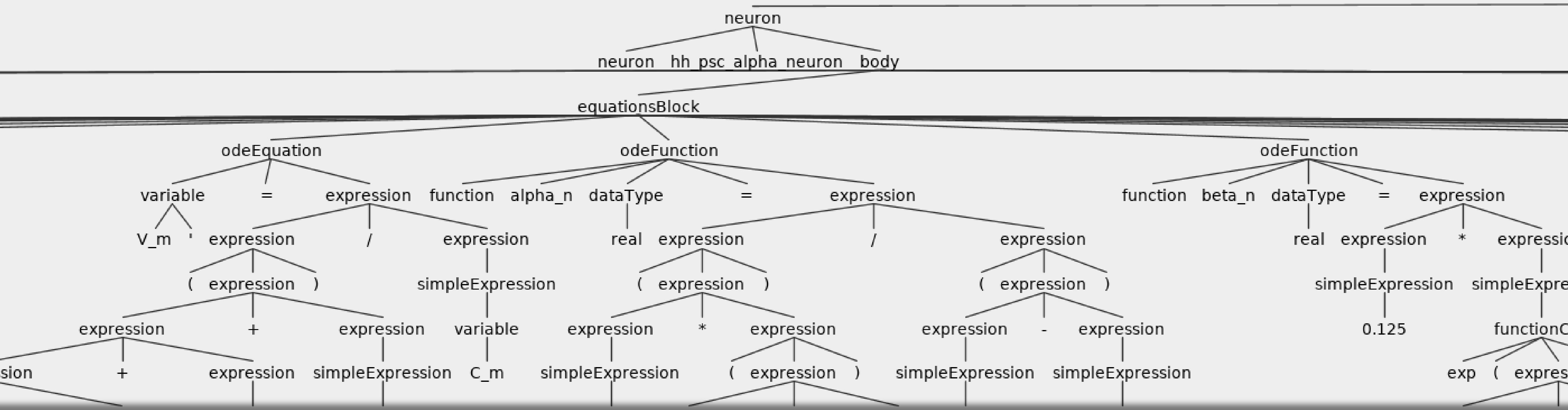

Neuron and synapse models in NESTML: From specification to simulation

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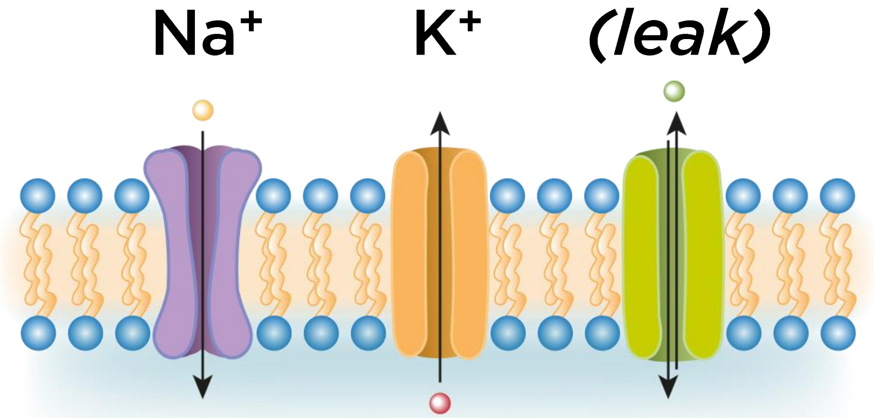
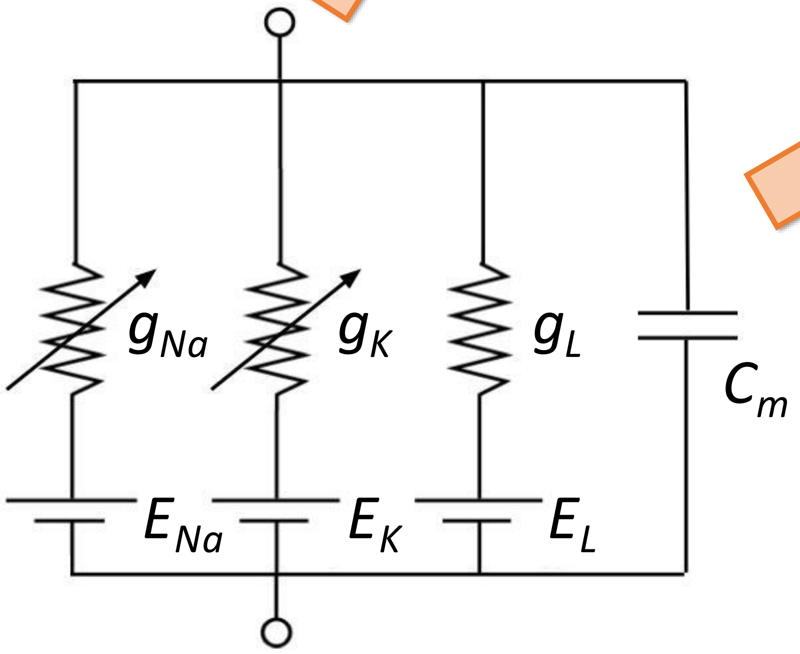
JÜLICH Forschungszentrum
Member of the Helmholtz Association






```
neuron hodgkin_huxley:
  state:
    V_m mV = -65 mV
    Act_m, Act_n, Inact_h ...
  end

  equations:
    shape syn_psc_kernel = exp(-t / tau_syn)
    inline I_Na pA = g_Na * Act_m**3 * Inact_h * (V_m - E_Na)
    inline I_K pA = ...
    inline I_L pA = g_L * (V_m - E_L)
    V_m' = -(I_Na + I_K + I_L) / C_m
           + convolve(syn_psc_kernel, spikes)
    Act_n' = (alpha_n * (1 - Act_n) - beta_n * Act_n) / ms
    Act_m' = ...
    Inact_h' = ...
  end

  parameters:
    C_m pF = 250 pF
    V_threshold mV = 40 mV
    ...
  end

  update:
    integrate_odes()
    if V_m >= V_threshold:
      emit_spike()
    end
  end
end
```

