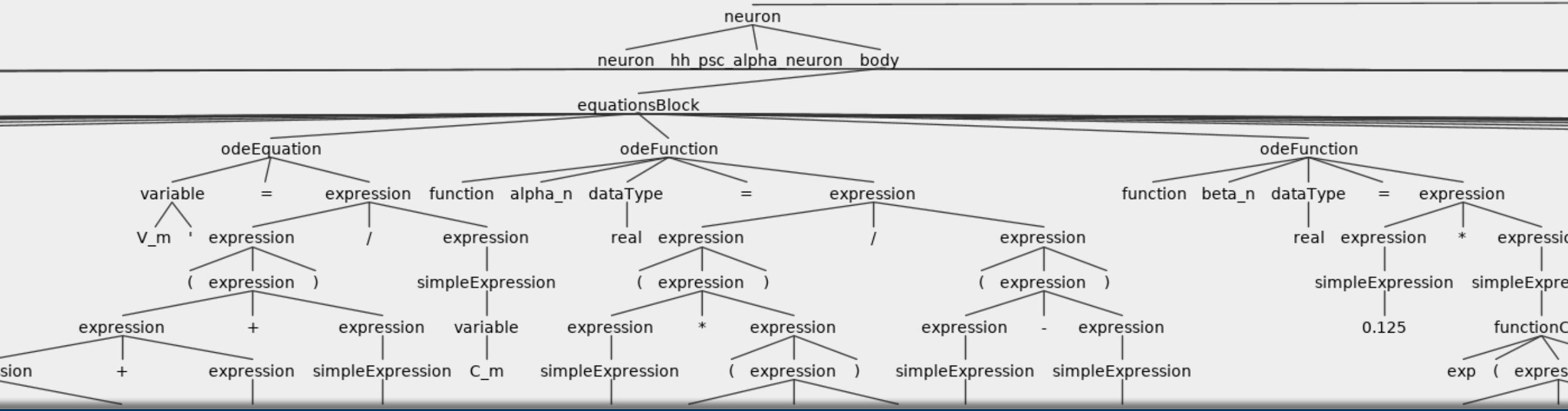

NESTML: CODE GENERATION FOR NEURON AND SYNAPSE MODELS

18 July 2020 I CNS2020 | Charl Linssen <c.linssen@fz-juelich.de>

Co-funded by the European Union

Human Brain Project

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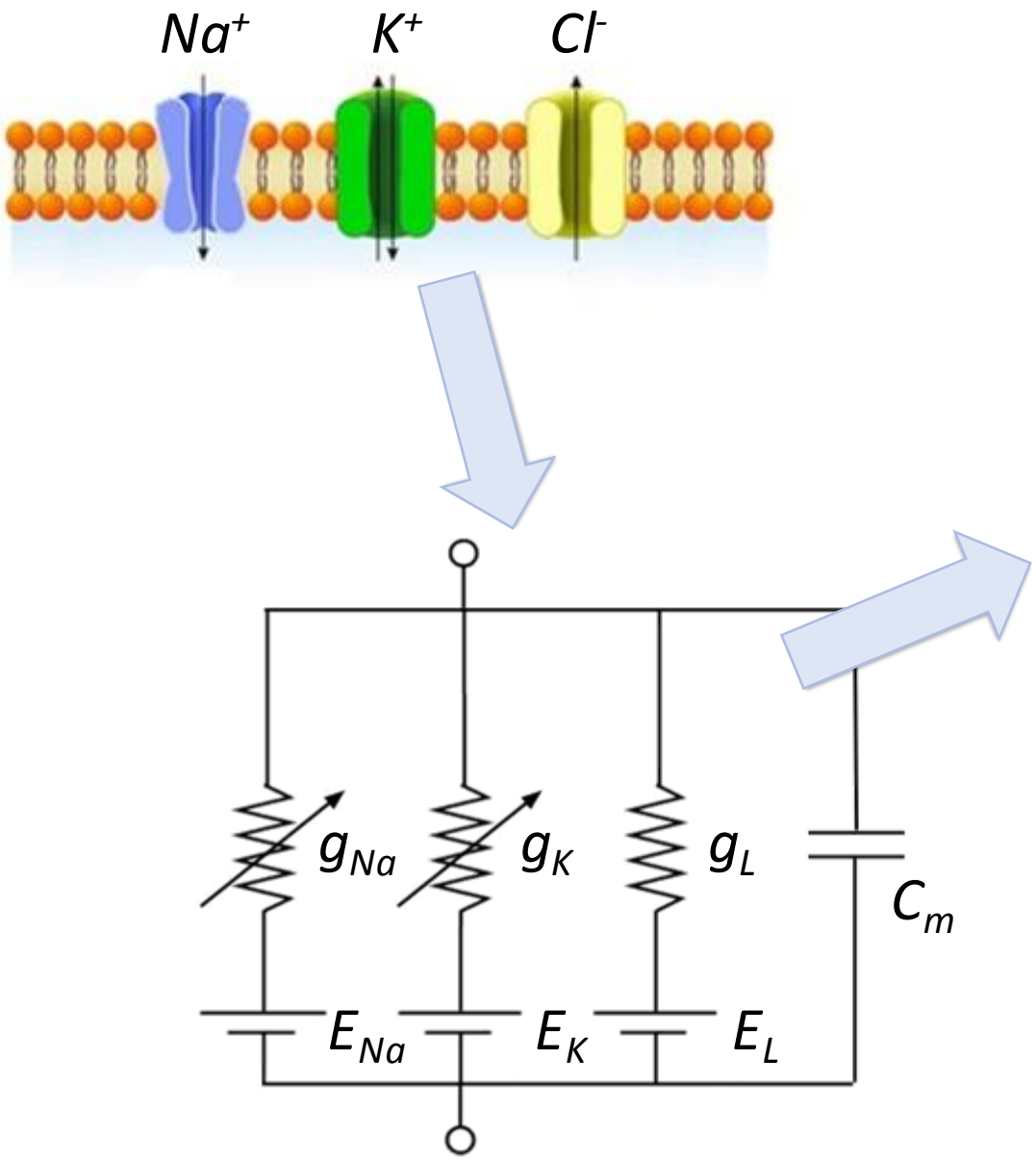


```
neuron hodgkin_huxley:
  state:
    V_m mV = -65 mV
    Act_m, Act_n, Inact_h ...
  end

  equations:
    shape syn_psc_kernel = exp(-t / tau_syn)
    function I_Na pA = g_Na * Act_m**3 * Inact_h * (V_m - E_Na)
    function I_K pA = ...
    function 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

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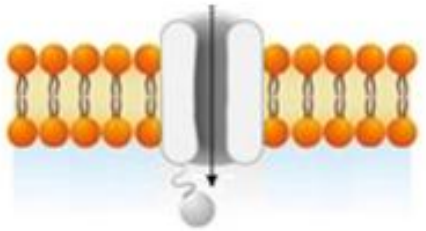
Image credit: Designua / Shutterstock

NMDA (Ca^{2+})



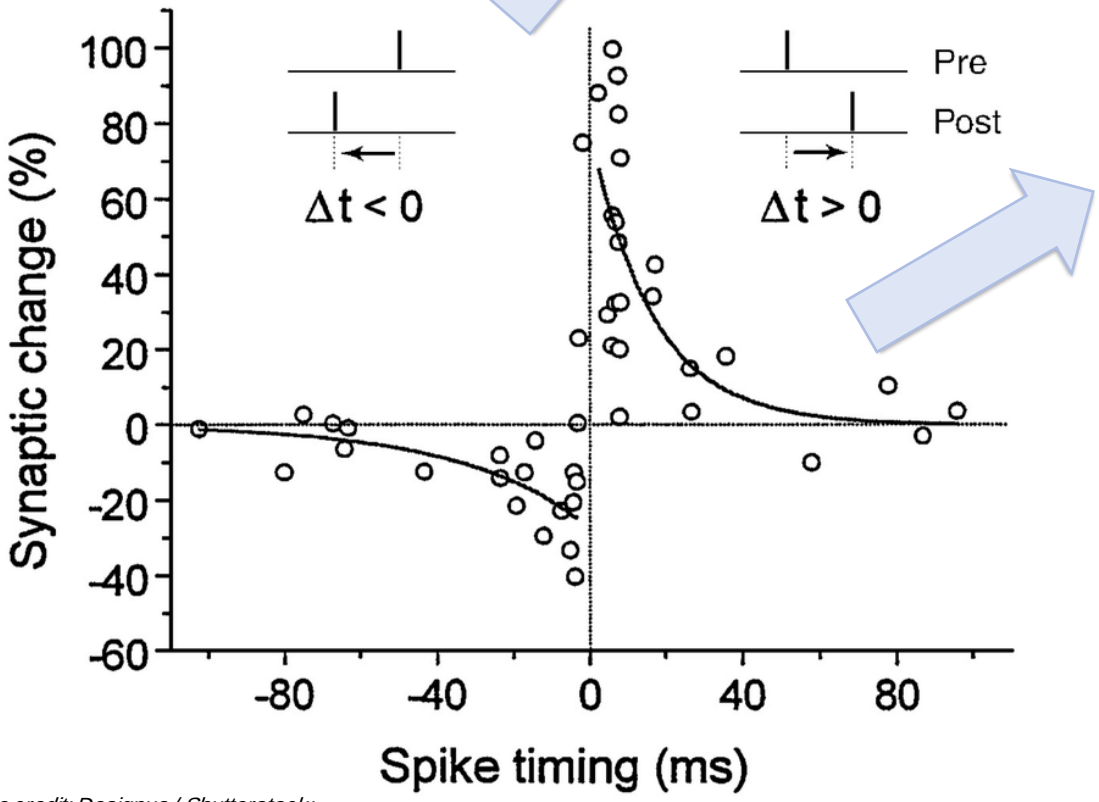


Image credit: Designua / Shutterstock; Bi & Poo 2001

