

Brian2 Basics: Neurons & Synapses

From LIF cells to spike-driven connections

Structure

- Brian2 core principles (units, clocks, magic network)
- LIF neuron in Brian2 (equations, threshold, reset, refractory)
- Monitoring spikes and voltages
- Synapses: `on_pre`, weights, delays

Brian2 Core Principles

- Units-aware quantities (mV , ms , nA) → automatic dimension checks
- Clock & time step: defaultclock.dt controls integration step (set before building)
- Magic network: After start_scope() , created objects are auto-collected by run()
- Core classes:
 - Neurons: NeuronGroup
 - Synapses: Synapses
 - I/O: StateMonitor , SpikeMonitor

The LIF Model

$$\tau_m \frac{dv}{dt} = -v + R \times I$$

Events

- **Threshold:** $(v > V_t) \rightarrow$ emit spike
- **Reset:** $(v \leftarrow V_r)$
- **Refractory:** hold dynamics for fixed time

Brian2 mapping: ODE + `threshold`, `reset`, and `(unless refractory)` flag in the equation.

Goal: one LIF neuron with constant input; monitor $v(t)$ and spikes.

Minimal LIF Neuron (fixed threshold)

```
from brian2 import *

start_scope()
defaultclock.dt = 0.1*ms

# Parameters
tau = 10*ms; V_t = 0.8; V_r = 0; tau_ref = 5*ms

# Dynamics (suspend during refractoriness)
eqs = '''
dv/dt = (-v + I)/tau : 1 (unless refractory)
I : 1
'''

G = NeuronGroup(1, eqs, threshold='v > V_t', reset='v = V_r', refractory=tau_ref, method='exact')

# Initial state & drive
G.v = V_r; G.I = 1; G.tau = tau

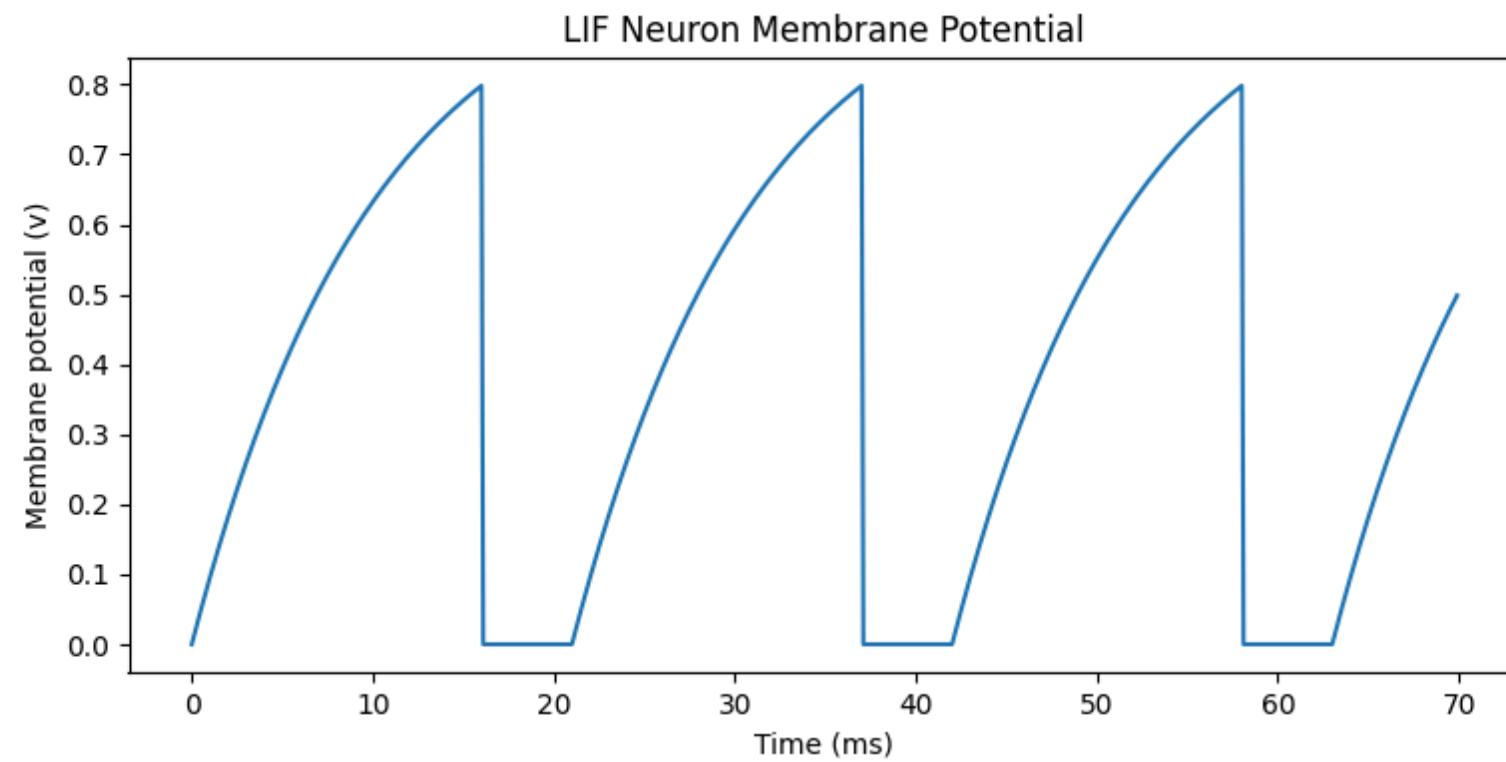
# Monitors
Vmon = StateMonitor(G, 'v', record=True)
Smon = SpikeMonitor(G)

run(70*ms)
```