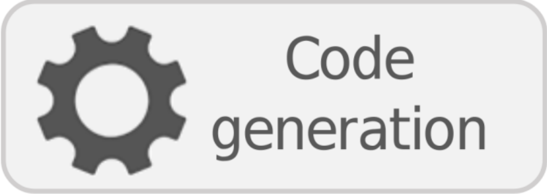
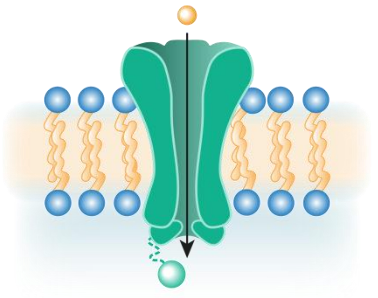
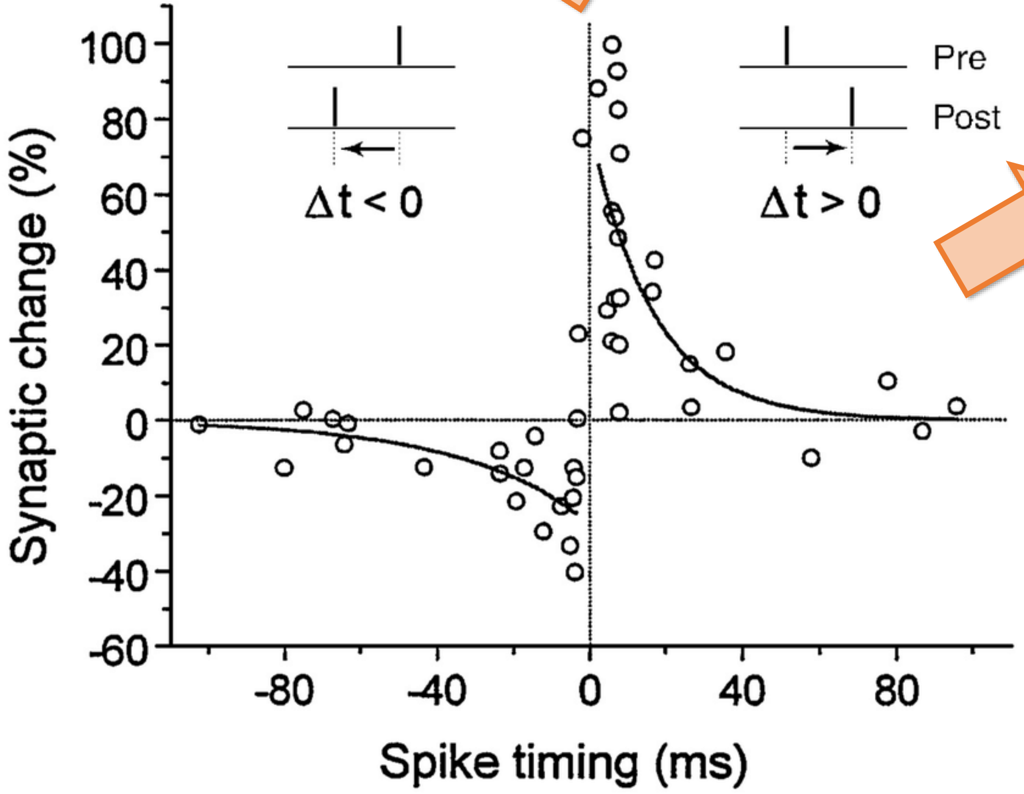