```
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
```

nest::ml

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What is NESTML?

SBML

NestML

NeuroML (v. 1)

PyNN

NineML

NeuroML (v. 2)

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What is NESTML?

NESTML is a **domain-specific language** for **neuron and synapse models**.

- Low on boilerplate, redundancy
- Speak in the vernacular of the neuroscientist (keywords such as "neuron", "synapse")
- Programming-language-like (`if V_m ≥ threshold: ...`)

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

- Code generation (model definition but *not* instantiation)
- Platform-awareness (loose platform coupling)

```
spiking_neuron iaf_psc_delta:
  state:
    V_m mV = 0
  end

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

  parameters:
    C_m      pF = 250 pF
    tau      ms = 10 ms
    ...
  end

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

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

Comparison between NESTML and generated code

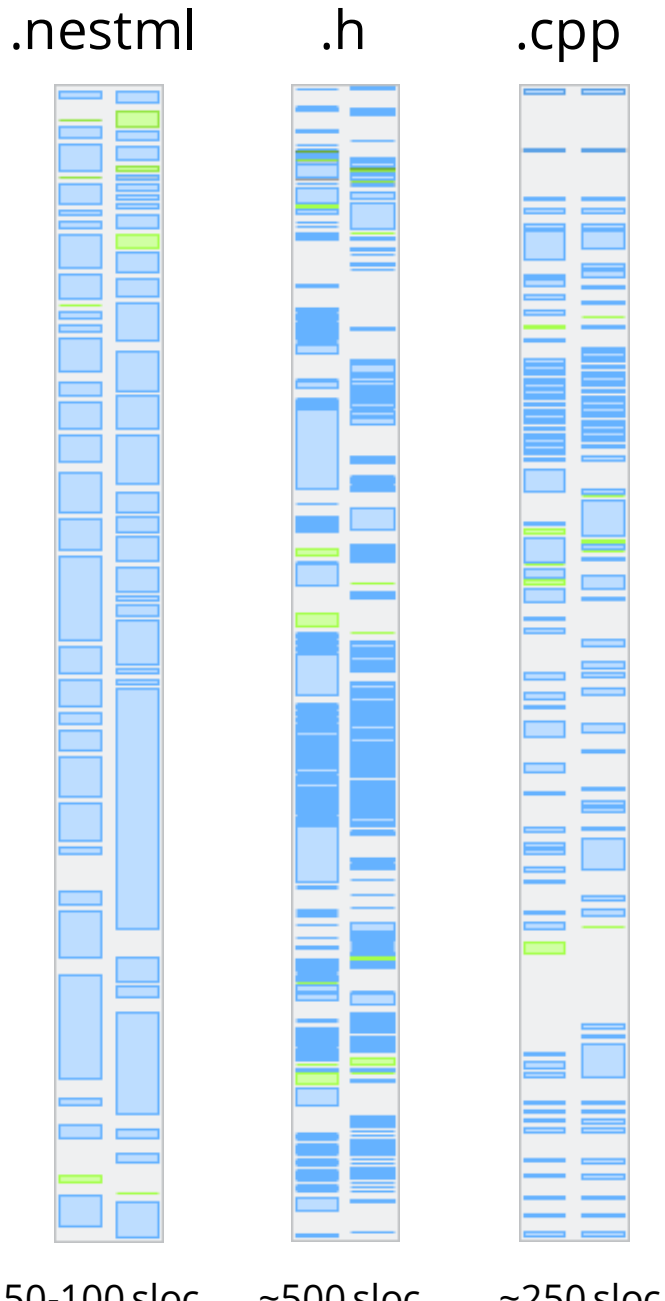
`terub_neuron_gpe` (left)

vs.

`aeif_cond_alpha` (right)

Legend:

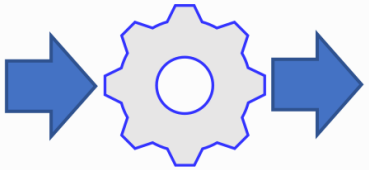
- lines can be matched, but content differs
- lines exist on one side but not the other
- complete match (no difference)

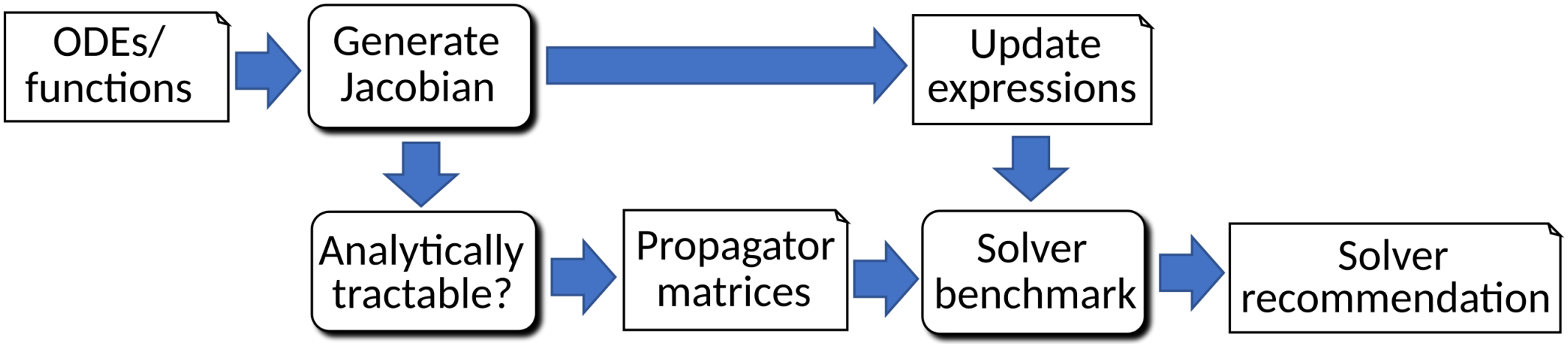


Automated processing of differential equations

```
equations:
    h_Na'   = (h_infNa  - h_Na) / t_hNa
    [...]
    shape g'' = (-2/tau_syn)  * g' - (1/tau_syn**2)  * g
    [...]
    V_m' = (-I_leak  - I_syn_exc  - I_syn_inh  + I_e) / C_m
    [...]
end
```