Reading out Results

- **Vmon.t, Vmon.v[0]** → membrane potential trace
- **Smon.t, Smon.i** → spike times and indices
- **Smon.count, Smon.num_spikes** → spike counts

LIF Simulation



Synapses in Brian2

Core Principle: Spikes trigger code on connections

- `Synapses(source, target, model='w : volt', on_pre='v_post += w', delay=1*ms)`
- Connectivity via `connect(...)` selectors (e.g., `i=0, j=[1,2]`, or `connect(condition)`).
- `on_pre` runs on pre-synaptic spike; use `_post` suffix to modify target variables (e.g., `v_post`).
- Possibility to introduce delays

Two LIF Neurons Example with a Synapse

```
from brian2 import *

start_scope()
defaultclock.dt = 0.1*ms

# Parameters
V_t = 0.8; V_r = 0; tau_ref = 5*ms

# Dynamics (suspend during refractoriness)
eqs = '''
dv/dt = (-v + I)/tau : 1 (unless refractory)
I : 1
tau : second
'''

G = NeuronGroup(2, eqs, threshold='v > V_t', reset='v = V_r', refractory=tau_ref, method='exact')

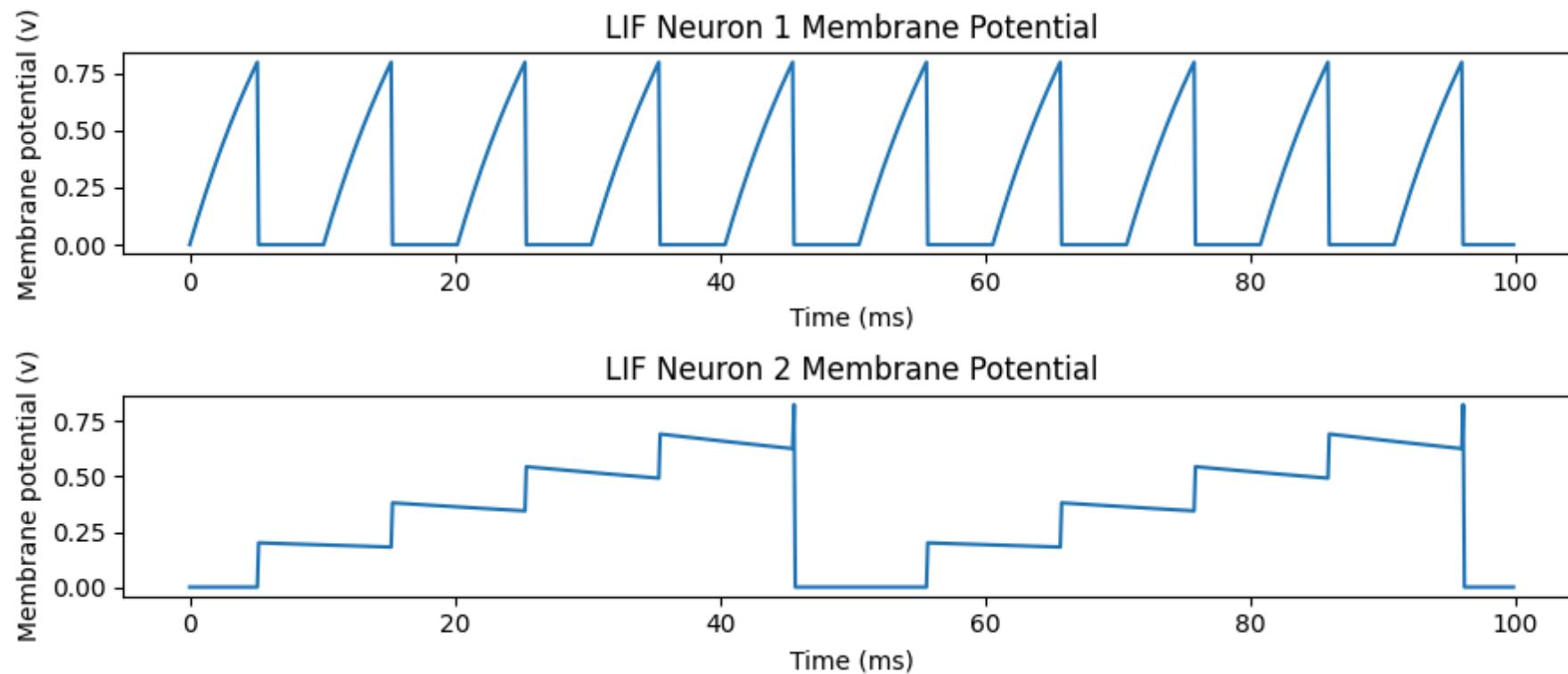
# Initial state & drive
G.v = V_r; G.I = [2, 0]; G.tau = [10, 100]*ms

S = Synapses(G, G, 'w : 1', on_pre='v_post += w')
S.connect(i=0, j=1)
S.w = 0.2

# Monitors
Vmon = StateMonitor(G, 'v', record=True)

run(100*ms)
```

