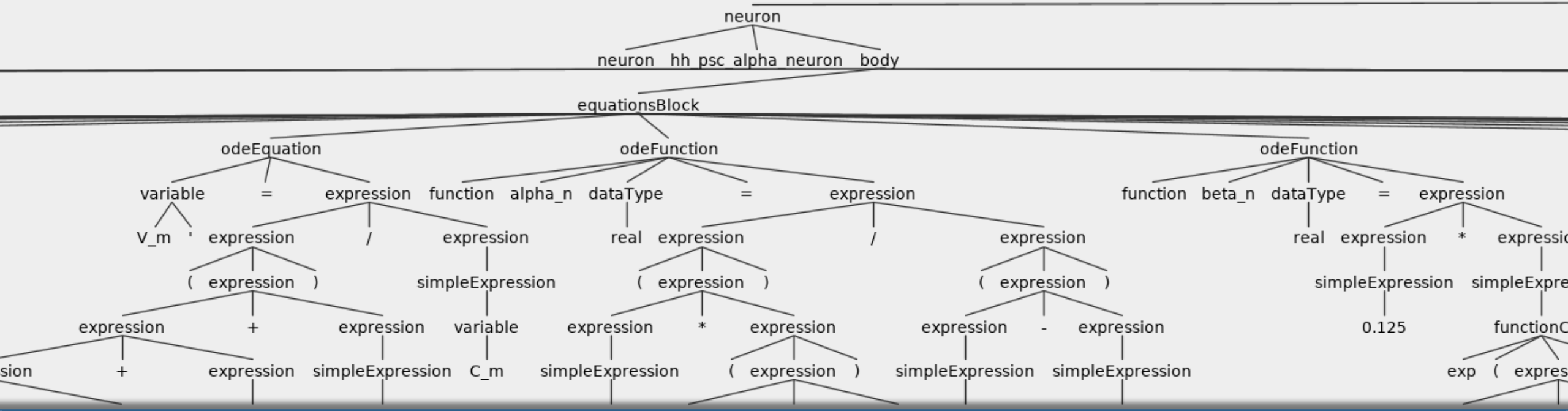


Neuron and synapse models in NESTML:
From specification to simulation

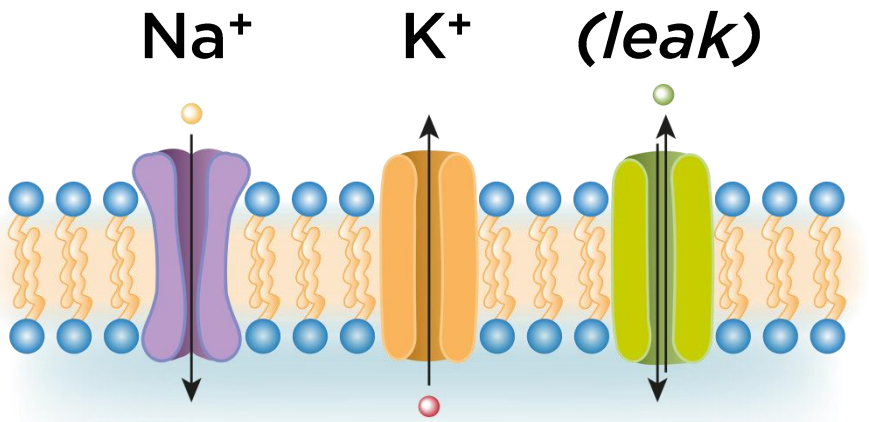
Charl Linssen & Pooja Babu | OCNS Melbourne 2022 | July 16th