ODE-toolbox





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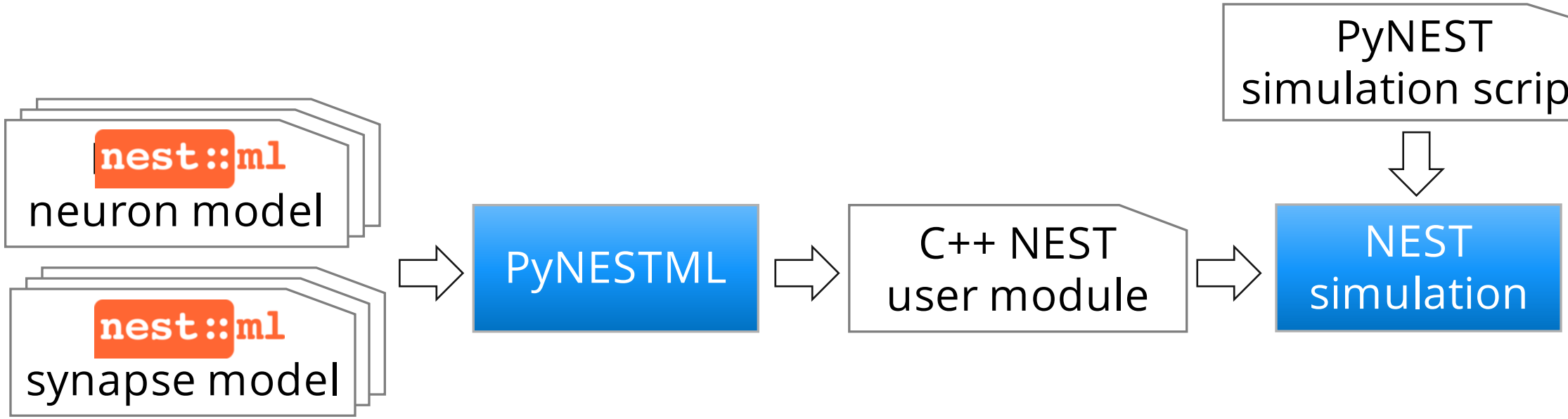
Typical NESTML workflow

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




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

$ nestml --input_path=models
```

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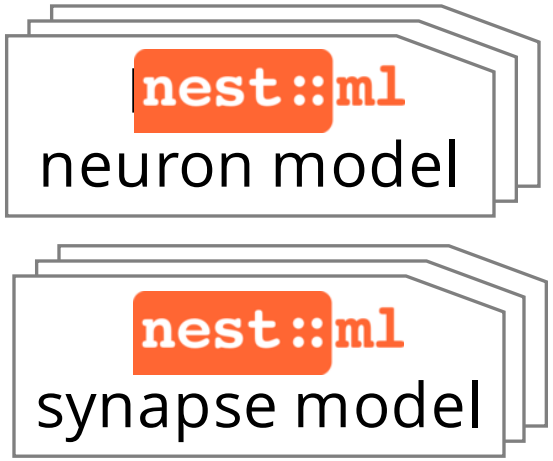
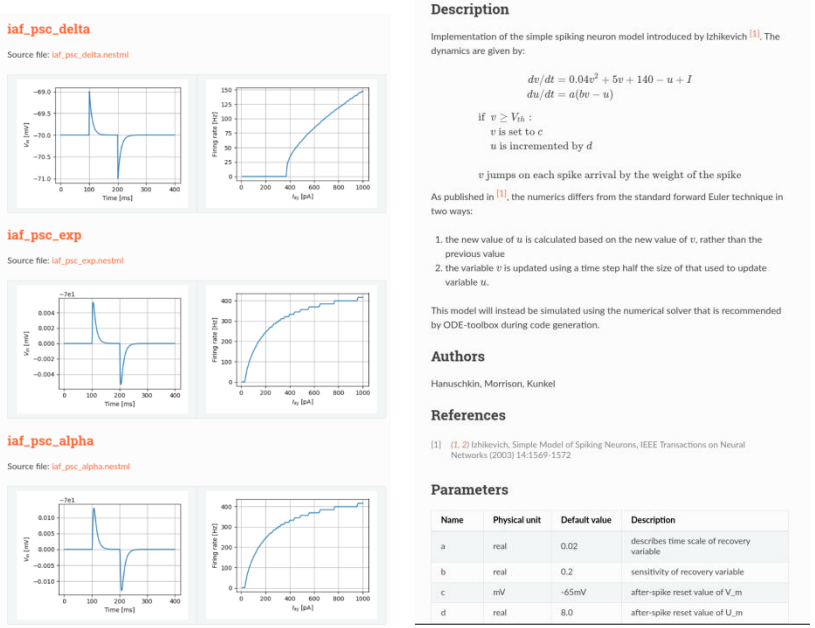
NESTML documentation workflow



PyNESTML

MarkDown

Read the Docs



View the NESTML models library at
https://nestml.readthedocs.io/en/latest/models_library/

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

$ nestml --input_path=models
```

