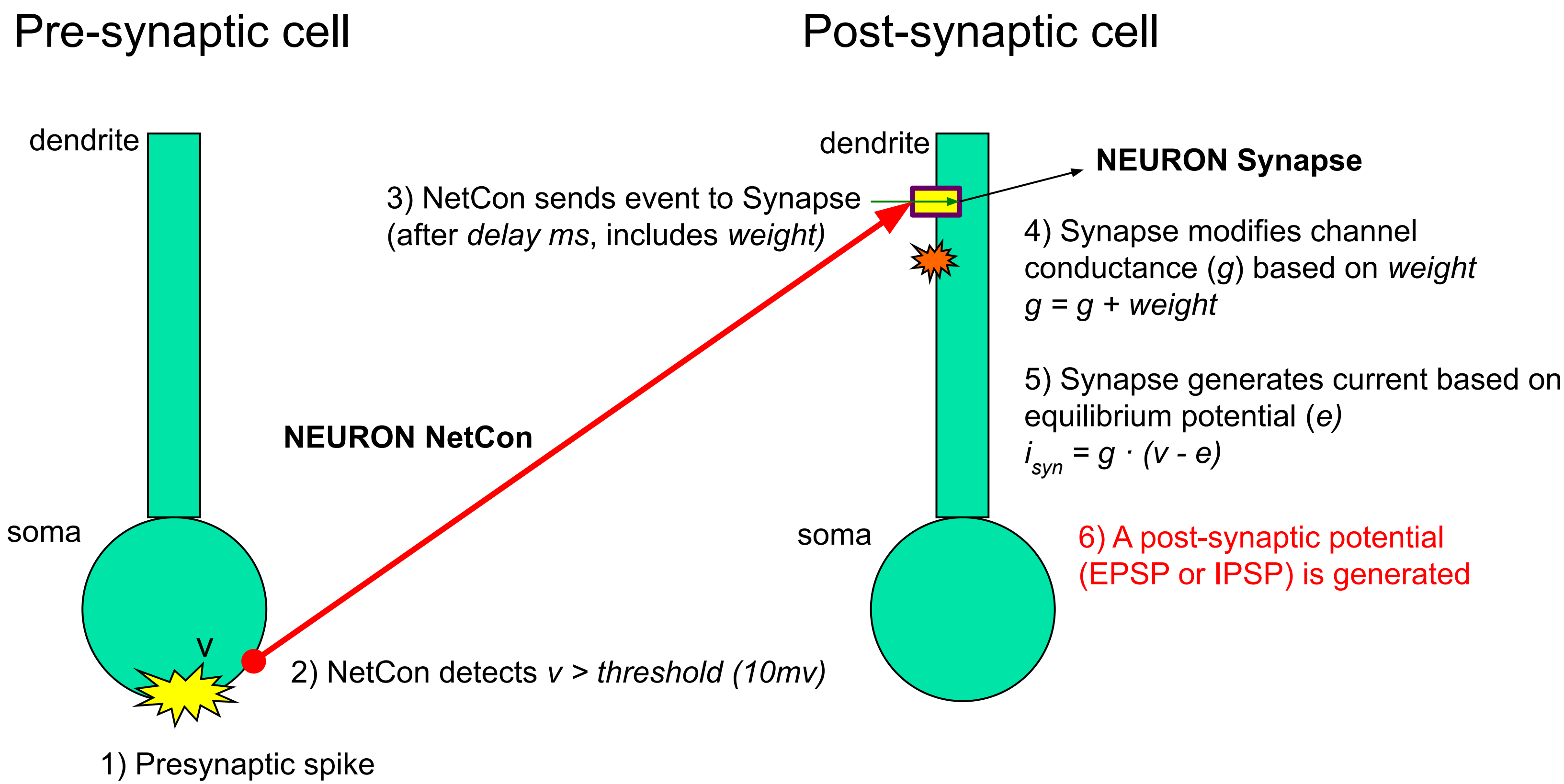
Synaptic connection model



Synaptic connection model



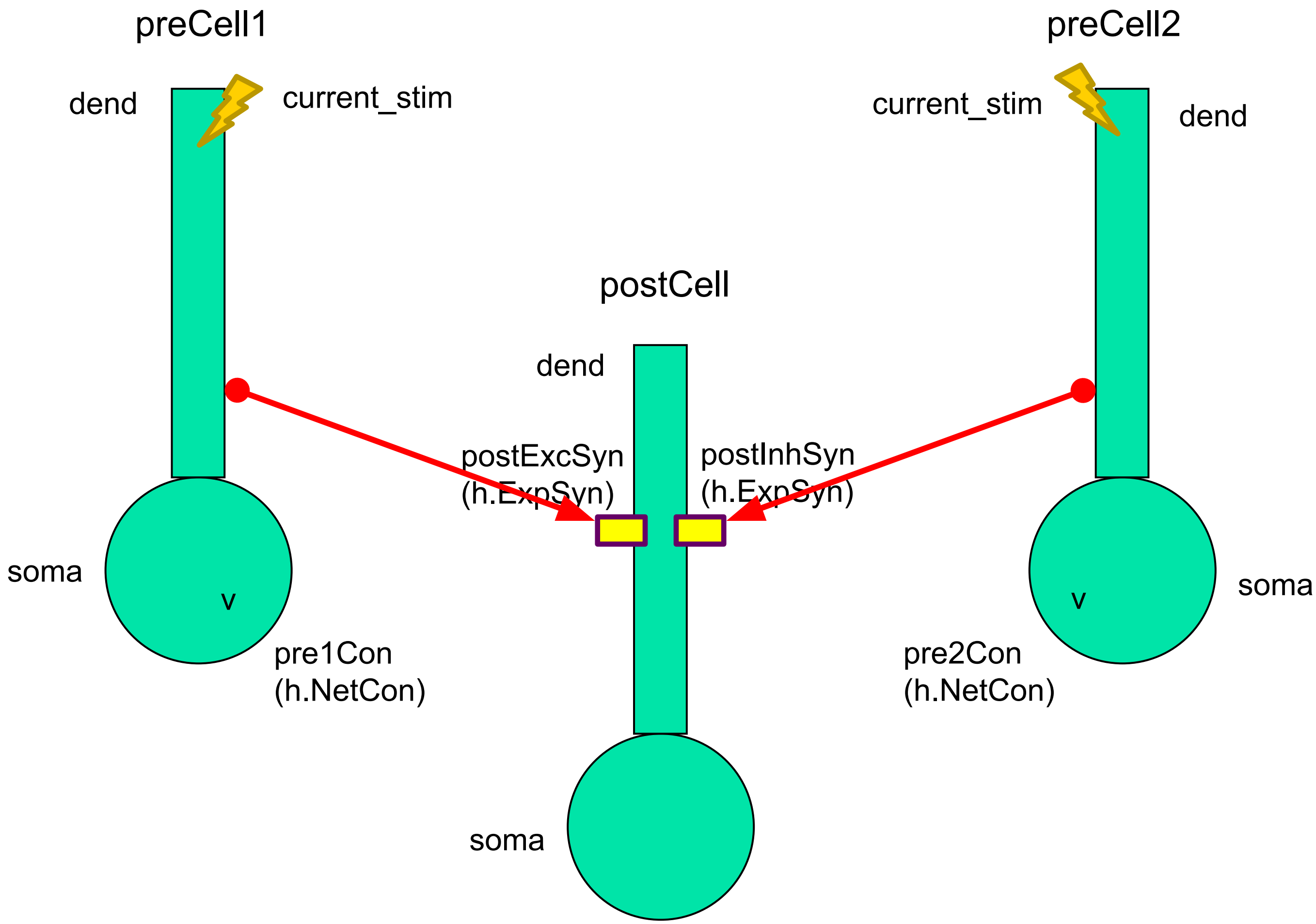
Synaptic connection model



Connections Tutorial

1) Start with *tutorial_3.py.* It contains a single ***postCell***, with no stimulation.
2) *S*et up recording and plot voltage. If needed, set limit on voltage axis, e.g.: `pyplot.ylim(-80,30)`
3) Add ***preCell1*** of same type *HHCell*, add a current stimulation to ***preCell1*** at 20 ms:
```
preCell1.add_current_stim(20) # add stimulation
```
4) Add an excitatory synaptic receptor at the dendrite of ***postCell***, with reversal potential of 0 mV and delay of 2 ms*:*
```
postSyn1 = h.ExpSyn(postCell.dend(0.5)) # add exc synapse
postSyn1.e = 0
postSyn1.tau = 2
```
5) Add a connection between the ***preCell1*** soma and the ***postCell*** dendrite with weight of 0.002 and delay of 1 ms.
```
pre1Con = h.NetCon(preCell1.soma(0.5)._ref_v, postSyn1, sec=preCell1.soma)
pre1Con.weight[0] = 0.002
pre1Con.delay = 1
```
6) Run simulation for 60 ms, plot voltage
7) Try different values of ExpSyn and NetCon parameters, to get (1) **small EPSP**, (2) **EPSP that leads to spike**, (3) **IPSP**.
8) * With fixed synapse params (hence fixed EPSP), play with synapse location that would or would not results in spike

Connections Tutorial



Connections Tutorial

1) Add a ***preCell2***
2) Add another excitatory synaptic receptor ***postSyn2*** at the dendrite of *postCell,* with reversal potential of 0 mV and tau of 2 ms
3) Add a connection between the ***preCell2*** soma and the ***postSyn2*** synapse ***postCell*** dendrite with weight of 0.002 and delay of 1 ms.
4) By commenting out either ***preCell1*** or ***preCell2****,* observe that spike in one of them doesn’t lead to postsynaptic spike, but spike is generated if both pre-cells are connected (spatial summation)
5) Modify ***postSyn2*** to be inhibitory (change reversal potential)
6) Try to show spatial cancellation (EPSP+IPSP)