Two-neuron LIF Simulation



What can be done with Brian2 ?

Any system of differential equations can be easily simulated. However, it works best to simulate networks of neurons.

Any input can be fed and any custom neuron/synaptic model can be used.

Remains consistent thanks to the units-aware quantities.

Possibility to specify different timesteps for different objects or run objects synchronously.

Possibility to compile C++ version of the code for faster simulations.

Brian2 Tutorials and Examples

- <https://brian2.readthedocs.io/en/stable/resources/tutorials/index.html>
- <https://brian2.readthedocs.io/en/stable/examples/index.html>

Multi-scale Neuron

$$\left\{ \begin{array}{l} \tau \frac{dV}{dt} = -V - I_f^- - I_s^+ - I_s^- - I_u^+ + I_{app} \\ I_f^- = \alpha_f^- * \tanh(V - \delta_f^-) \\ I_s^- = \alpha_s^- * \tanh(V_s^- - \delta_s^-) \\ \tau_s \frac{dV_s^-}{dt} = V - V_s^- \\ I_s^+ = \alpha_s^+ * \tanh(V_s^+ - \delta_s^+) \\ \tau_s \frac{dV_s^+}{dt} = V - V_s^+ \\ I_u^+ = \alpha_u^+ * \tanh(V_u^+ - \delta_u^+) \\ \tau_u \frac{dV_u^+}{dt} = V - V_u^+ \end{array} \right.$$