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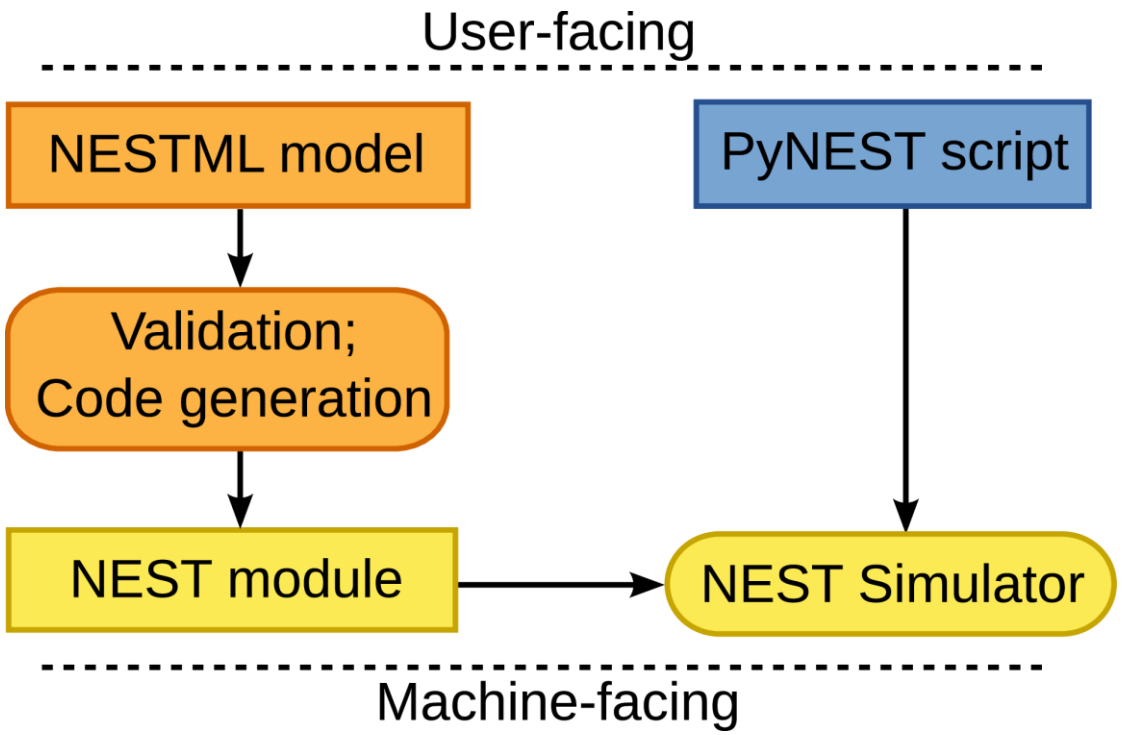
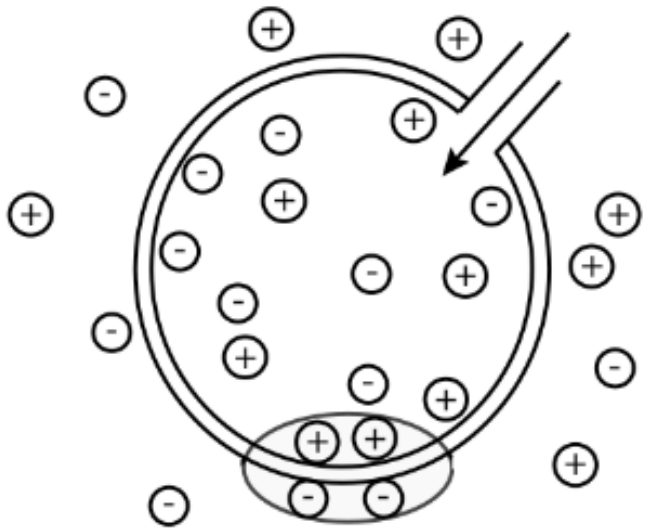
Integration with NEST Simulator



Mapping biological neurons to NESTML

Model

neuron-model based on an RC-circuit



NESTML

<<rc_neuron.nestml>>

```
neuron rc_neuron:


end
```

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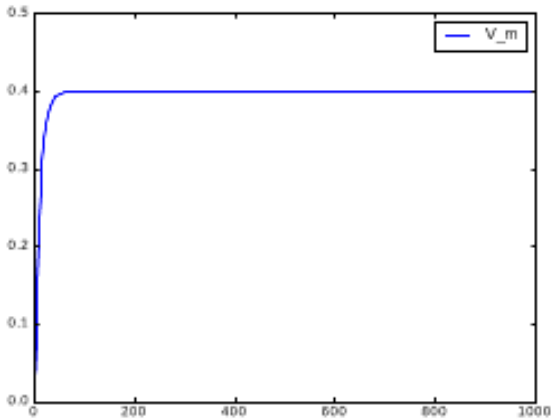
Mapping biological neurons to NESTML

Model

$$\frac{d\,V_\mathrm{m}}{dt} = -\frac{V_\mathrm{m}}{\tau_\mathrm{m}} + \frac{I_\mathrm{syn}}{C_\mathrm{m}}$$



NESTML

<<rc_neuron.nestml>>

```
neuron rc_neuron:

  initial_values:
    V_m mV = 0 mV
  end

  equations:
    V_m' = -V_m/tau_m + I_syn/C_m
  end

  parameters:
    # values taken from experiments
    C_m pF    = 250 pF
    tau_m ms  = 10 ms
    I_syn pA  = 10 pA
  end

  update:
    integrate_odes()
  end

end
```

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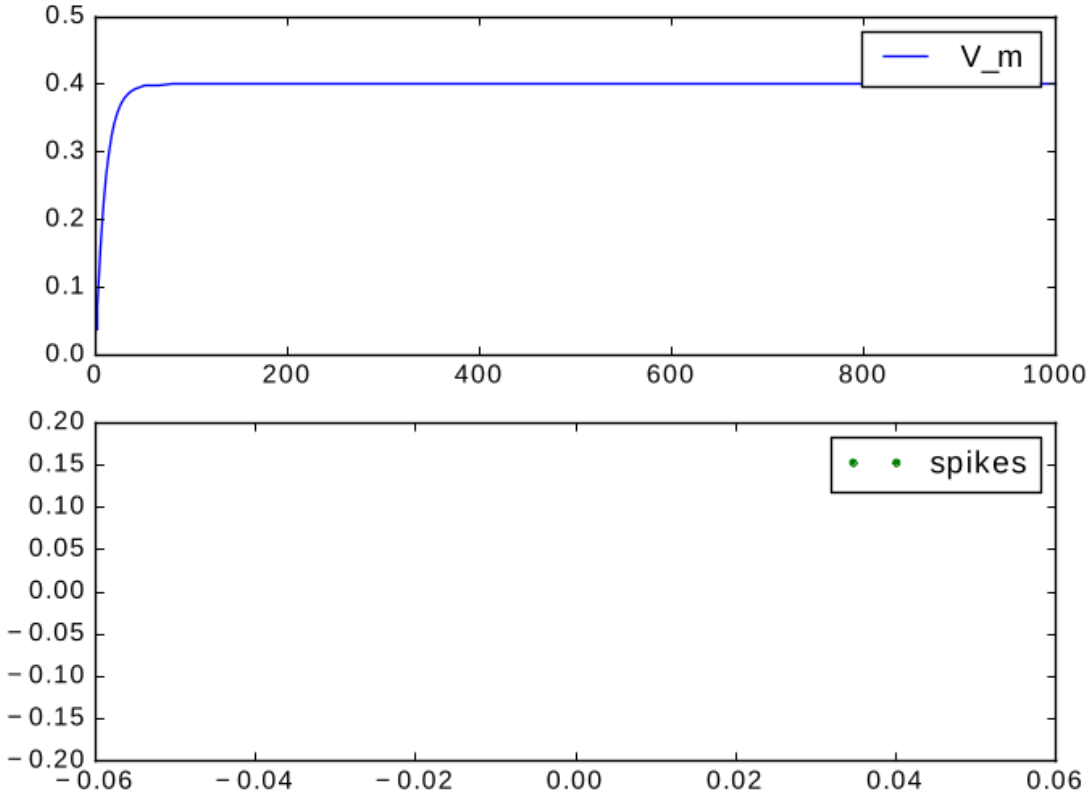
Mapping biological neurons to NESTML

- Simulating `rc_neuron` for 1000 ms with constant input current of 10 pA

→ Strictly positive membrane potential

→ No spikes



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Adding the resting potential E_L

- Shift V_m by E_L:

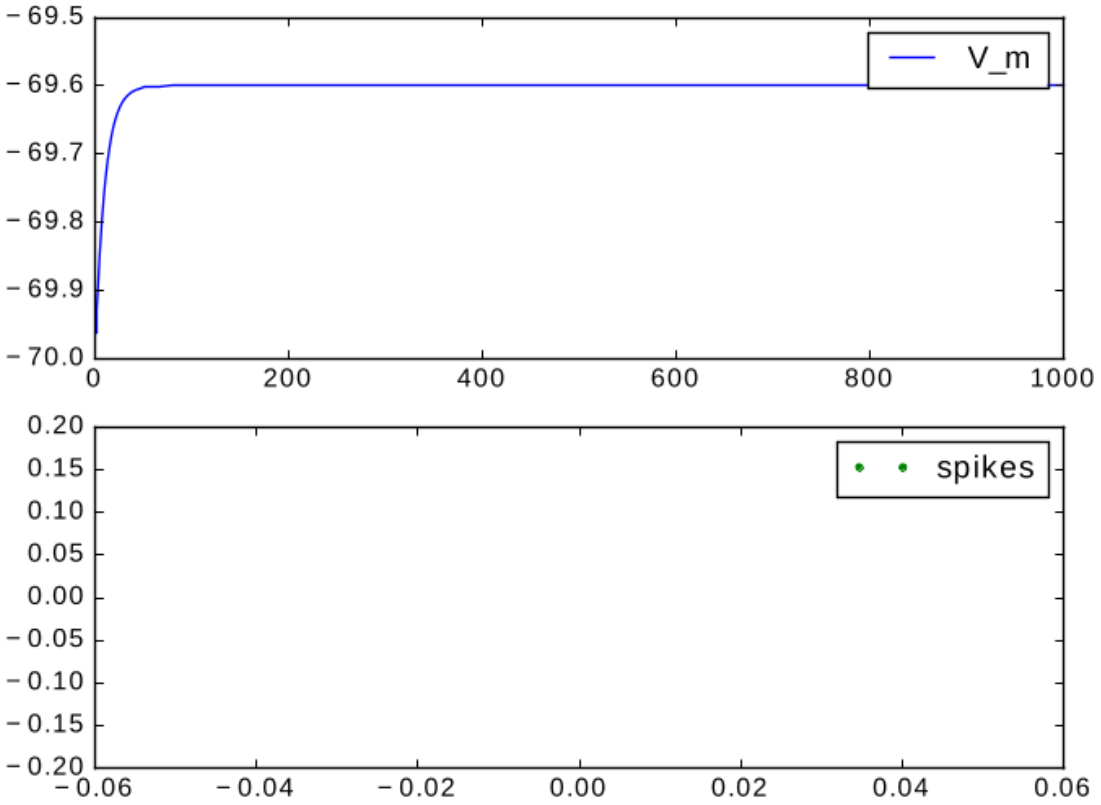
```
neuron rc_neuron_rest:
  initial_values:
    V_m mV = E_L
  end

  equations:
    V_m' = -(V_m-E_L)/tau_m + I_syn/C_m
  end

  parameters:
    E_L mV = -70 mV
  end

  ...
end
```

→ Still no spikes



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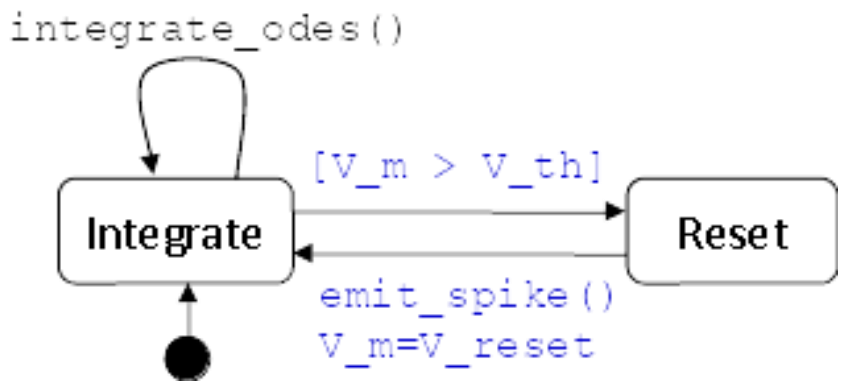
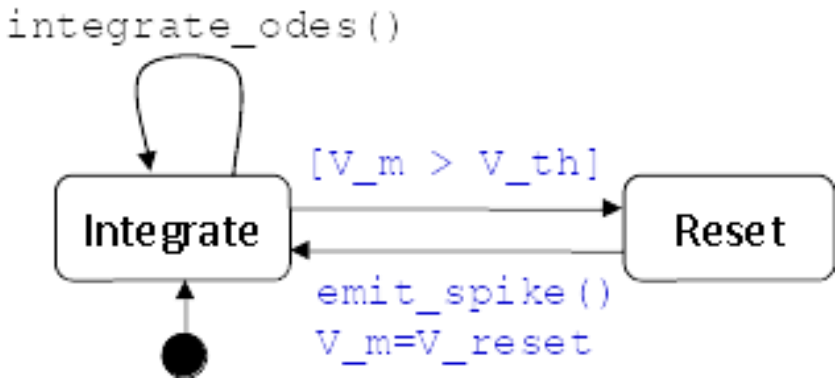
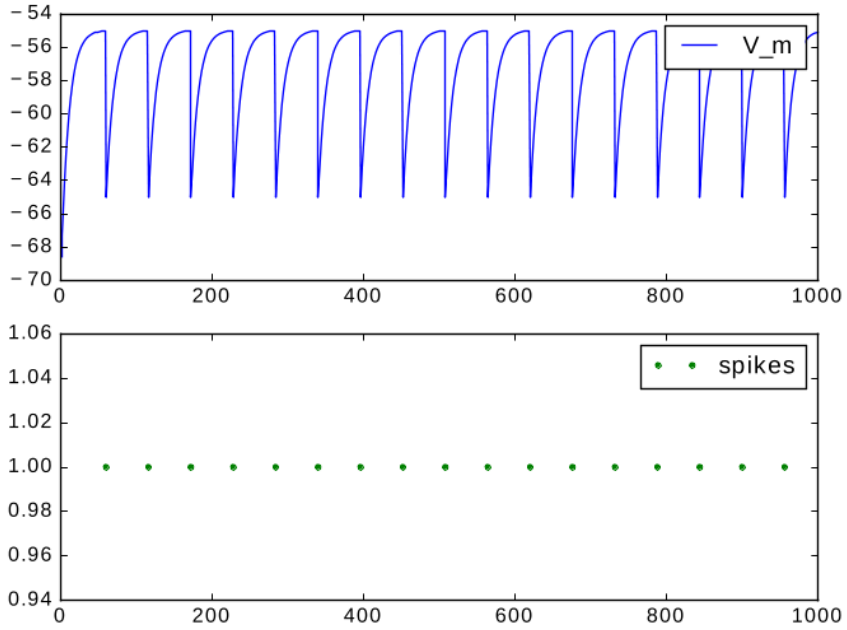
Spiking and reset




```
neuron rc_fire:
  parameters:
    V_th mV = -55 mV - E_L
  end
  update:
    integrate_odes()
    if V_m >= V_th:
      V_m = V_reset
      emit_spike()
    end
  end
  ...
end
```