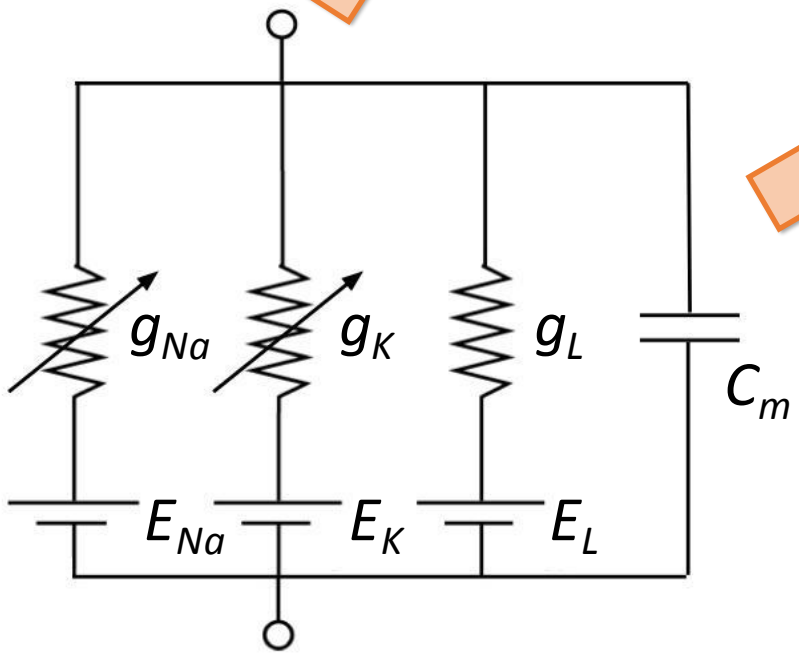
JÜLICH
Forschungszentrum
Member of the Helmholtz Association

NESTML enhances your simulation platform with **new neuron and synapse models**. Write your own, custom model, or pick one from our models library to get started straight away.

HPC use case

Interactive use case






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

  equations:
    kernel 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
```

nest::ml

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

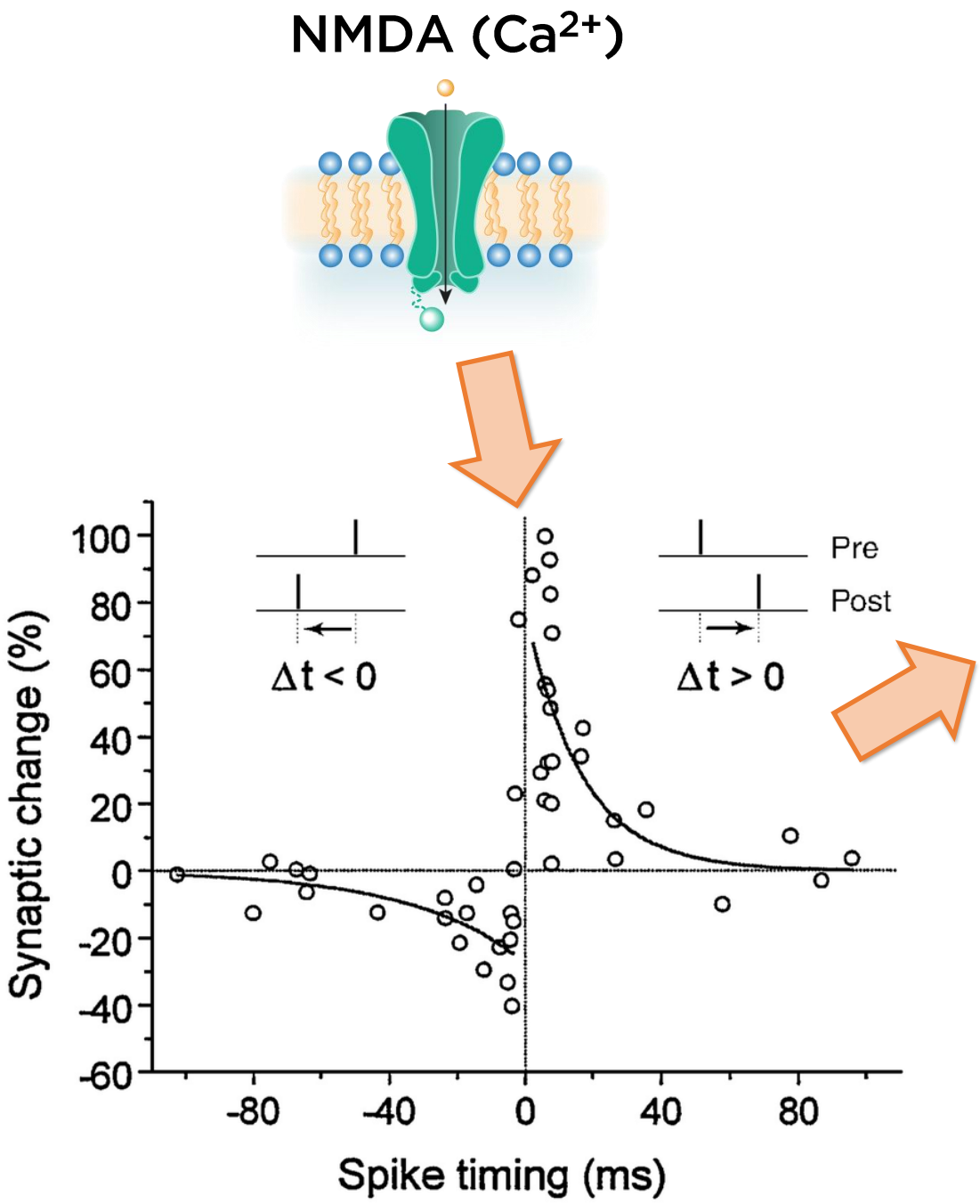


Image credit: (c) S.B.C. Lehmann, FZ Jülich, (m) C. Linssen; Bi & Poo 2001