Image credit: (c) S.B.C. Lehmann, FZ Jülich, (m) C. Linssen

NMDA (Ca^{2+})





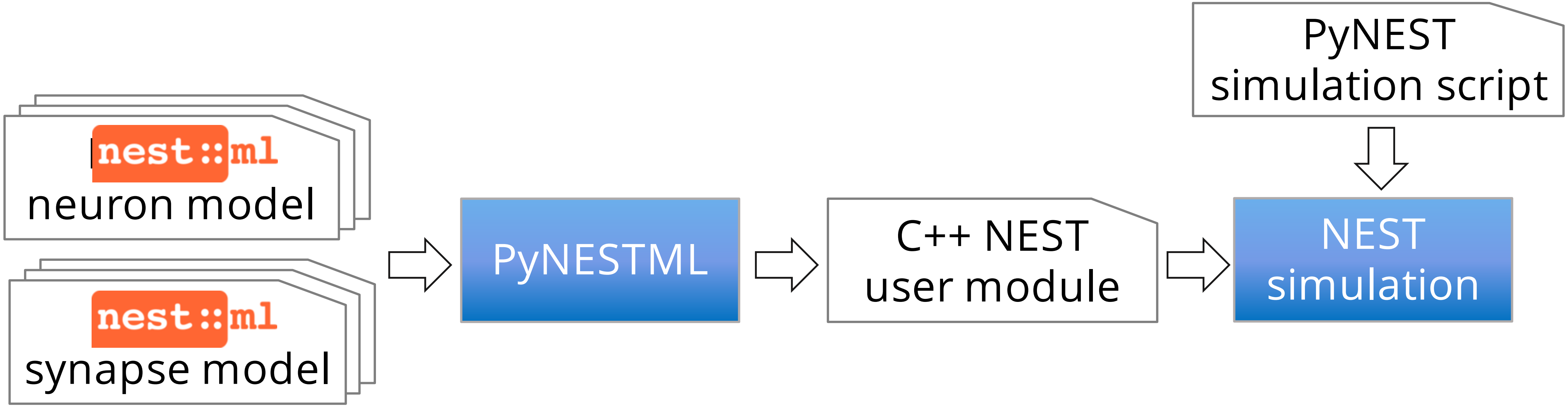

```
synapse stdp:
  state:
    w real = 1
    tr_post real = 0
    tr_pre real = 0
  end

  equations:
    tr_pre' = -tr_pre / tau_tr
    tr_post' = -tr_post / tau_tr
  end

  input:
    pre_spikes real <- spike
    post_spikes real <- spike
  end

  onReceive(pre_spikes):
    w -= alpha * tr_post        # depress synapse
    tr_pre += 1                 # update presynaptic trace
    deliver_spike(w, delay)     # to postsynaptic partner
  end

  onReceive(post_spikes):
    w += alpha * tr_pre         # potentiate synapse
    tr_post += 1                # update postsynaptic trace
  end

  parameters:
    delay ms = 1 ms             # dendritic delay
    tau_tr ms = 50 ms           # pre/post trace time const.
    alpha real = .02            # learning rate
  end
end
```