Spiking and reset





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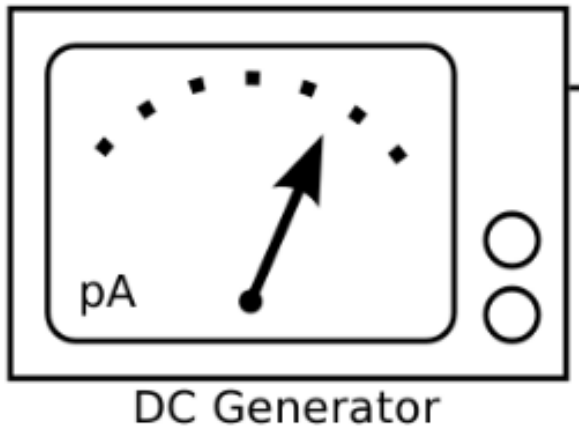
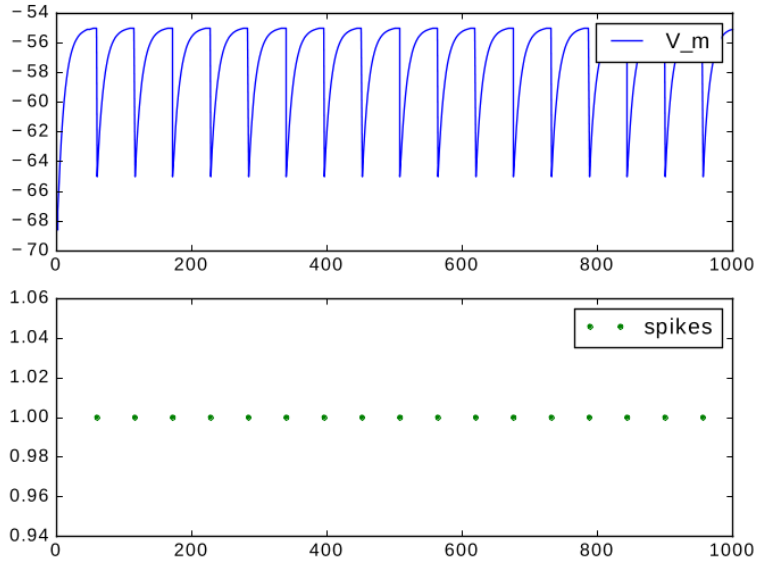
Injecting currents

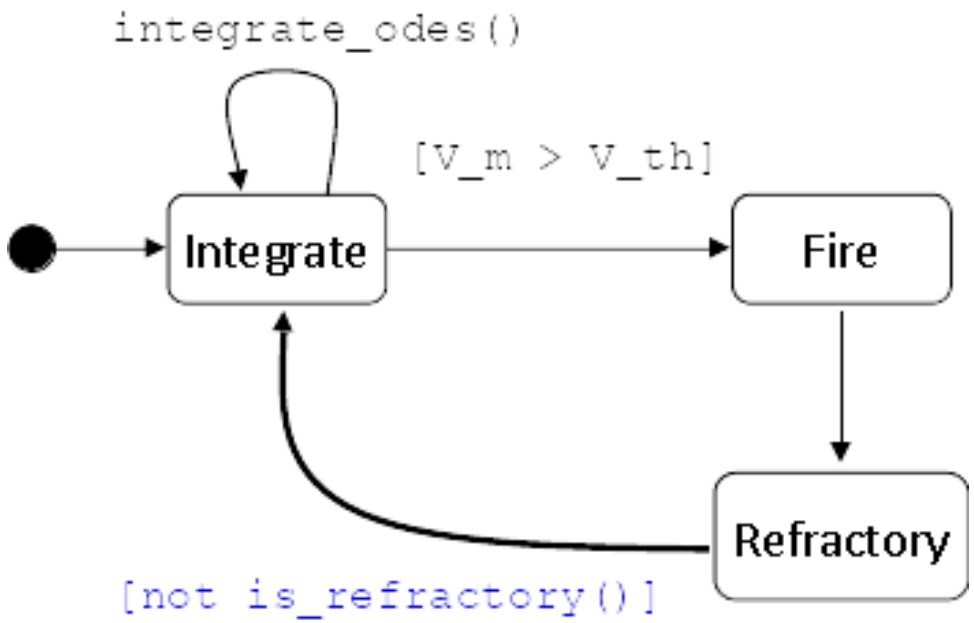



```
currents = nest.Create('dc_generator', 1,
                       {'amplitude':
100.0})
nest.Connect(currents, rc_neuron)
```

```
neuron rc_neuron:
...
  equations:
     function I_syn pA = I_e + convolve(I_a, spikes) + currents
     V_m' = -V_m/tau_m + I_syn/C_m
  end

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

  output: spike

...

end
```



Refractoriness




```
neuron rc_refractory:
  parameters:
    ref_counts integer = 0
    ref_timeout ms = 2 ms
  end
  internals:
    timeout_ticks integer = steps(ref_timeout)
  end
  update:
    if ref_counts == 0:
      integrate_odes()
      if V_m >= V_th:
        emit_spike()
        ref_counts = timeout_ticks
        V_m = V_reset
      end
    else:
      ref_counts -= 1
    end
  end
end
```

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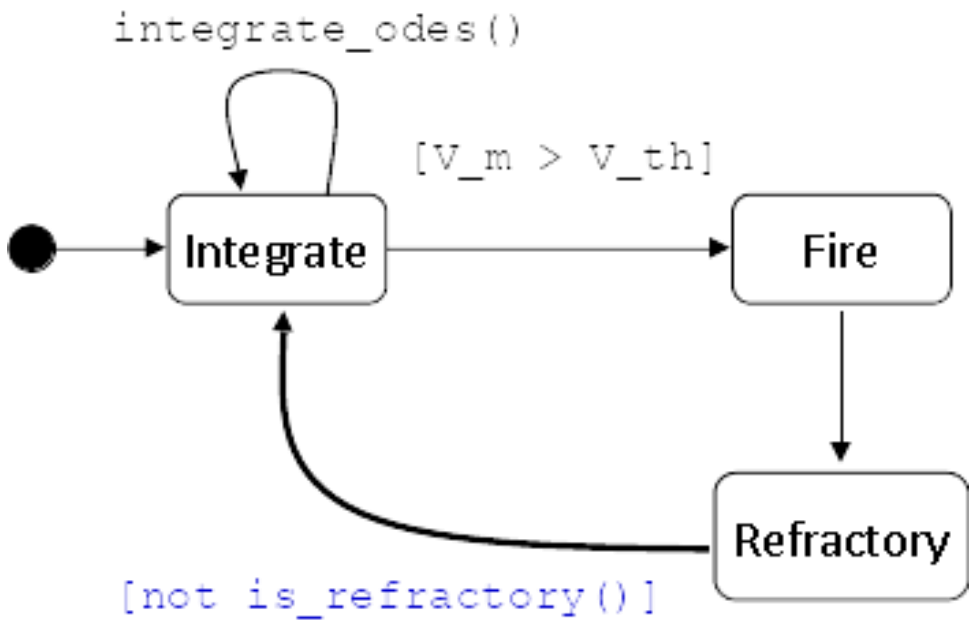
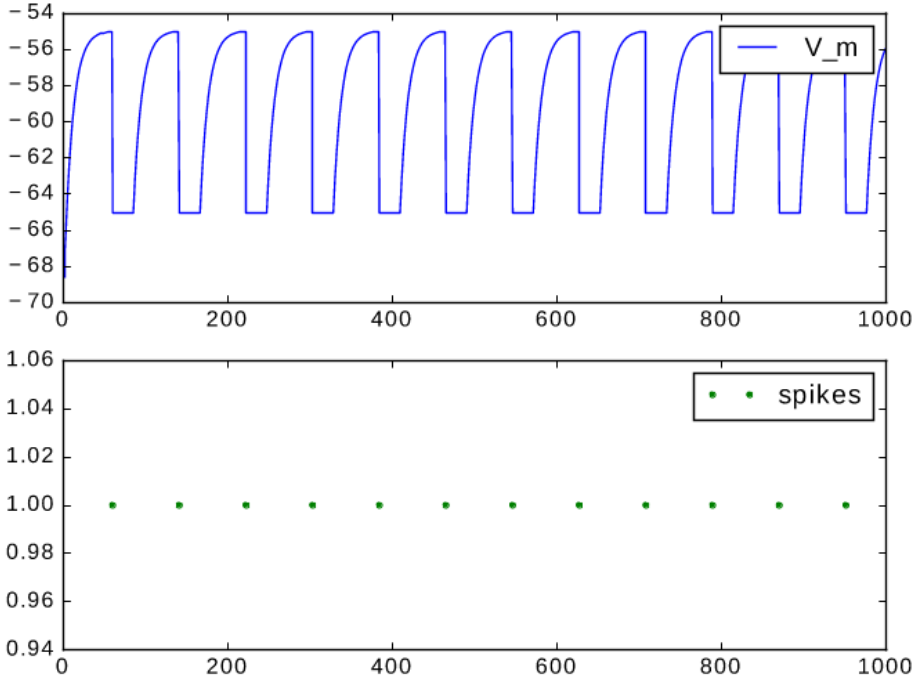
Refractoriness





