NESTML Tutorial

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nest::ml

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Human Brain Project
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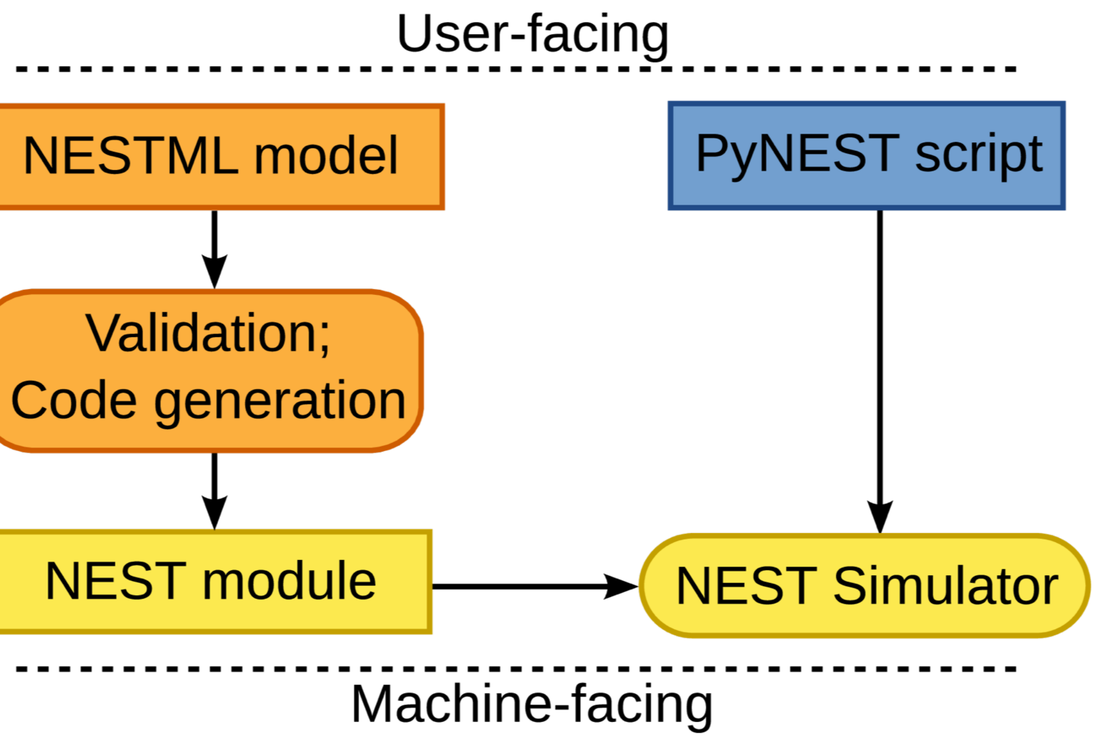
Introducing NESTML

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



Using PyNEST, you instantiate and connect the models that you define in NESTML.

Introducing NESTML

- Concise; low on boilerplate
- Speak in the vernacular of the neuroscientist (keywords such as `neuron`, `synapse`)
- Easy (dynamical) equation handling coupled with imperative-style programming (`if V_m >= V_threshold: ...`)

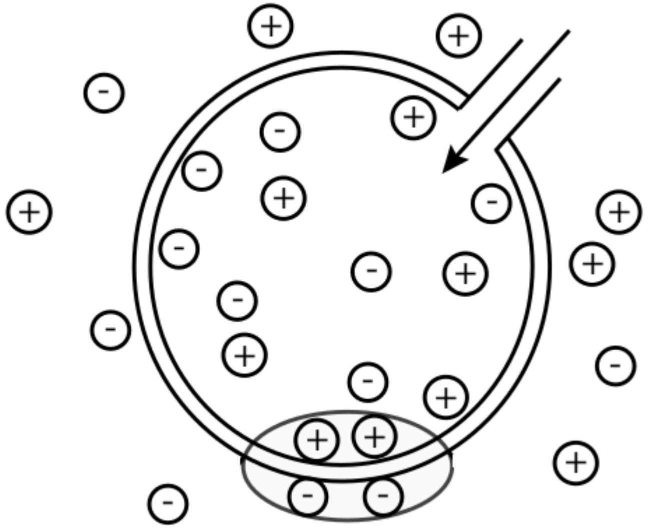
NESTML comes with a **code generation** toolbox.