nest::ml

Image credit: (c) S.B.C. Lehmann, FZ Jülich, (m) C. Linssen; Bi & Poo 2001

Typical workflow

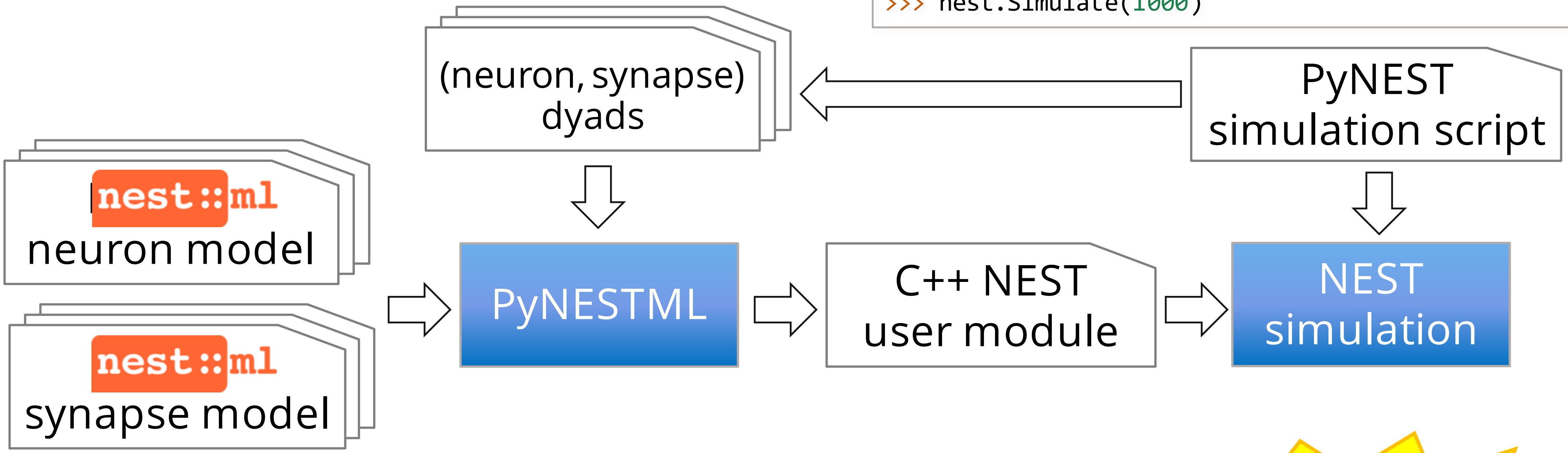
```
>>> nest.Install('nestmlmodule')
>>> pre, post = nest.Create('hodgkin_huxley', 100)
>>> nest.Connect(pre, post,
     'all_to_all', syn_spec={'synapse_model': 'stdp'})
>>> nest.Simulate(1000)
```




```
$ ls -l models
hodgkin_huxley.nestml
stdp.nestml

$ nestml --input_path=models
```

New workflow (with JIT)

```
>>> pre, post = nest.Create('hodgkin_huxley', 100)
>>> nest.Connect(pre, post,
     'all_to_all', syn_spec={'synapse_model': 'stdp'})
>>> nest.Simulate(1000)
```




```
$ ls -l models
hodgkin_huxley.nestml
stdp.nestml
```

```
synapse stdp:
  state:
    w nS = 1 nS
    tr_post real = 0
    tr_pre real = 0
  end

  equations:
    tr_pre' = tr_pre / tau_tr
    tr_post' = tr_post / tau_tr
  end

  input:
    pre_spikes nS <- spike
    post_spikes nS <- post spike
  end

  preReceive:
    w -= alpha * tr_post          # depress synapse
    tr_pre += 1                   # update presynaptic trace
    deliver_spike(w, delay)       # to postsynaptic partner
  end

  postReceive:
    w += alpha * tr_pre           # potentiate synapse
    tr_post += 1                  # update postsynaptic trace
  end

  # parameters: tau_tr, alpha, delay
end
```

```
neuron hodgkin_huxley:
  state:
    V_m mV = -65 mV
    Act_m, Act_n, Inact_h ...
  end

  equations:
    shape syn_psc_kernel = exp(-t / tau_syn)
    inline I_Na pA = ...
    inline I_K pA = ...
    inline I_L pA = g_L * (V_m - E_L)
    V_m' = -(I_Na + I_K + I_L) / C_m
           + convolve(syn_psc_kernel, spikes)
    [...]
  end

  parameters:
    C_m pF = 250 pF
    V_threshold mV = 40 mV
    ...
  end

  update:
    integrate_odes()
    if V_m >= V_threshold:
      emit_spike()
    end
  end
end
```