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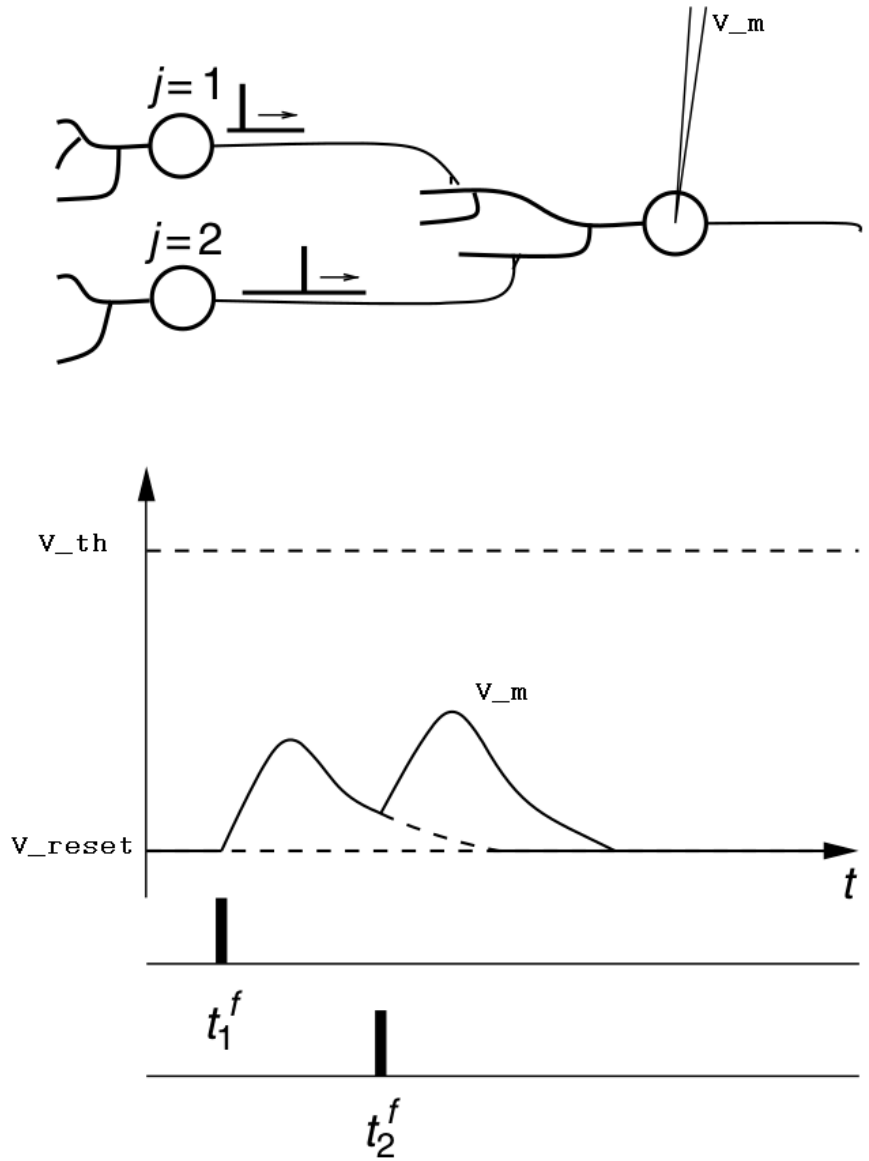
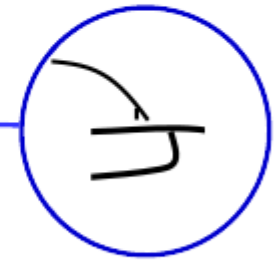
Input handling



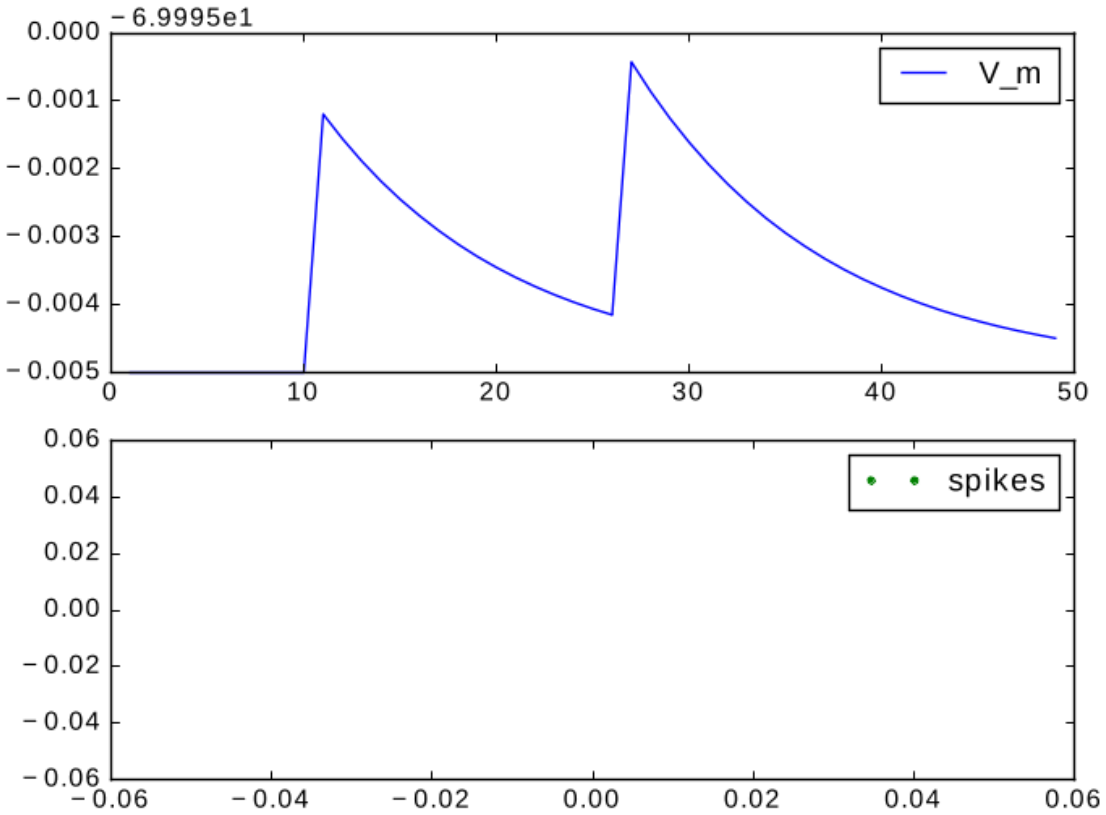
(Source: Wulfram Gerstner, Werner M. Kistler, Richard Naud, Liam Paninski-Neuronal Dynamics From Single Neurons to Networks and Models of Cognition)

Input handling

```
neuron rc_input:
  initial_values:
    V_m mV = E_L
  end

  equations:
    V_m' = -(V_m-E_L)/tau_m + I_syn/C_m
  end

  parameters:
    E_L mV = -70 mV
    ...
  end

  input:
    I_syn pA <- spike
  end

  output: spike

end
```



buffer can be `inhibitory`, `excitatory` or both (if nothing else stated)