```
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
```

```
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 <- 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
```

```
synapse stdp:
  state:
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  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

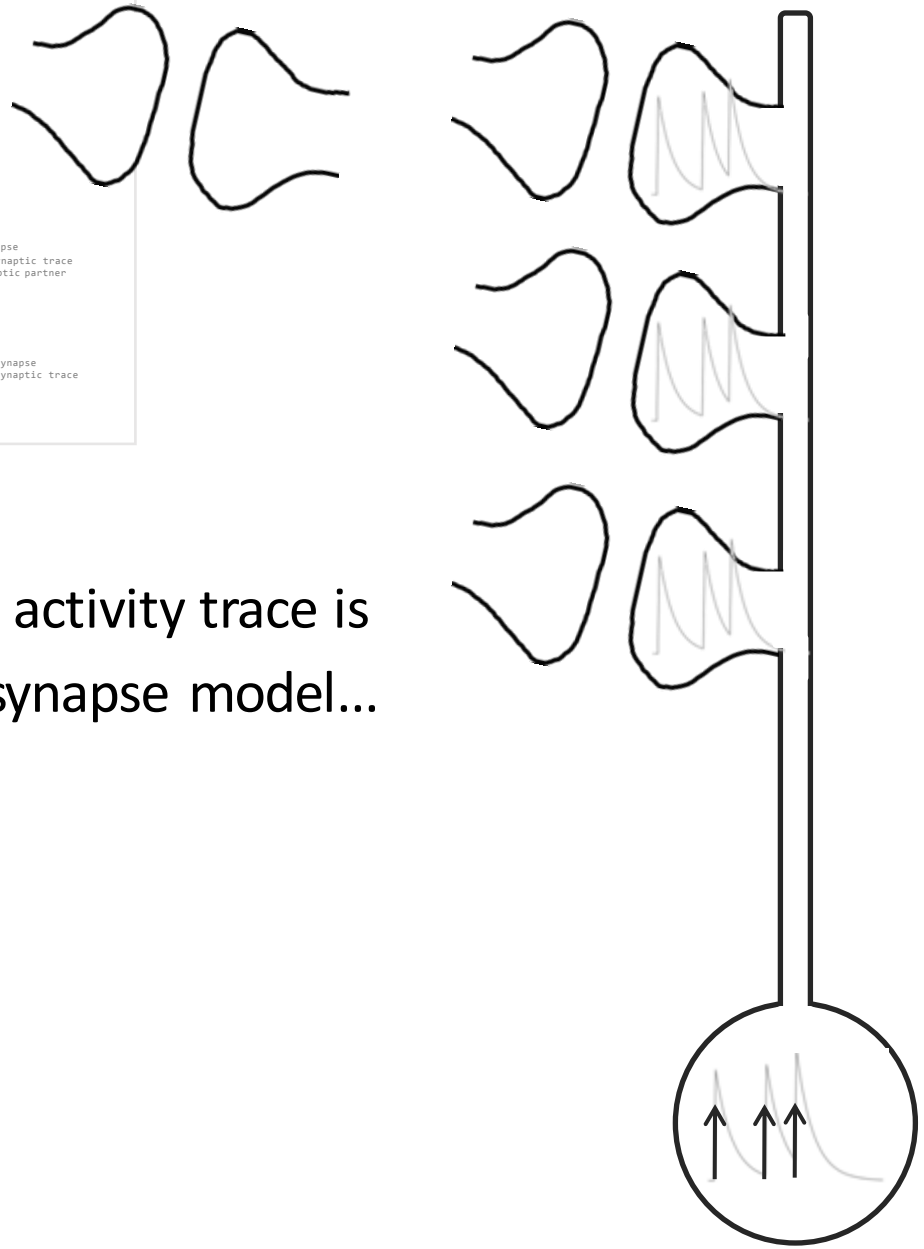
  preReceive:
    w -= alpha * tr_post        # depress synapse
    tr_pre += 1                 # update presynaptic trace
    deliver_spike(w, delay)     # to postsynaptic partner
  end