PyNESTML toolchain:
modular and extensible

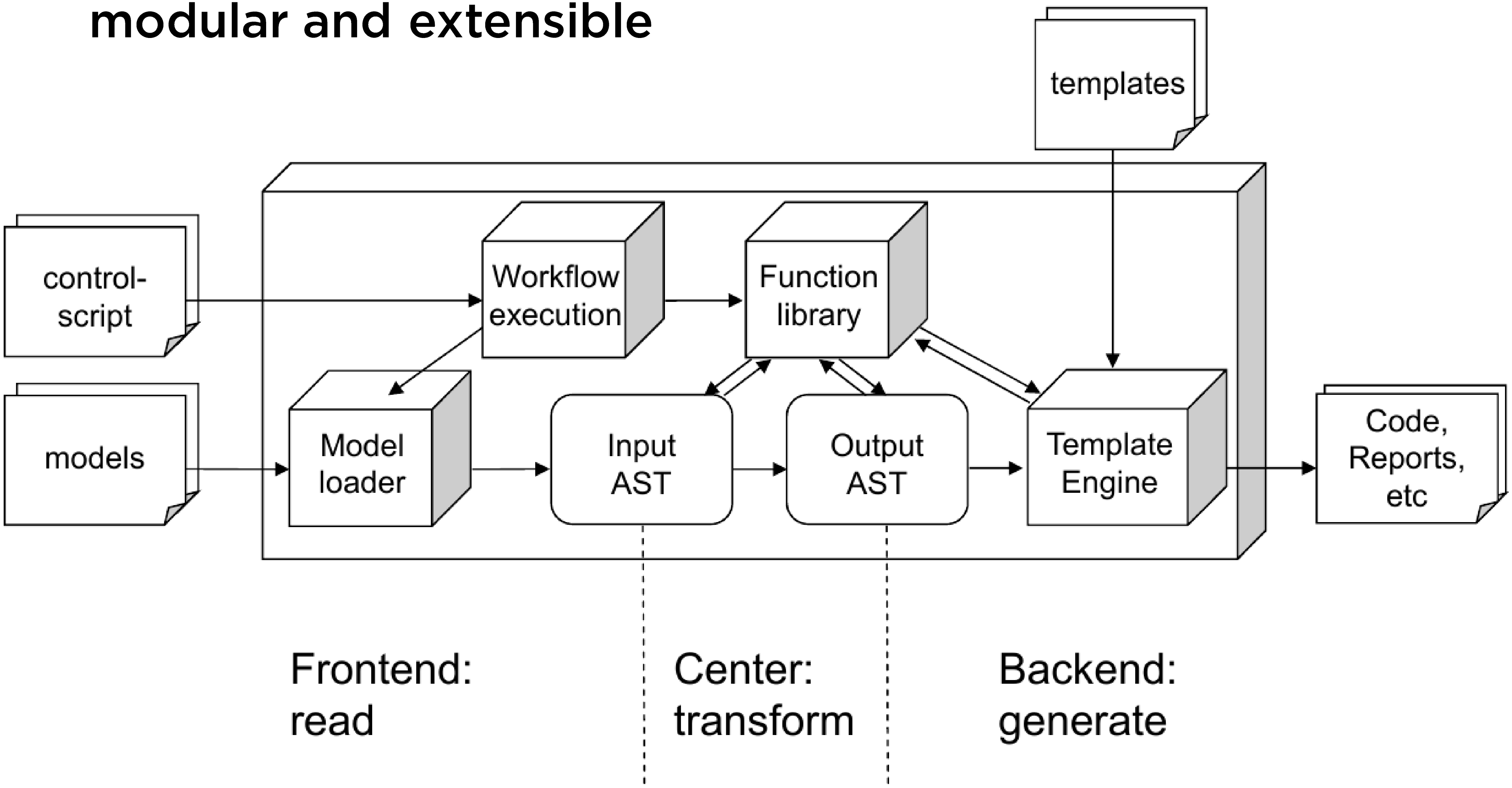
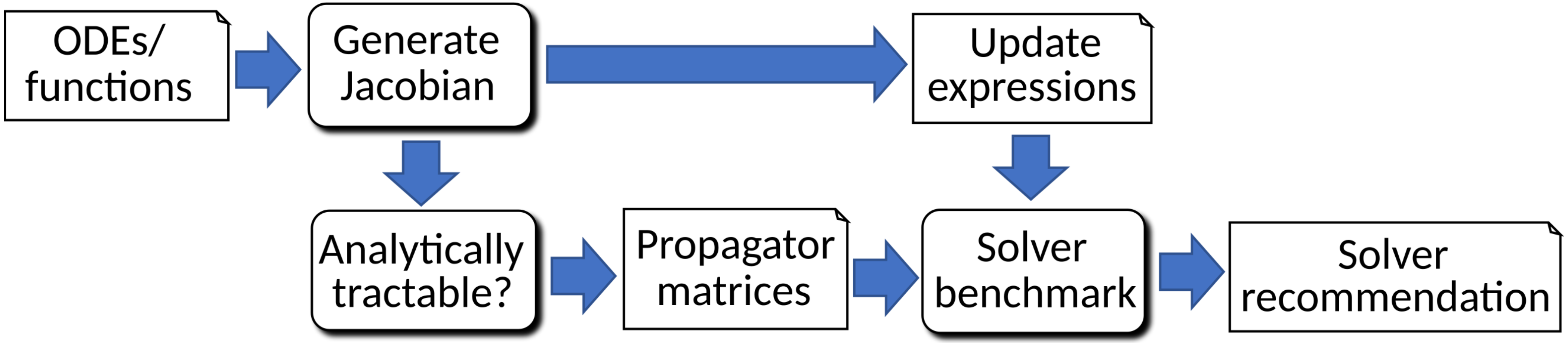


Image credit: Rumpe & Hölldobler 2017

ODE-toolbox:

Automatic selection and generation of integration schemes for systems of ordinary differential equations

- Inputs can be formulated as kernels $f(t) = \ldots$ or as differential equations of any order $d^n f/dt^n = \ldots$
- Symbolic rewriting into system of first-order ODEs
- Propagator matrices for dynamics that admits an analytic solution
- Solver benchmarking and recommendation