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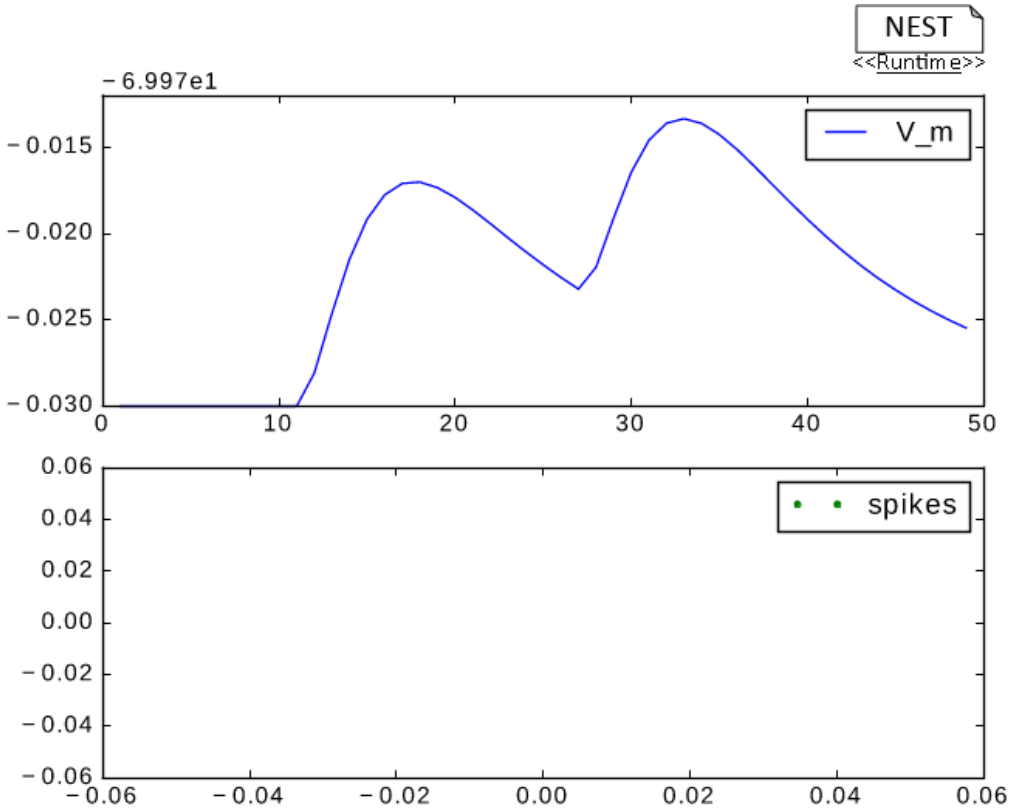
Input handling

```
neuron rc_alpha_response:
  initial_values:
    V_m mV = E_L
    I_a pA = 0 pA
    I_a' pA/ms = e/tau_syn * pA
  end


  equations:
    shape I_a'' = -2 * I_a' / tau_syn - I_a / tau_syn**2
    V_m' = -(V_m-E_L)/tau_m + convolve(I_a, spikes)/C_m
  end

  input:
    spikes pA <- spike
  end

  output: spike

  update:
    integrate_odes()
    ...
  end

end
```

$$\sum_{t_i \le t, i \in \mathbb{N}} \sum_{w \in W} w \cdot I_a(t_i - t) = \sum_{t_i \le t, i \in \mathbb{N}} I_a(t_i - t) \sum_{w \in W} w$$



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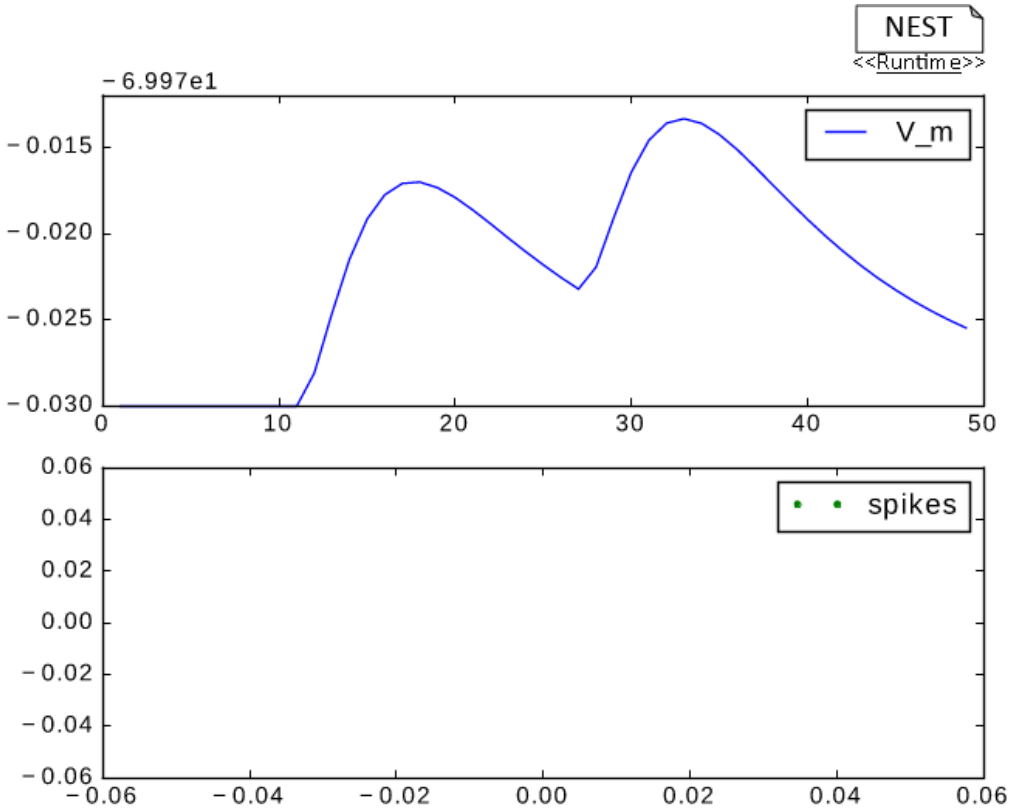
Shape notation

```
neuron rc_alpha_response_shape:
  state:
    V_m mV = E_L
  end


  equations:
    shape I_a = (e/tau_syn) * t * exp(-t/tau_syn)
    V_m' = -(V_m-E_L)/tau_m + convolve(I_a, spikes)/C_m
  end

  input:
    spikes pA <- spike
  end

  output: spike

  update:
    integrate_odes()
    ...
  end


end
```

initial values
computed automatically



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PyNEST API of generated NEST module

PyNEST

```
import nest

nest.Install("nestmlmodels")

neuron = Create("rc_neuron")
nest.SetStatus(neuron, {"V_m":-72.0,
                        "C_m":300.0})

mm = nest.Create('multimeter')
nest.SetStatus(mm, {"record_from":["V_m"]})
Connect(mm, neuron)
```

NESTML

<<rc_neuron.nestml>>

```
neuron rc_neuron:

  initial_values:
    V_m mV = -70mV
  end

  equations:
    V_m' = -(V_m-70mV)/tau_m + I_syn/C_m
  end

  parameters:
    C_m pF    = 250pF
    tau_m ms  = 10ms
    I_syn     = 10pA
  end

end
```

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Thank you!

nest::ml

https://github.com/nest/nestml

Jochen M. Eppler
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Inga Blundell
Tanguy Fardet
Jessica Mitchell
Sara Konradi

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