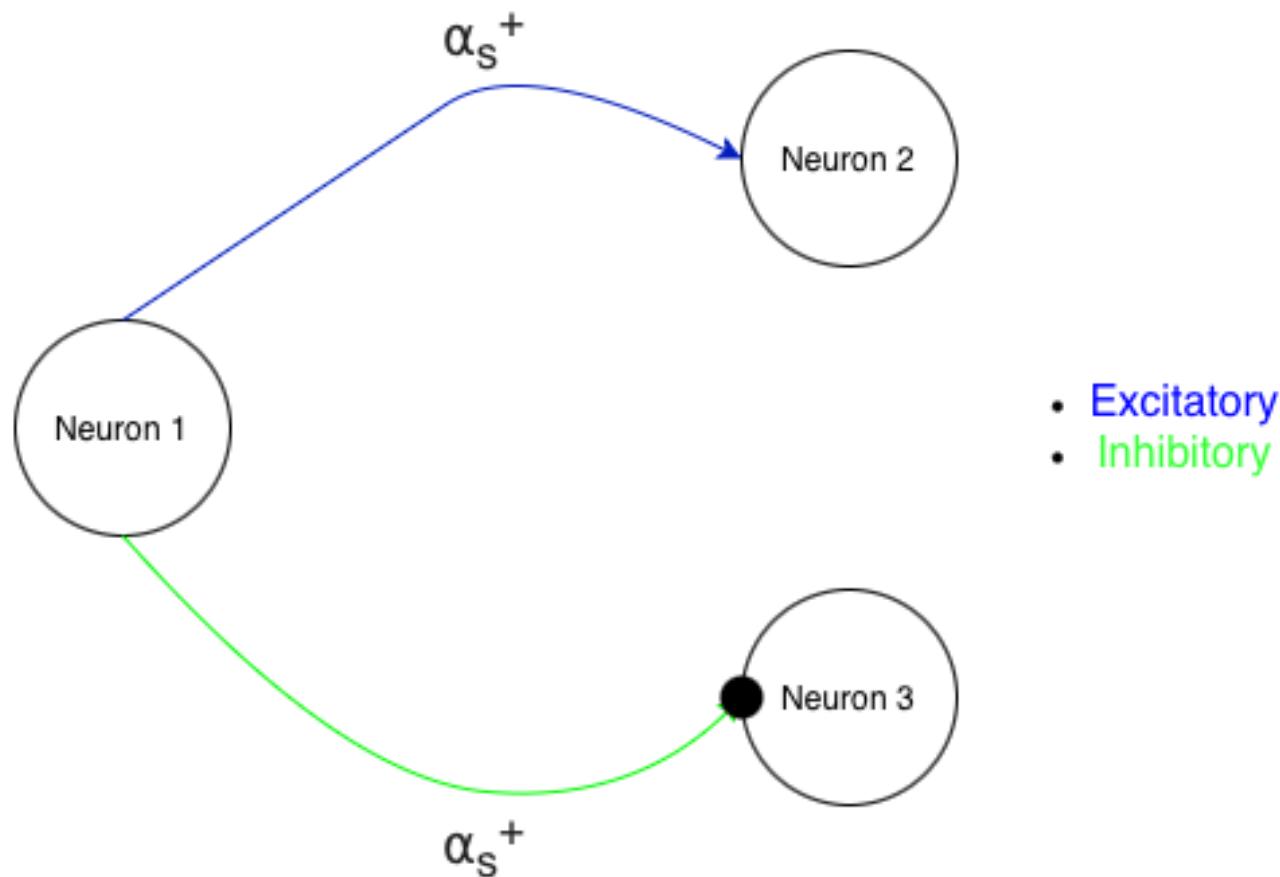
Ribar, L. & Sepulchre, R. Neuromodulation of Neuromorphic Circuits.(2019).