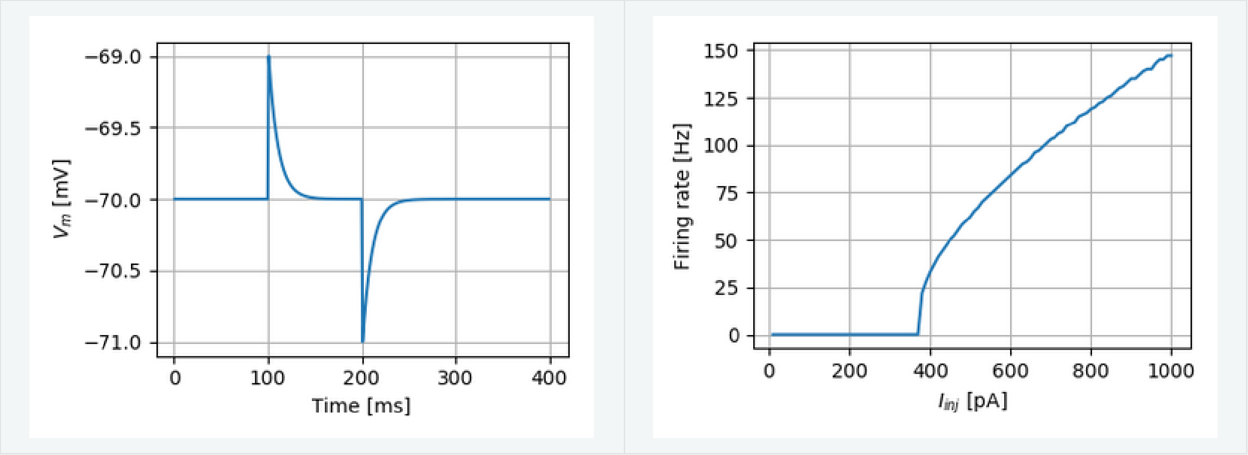
NESTML software development uses best practices in software engineering.

- Unit tests: language feature tests; physical units consistency; etc.
- Integration tests: models are behaviourally validated in one or more simulation runs
- Extensive documentation and automated HTML documentation generation for models: https://nestml.readthedocs.org/
- Open development: https://github.com/nest/nestml
- GNU GPL v2.0 licensed

Models library

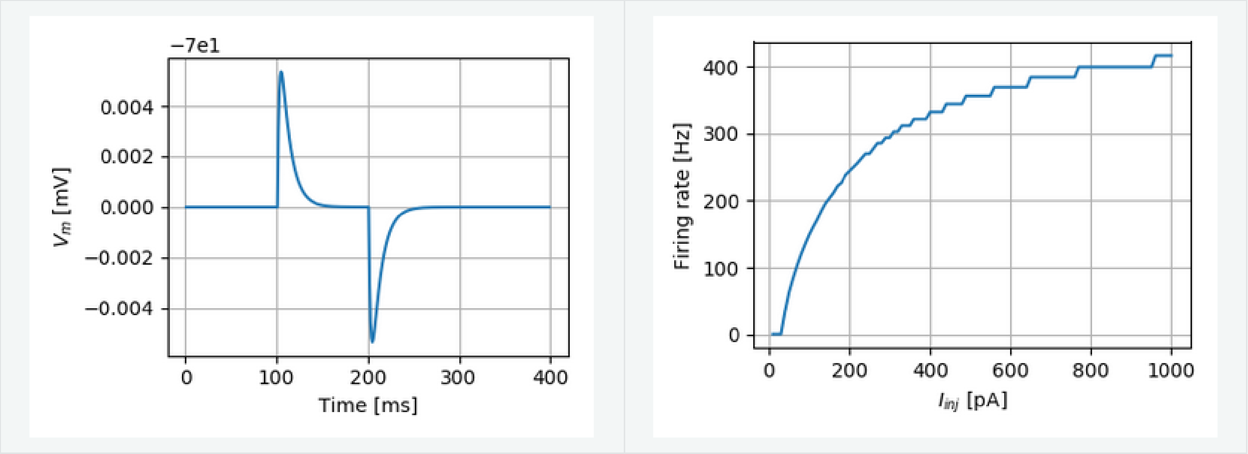
iaf_psc_delta

Source file: iaf_psc_delta.nestml



iaf_psc_exp

Source file: iaf_psc_exp.nestml



NESTML is a **domain-specific modeling language** for the dynamical simulation of point neurons (spiking and rate-based), as well as synapses and synaptic plasticity rules (in alpha version).