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

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

Postsynaptic activity trace is specified in synapse model…



… but needs to be simulated as part of the neuron model to avoid redundant computations.

```
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  end

  equations:
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    [...]
  end

  parameters:
    C_m pF = 250 pF
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```

```
synapse stdp:
  state:
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    tr_pre' = tr_pre / tau_tr
    tr_post' = tr_post / tau_tr
  end

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

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```
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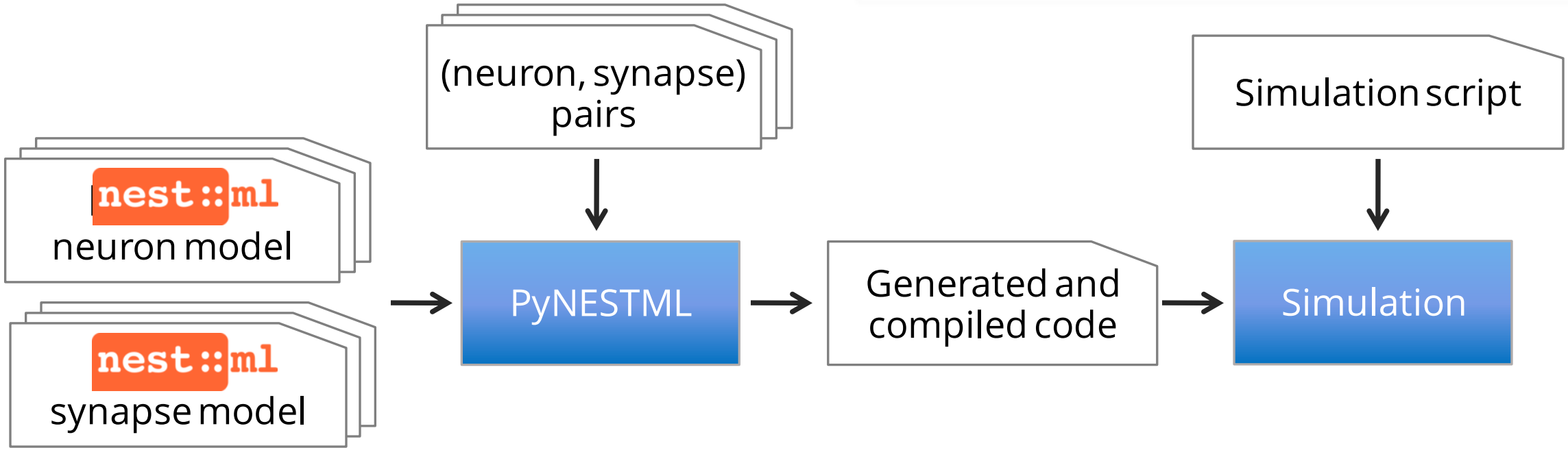
    V_m' = -(I_Na + I_K + I_L) / C_m
           + convolve(syn_psc_kernel, spikes)
    [...]
  end