Multi-Scale Neuron Simulation

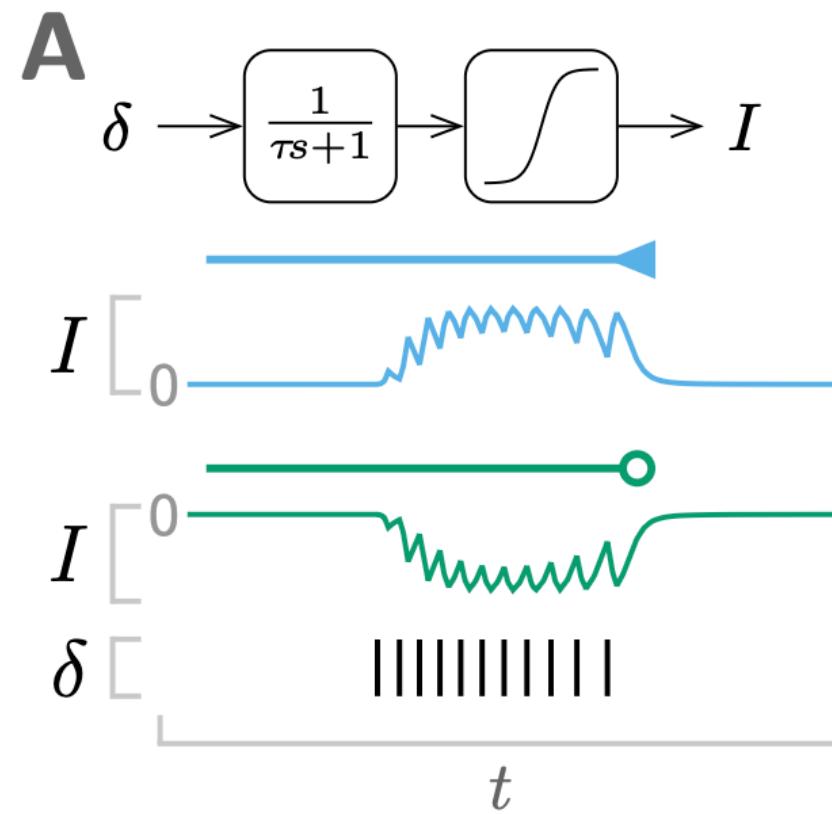
See GUI Demo

Neuromodulation of Slow Positive Conductance Gain

α_s^+



Additive Synapses



"Neuromorphic Toolbox. FERNANDEZ LORDEN Christian"

Neuromodulation with Additive Synapses

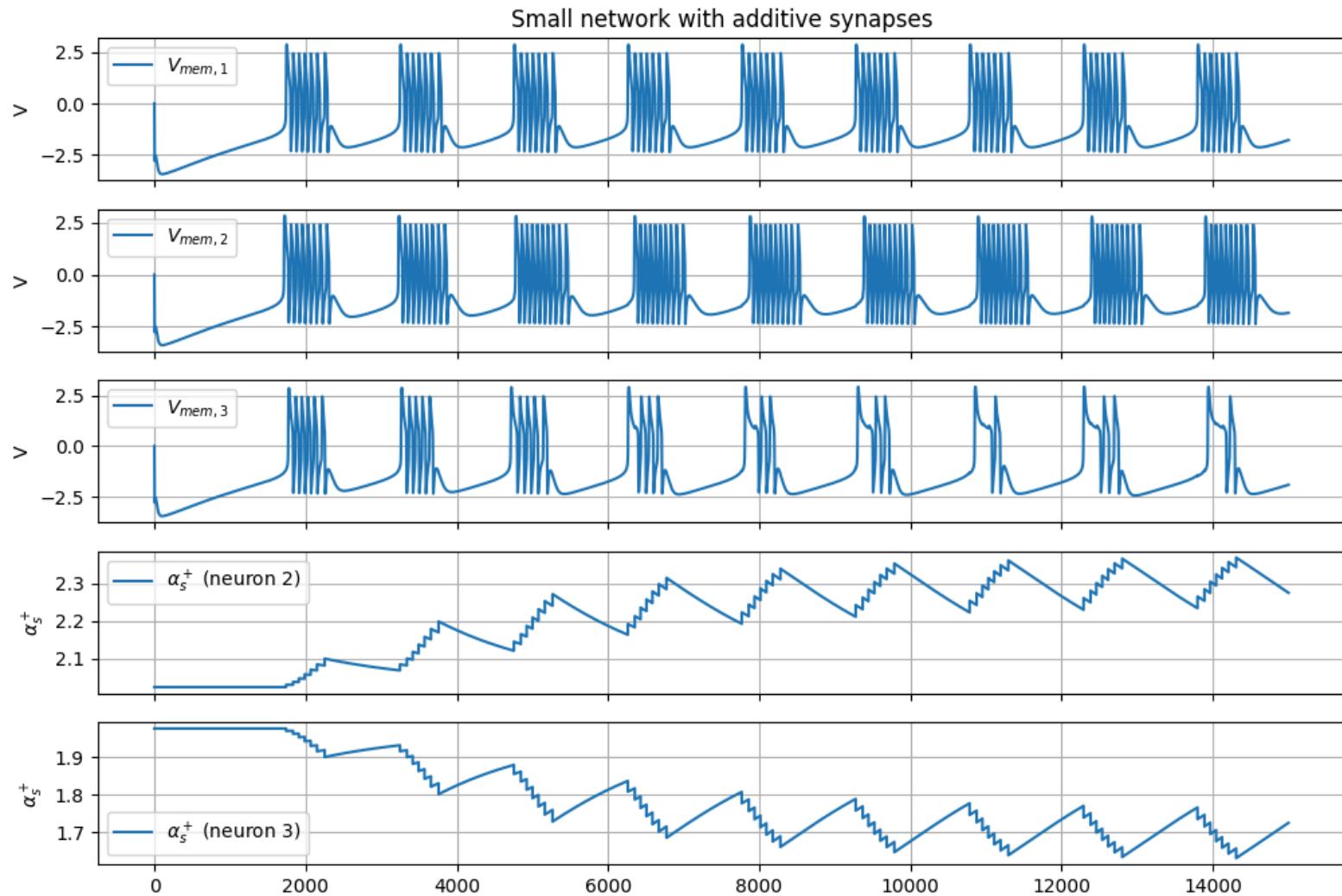
Synaptic Dynamics:

$$\left\{ \tau_s \frac{ds(t)}{dt} = -s(t) + \sum_k \delta(t - t_k) \right.$$

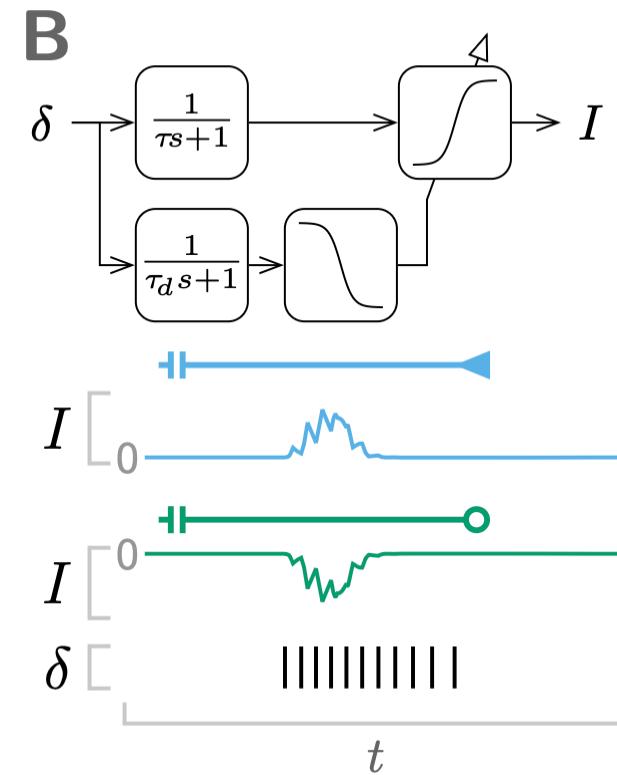
Updated Neuron Dynamics:

$$\begin{cases} \alpha_{mod}(t) = sign(t) * \sigma(\beta * s(t) - \theta) \\ I_s^+(t) = (\alpha_s^+ + \alpha_{mod}(t)) * \tanh(V_s^+(t) - \delta_s^+) \end{cases}$$

Simulation



Depressive Synapses



"Neuromorphic Toolbox. FERNANDEZ LORDEN Christian"