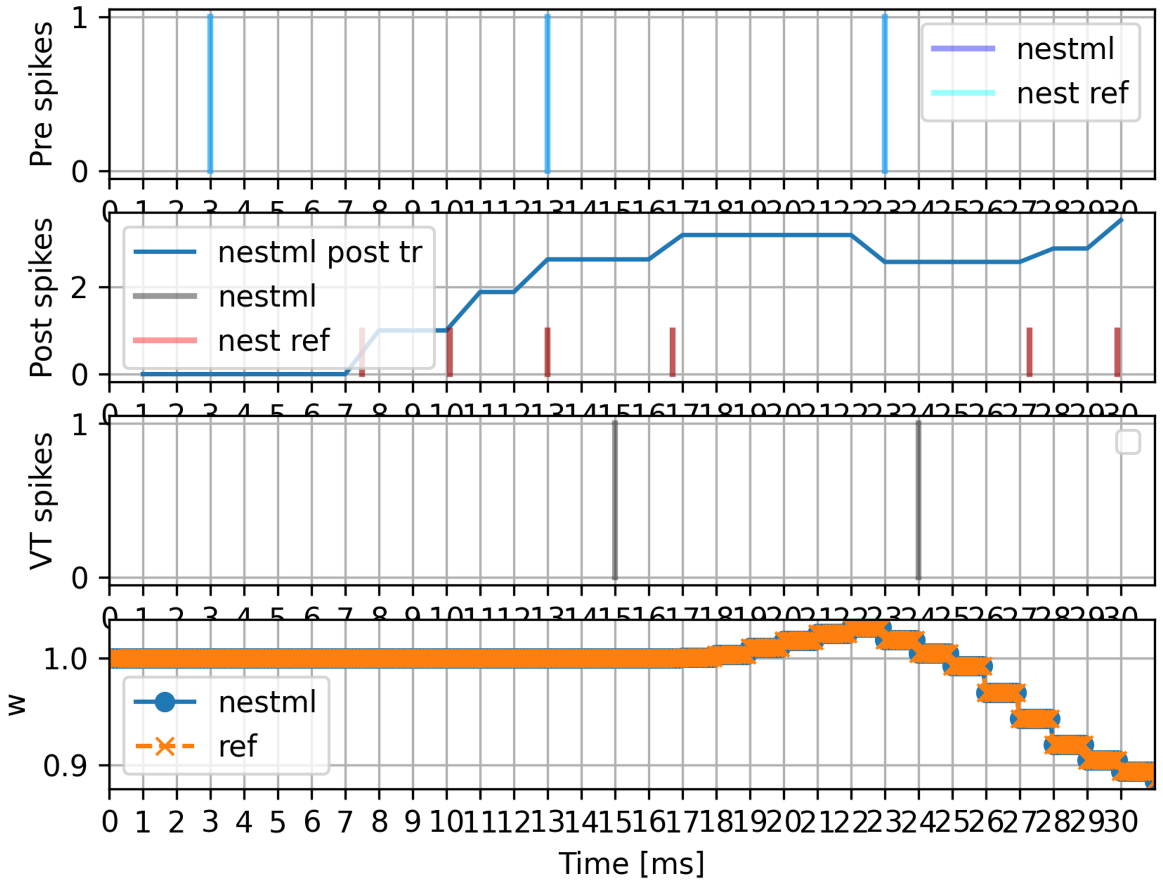
- Low on boilerplate; concise yet expressive syntax
- Direct language support for dynamical equations
- Imperative programming style specification of event handling and generation

NESTML comes with a **code generation** toolbox.

- Code generation (model definition but not instantiation)
- Automated ODE analysis and solver selection
- Flexible addition of targets using Jinja2 templates