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

Mapping biological neurons to NESTML

Model

neuron-model based on an RC-circuit



NESTML

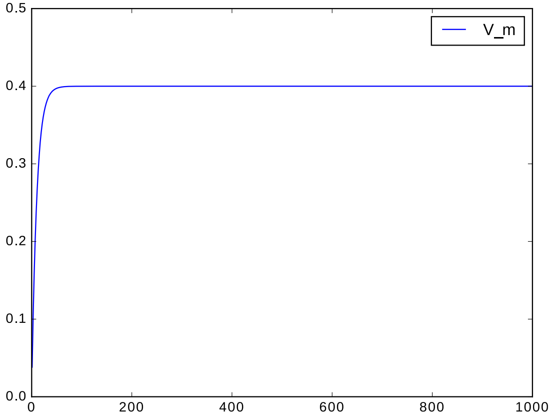
<<rc_neuron.nestml>>

```
neuron rc_neuron:

end
```

Mapping biological neurons to NESTML

Model

$$\frac{d\,V_m}{dt} = -\frac{V_m}{\tau_m} + \frac{I_{syn}}{C_m}$$



NESTML

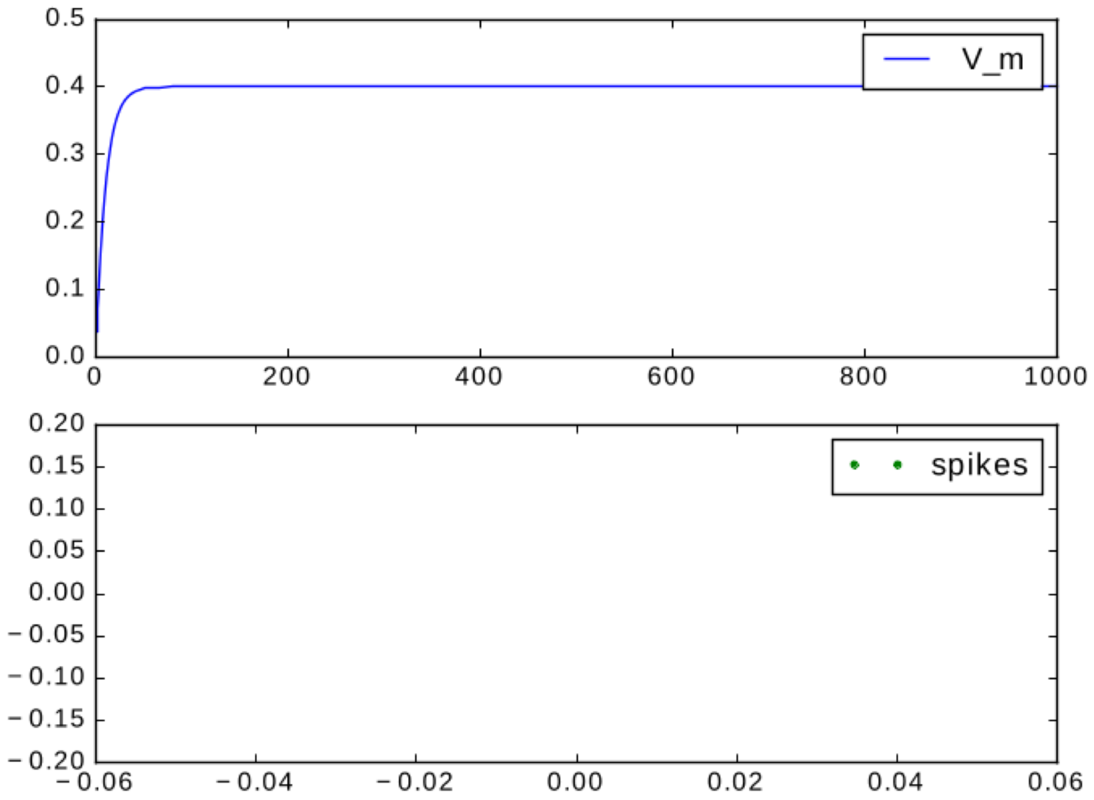
<<rc_neuron.nestml>>

```
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
```