  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
```

Workflow

```
>>> import nest
>>> pre, post = nest.Create('hodgkin_huxley', 2)
>>> nest.Connect(pre, post,
     'all_to_all', syn_spec={'synapse_model': 'stdp'})
>>> nest.Simulate(1000)
```



Workflow

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>>> import nest
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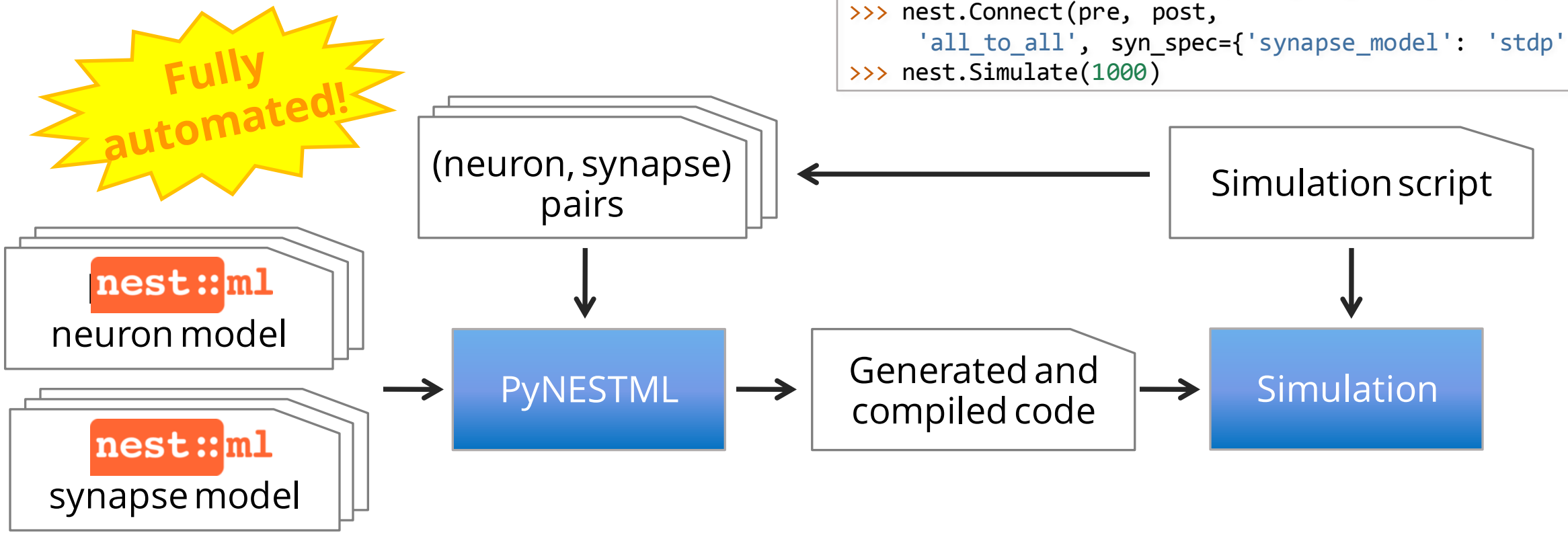
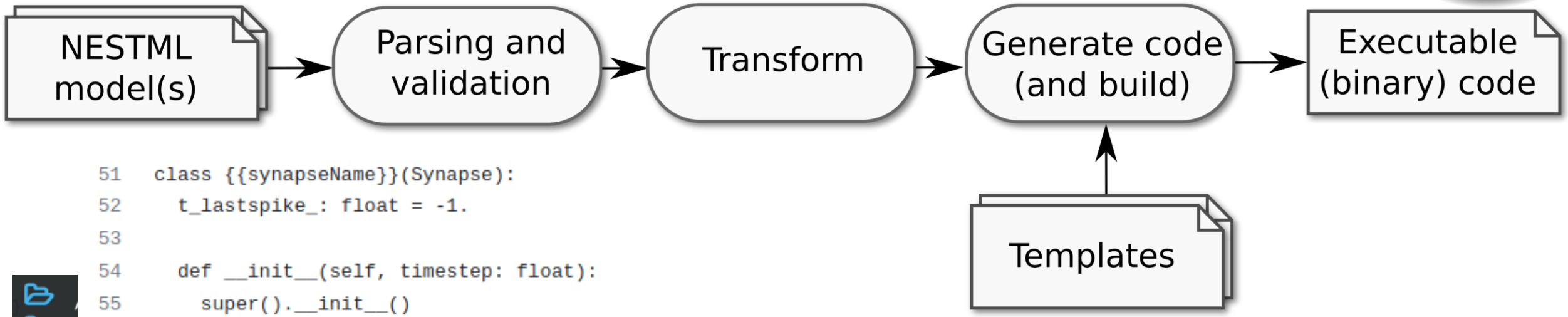
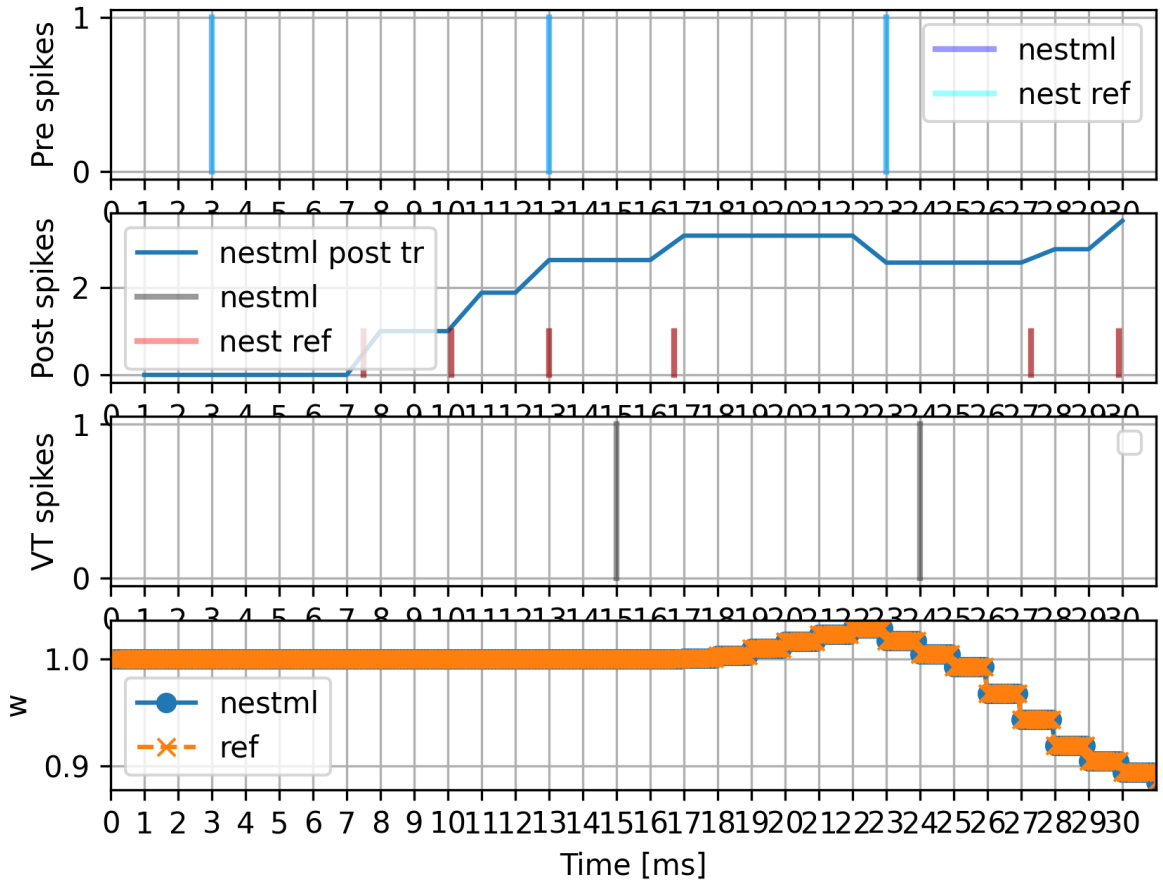


PyNESTML toolchain: modular and extensible