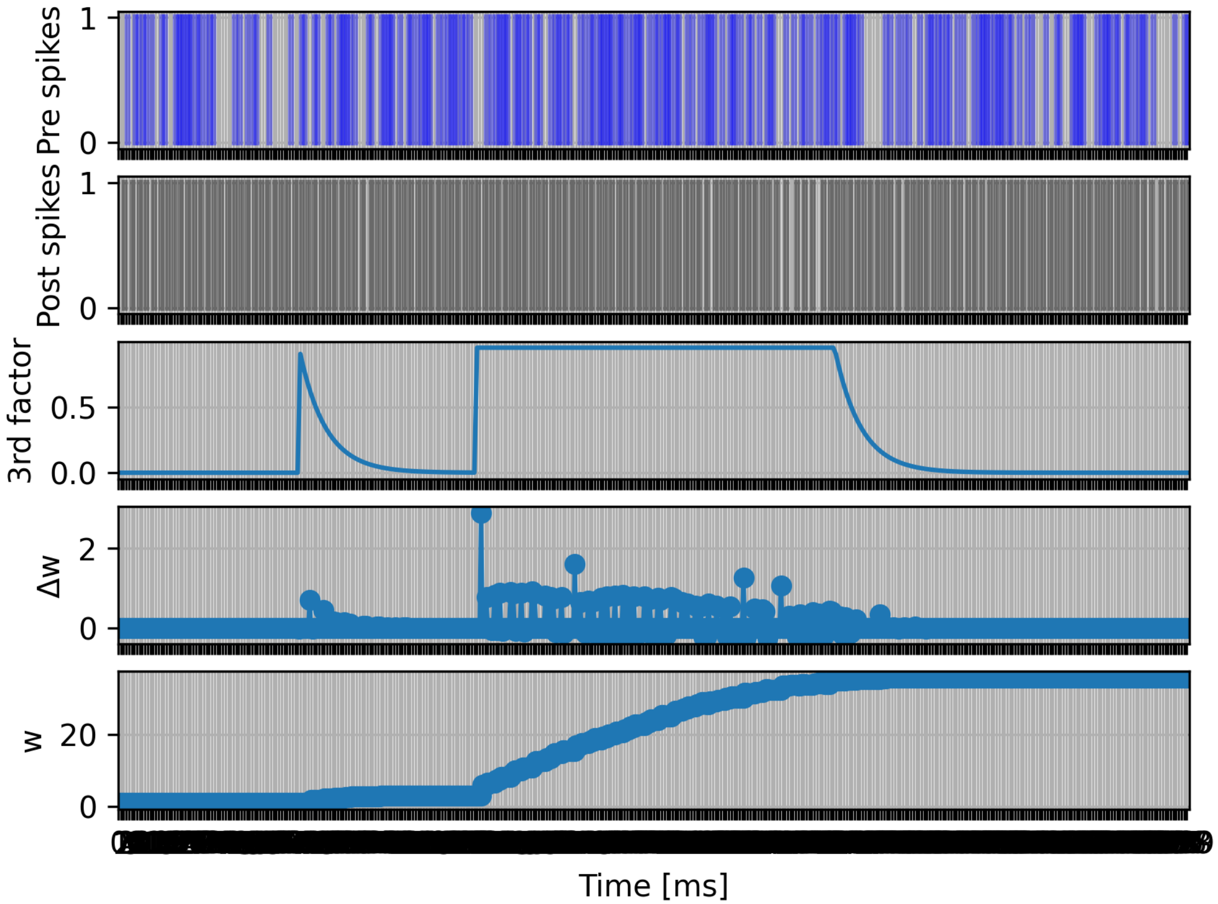
```
neuron iaf_psc_exp:
  state:
    V_m mV = 0 mV
  end

  equations:
    shape G = exp(-t / tau_syn)
    V_m' = -V_abs / tau_m
           + (I_ext + convolve(G, spikes)) / C_m
  end

  parameters:
    C_m      pF = 250 pF
    tau_m    ms = 10 ms
    tau_syn  ms = 2 ms
    V_threshold  mV = 40 mV    # w.r.t. zero!
  end

  input:
    spikes pA <- spike
    I_ext pA <- current
  end

  update:
    integrate_odes()
    if V_abs >= V_threshold:
      V_abs = 0 mV
      emit_spike()
    end
  end
end
```

Neuromodulated STDP




```
synapse stdp_dopa:

  input:
    [...]
    mod_spikes real <- spike
  end

  onReceive(mod_spikes):
    n += 1. / tau_n
  end

  update:              # update from time t to t + resolution()
    # the sequence here matters: the update step for w requires
    # the "old" values of c and n
    w -= c * ( n / tau_s * expm1( -tau_s * resolution() ) \
             - b * tau_c * expm1( -resolution() / tau_c ))
    [...]
    n = n * exp(-resolution() / tau_n)
  end

  [...]
end
```

Postsynaptic dendritic current-modulated STDP




```
synapse stdp_third_factor:
  state:
    w real = .5                                    # assume 0 <= w <= 1
  end

  input:
    [...]
    I_post_dend pA <- continuous
  end

  onReceive(post_spikes):                          # potentiate synapse
    dw real = lambda * pre_trace * ( 1 - w )**mu_plus
    new_w real = w + dw
    I_post_dend = min(I_post_dend, 1 pA)           # clip to 1 pA
    new_w = (I_post_dend / pA) * new_w             # "gating"
            + (1 - I_post_dend / pA) * w           # of the weight update
    w = min(1, new_w)                              # enforce w <= 1
  end

  [...]
end
```

Thank you

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Tanguy Fardet
Jessica Mitchell
Sara Konradi

... and to all our users!

Human Brain Project

EBRAINS

JÜLICH
FORSCHUNGSZENTRUM

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