Simulating `rc_neuron`

NEST
<<Runtime>>

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



→ Strictly positive membrane potential

→ No spikes

Adding the resting potential `E_L`

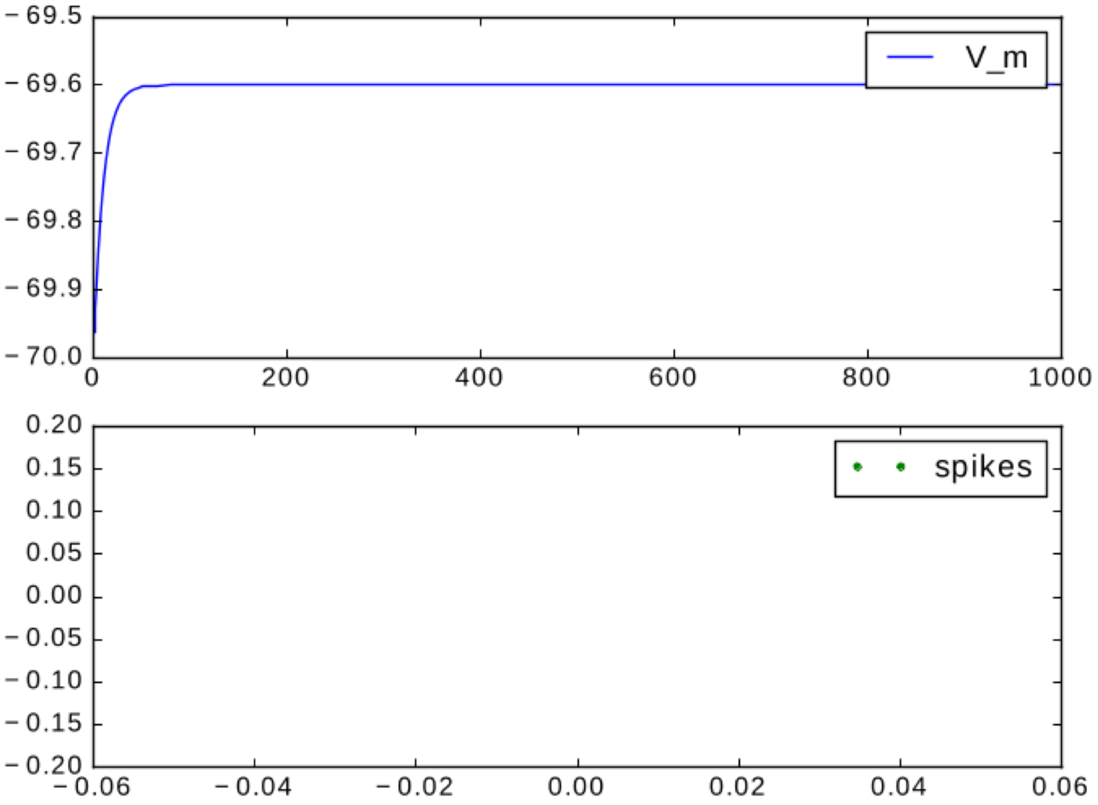
NEST