```
51  class {{synapseName}}(Synapse):
52    t_lastspike_: float = -1.
53
54    def __init__(self, timestep: float):
55      super().__init__()
56
57      self.P_ = self.Parameters_()
58      self.S_ = self.State_()
59      self.V_ = self.Variables_()
60      self.B_ = self.Buffers_()
61
62  {%- if parameter_syms_with_iv|length > 0 %}
63      # initial values for parameters
64  {%- filter indent(4) %}
65  {%- for parameter in parameter_syms_with_iv %}
66  {%-   with variable = parameter %}
67  {%-     include "directives/MemberInitialization.jinja2" %}
```

Neuromodulated STDP



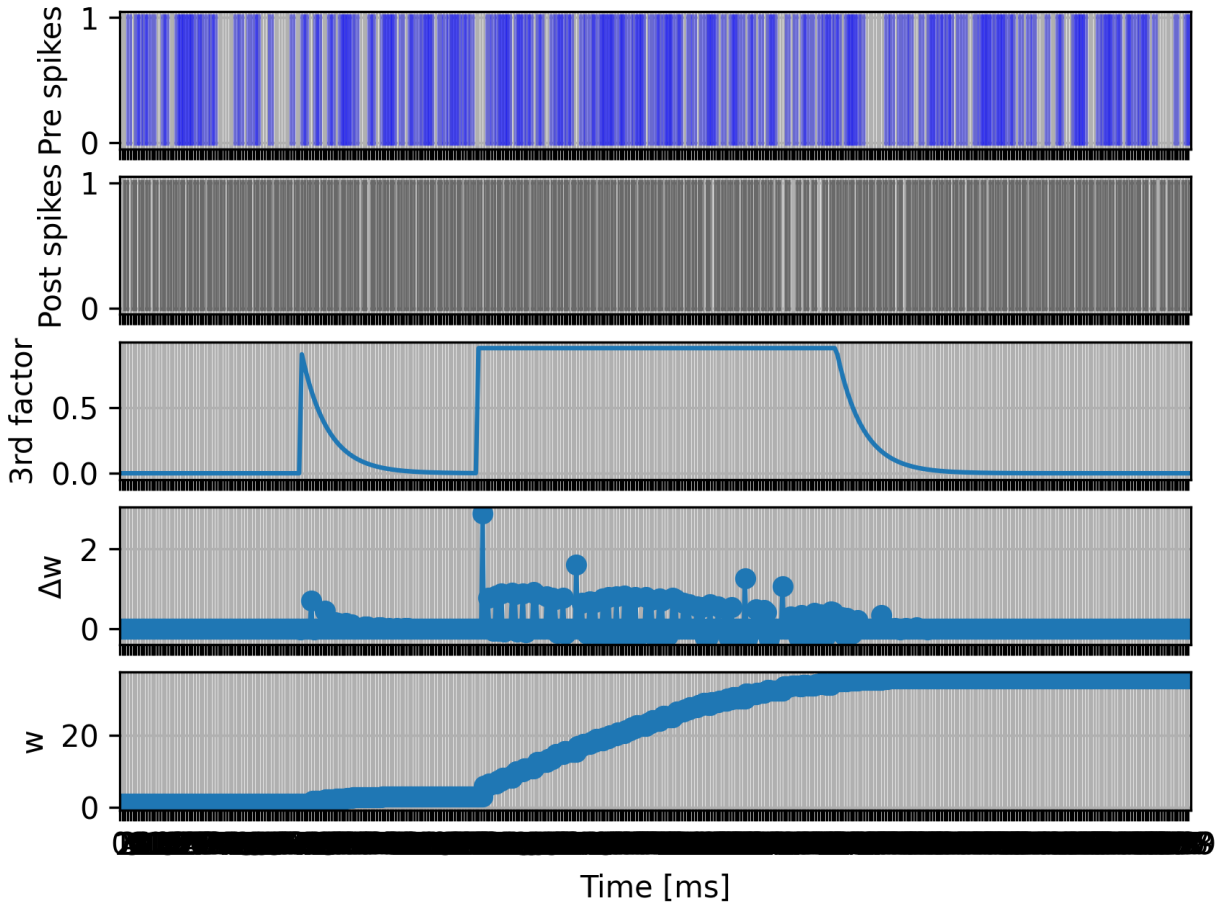