Neuromodulation with Depressive Synapses

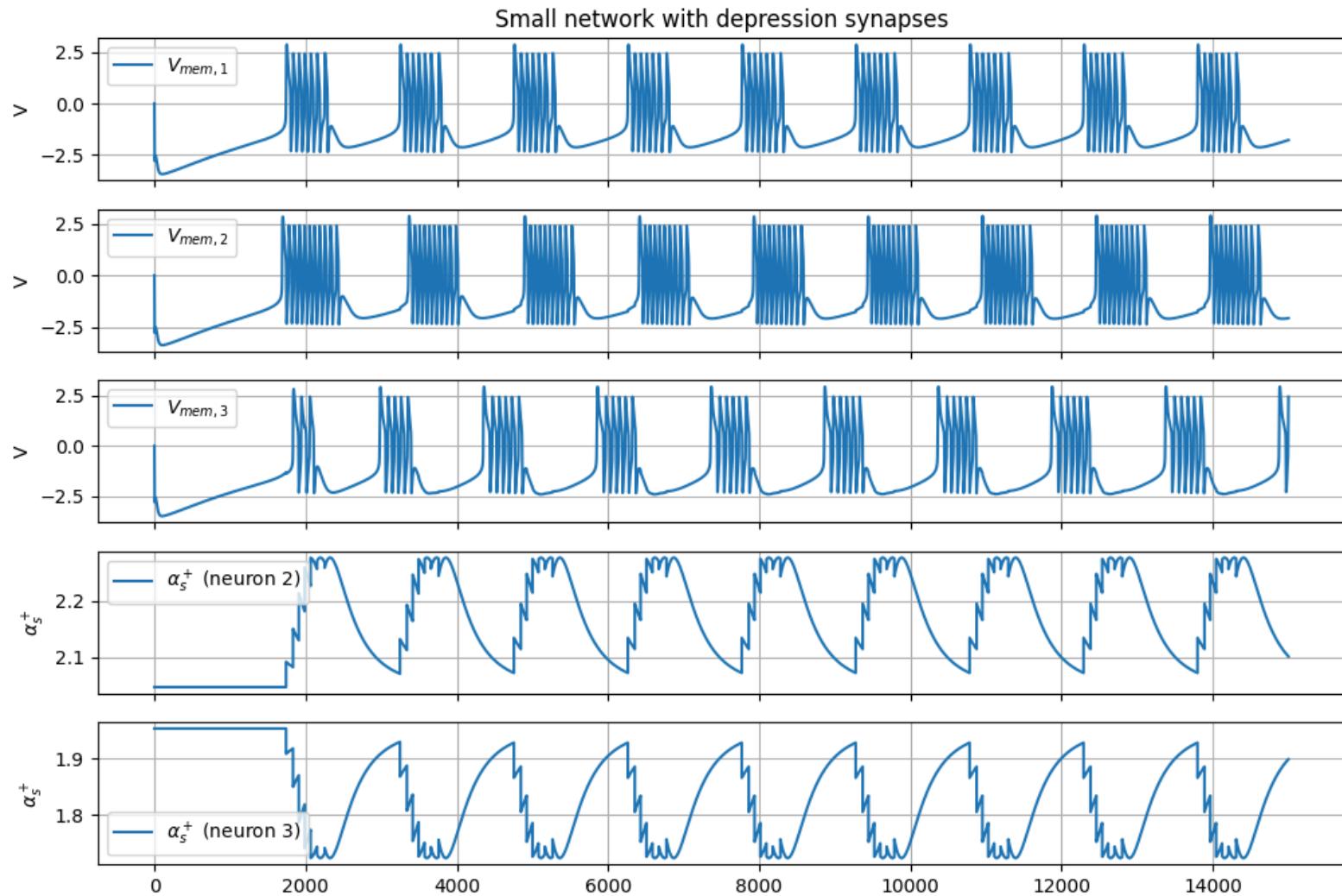
Synaptic Dynamics:

$$\begin{cases} \tau_{fac} \frac{ds_{fac}(t)}{dt} = -s_{fac}(t) + \sum_k \delta(t - t_k) \\ \tau_{dep} \frac{ds_{dep}(t)}{dt} = -s_{dep}(t) + \sum_k \delta(t - t_k) \end{cases}$$

Updated Neuron Dynamics:

$$\begin{cases} \alpha_{mod}(t) = sign(t) * \sigma(\beta_{fac} * s_{fac}(t) - \theta_{fac}) \\ g(t) = g_0 * \sigma(-\beta_{dep} * s_{dep}(t) - \theta_{dep}) \\ I_s^+(t) = (\alpha_s^+ + g(t) * \alpha_{mod}(t)) * \tanh(V_s^+(t) - \delta_s^+) \end{cases}$$

Simulation



C++ standalone mode

Standalone mode:

- Use `set_device("cpp_standalone")`
- Generates C++ project for fast simulation
- In the code, everything needs to be defined before compilation (cannot change parameters value with python).
- Useful for large networks or heavy models

Recap: Brian2 Essentials

- Units-aware simulation framework for neural models
- Monitoring activity: `StateMonitor`, `SpikeMonitor`
- Synapses: `on_pre`, weights, delays, connectivity patterns
- From simple neuron model to any complex model
- Efficient execution with code generation (C++ backend)