<<Runtime>>

- 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
```

NESTML
<<rc_neuron_rest.nestml>>

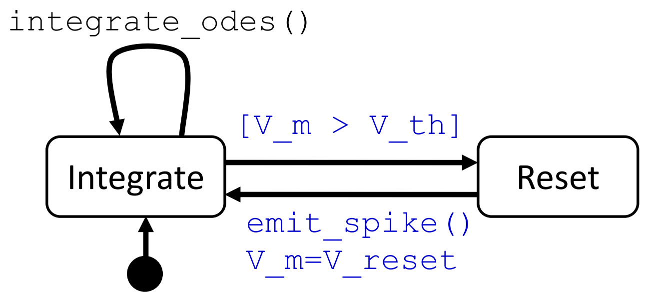
→ Still no spikes



Spiking and reset

Model

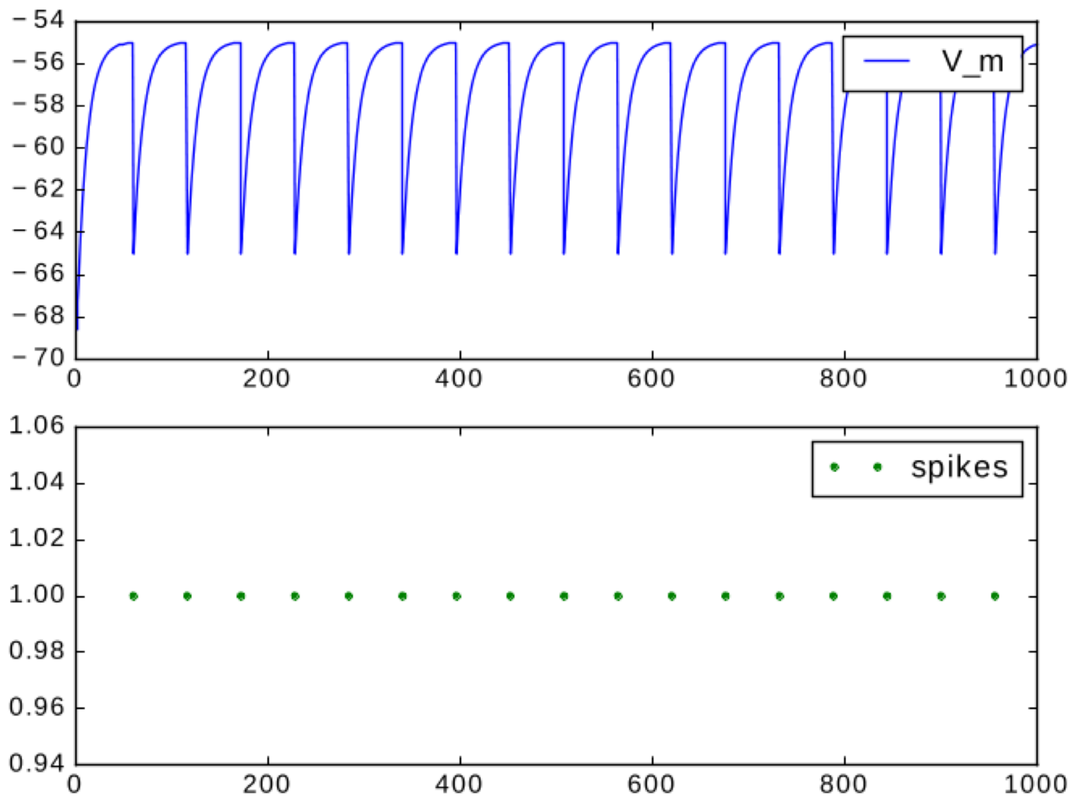
AD