```
synapse stdp_dopa:
  input:
    [...]
    mod_spikes real <- spike
  end

  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
```

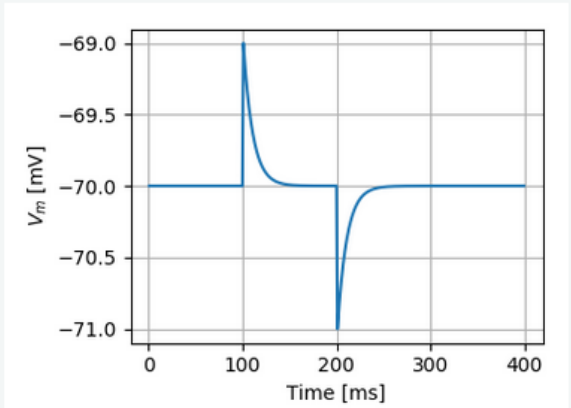
NESTML software development uses best practices in software engineering.

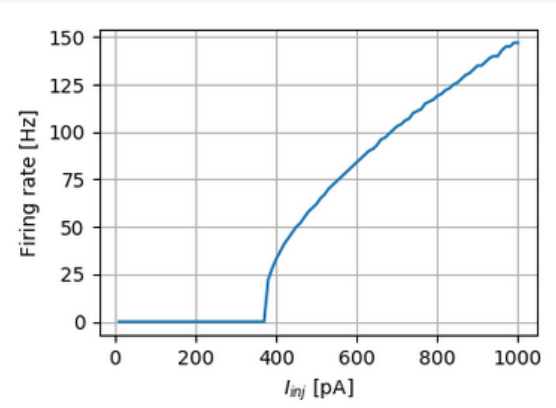
- Unit tests: language feature tests; physical units consistency; etc.
- Integration tests: models are behaviourally validated in one or more simulation runs
- Extensive documentation and automated HTML documentation generation for models: https://nestml.readthedocs.org/
- Open development: https://github.com/nest/nestml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

Models library

iaf_psc_delta

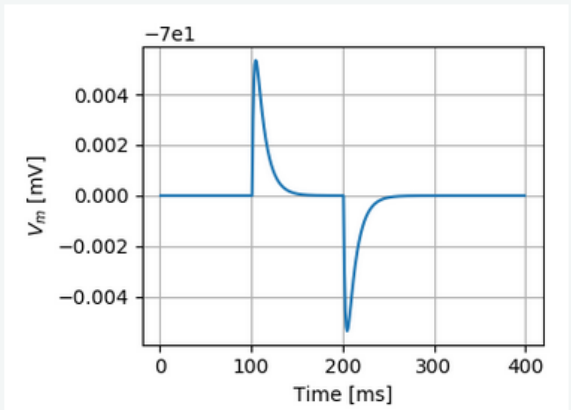
Source file: iaf_psc_delta.nestml

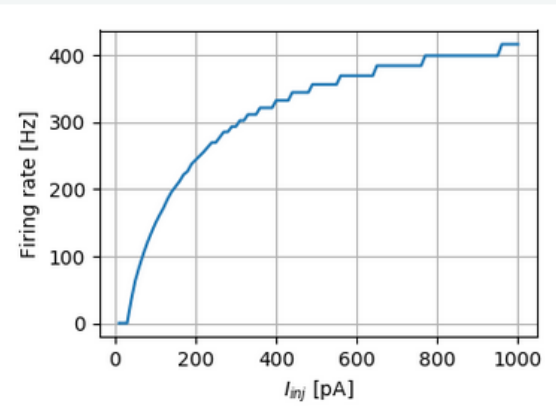




iaf_psc_exp

Source file: iaf_psc_exp.nestml

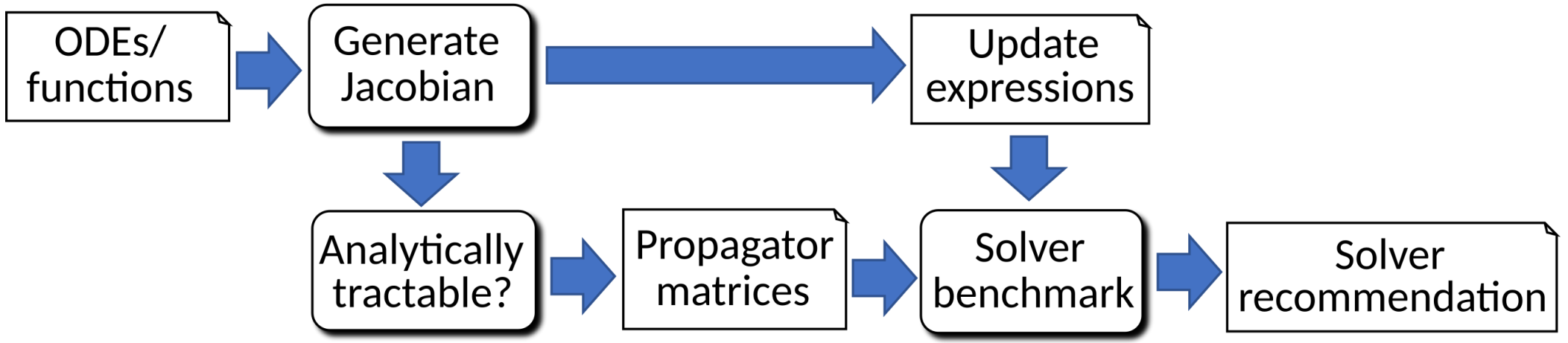




ODE-toolbox:

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



Thank you

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... and to all our users!

EBRAINS

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