```
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
```

NESTML
<<rc_fire.nestml>>

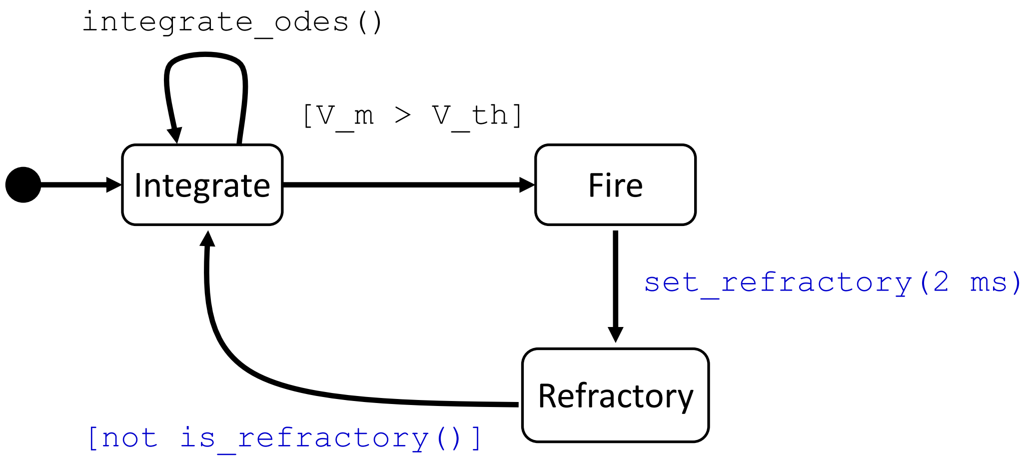
NEST
<<Runtime>>



Refractoriness

Model

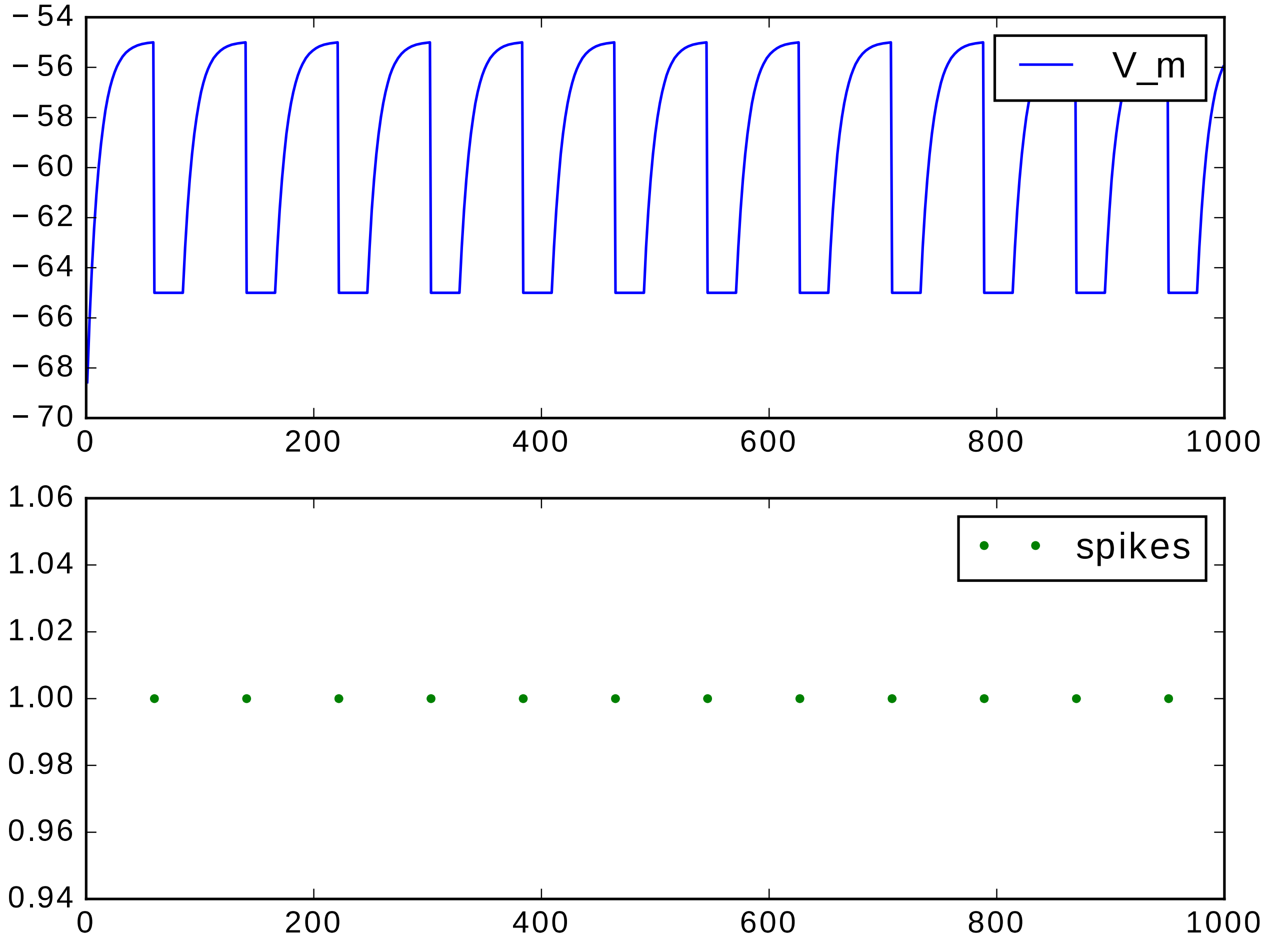
AD



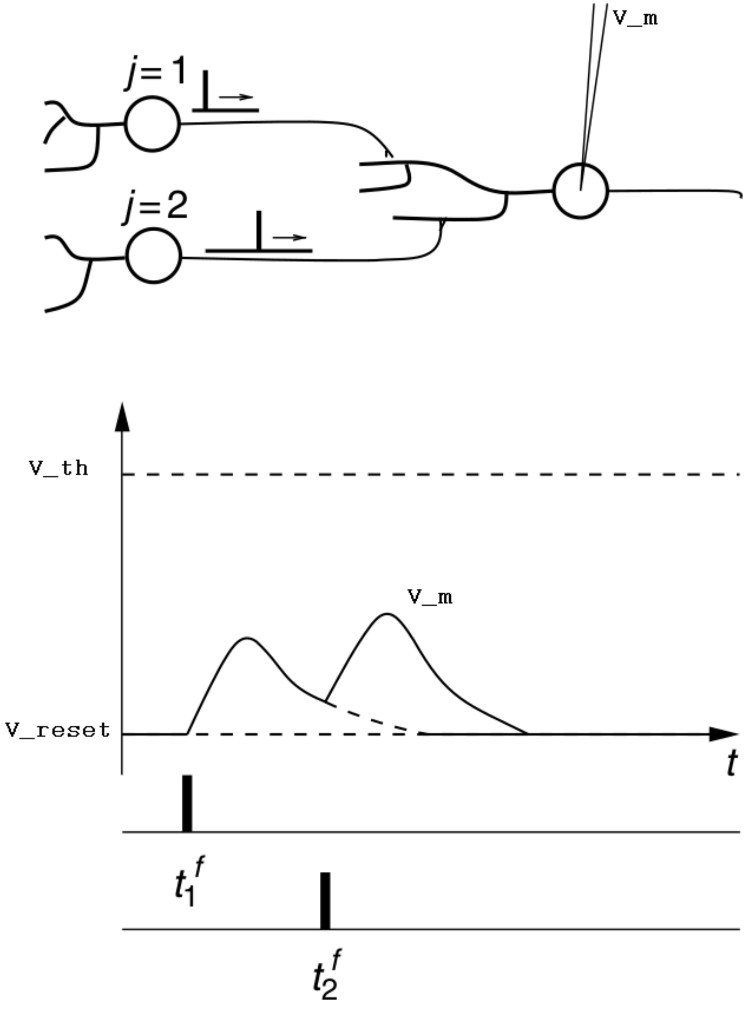
NESTML
<<rc_refractory>>
...

```
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
```

Simulating `rc_refractory`



Input handling

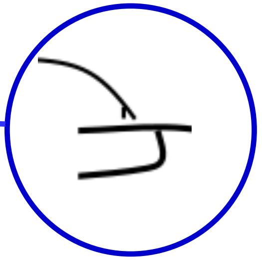


(Source: Wulfram Gerstner, Werner M. Kistler, Richard Naud, Liam Paninski-Neuronal Dynamics From Single Neurons to Networks and Models of Cognition)

Spike input

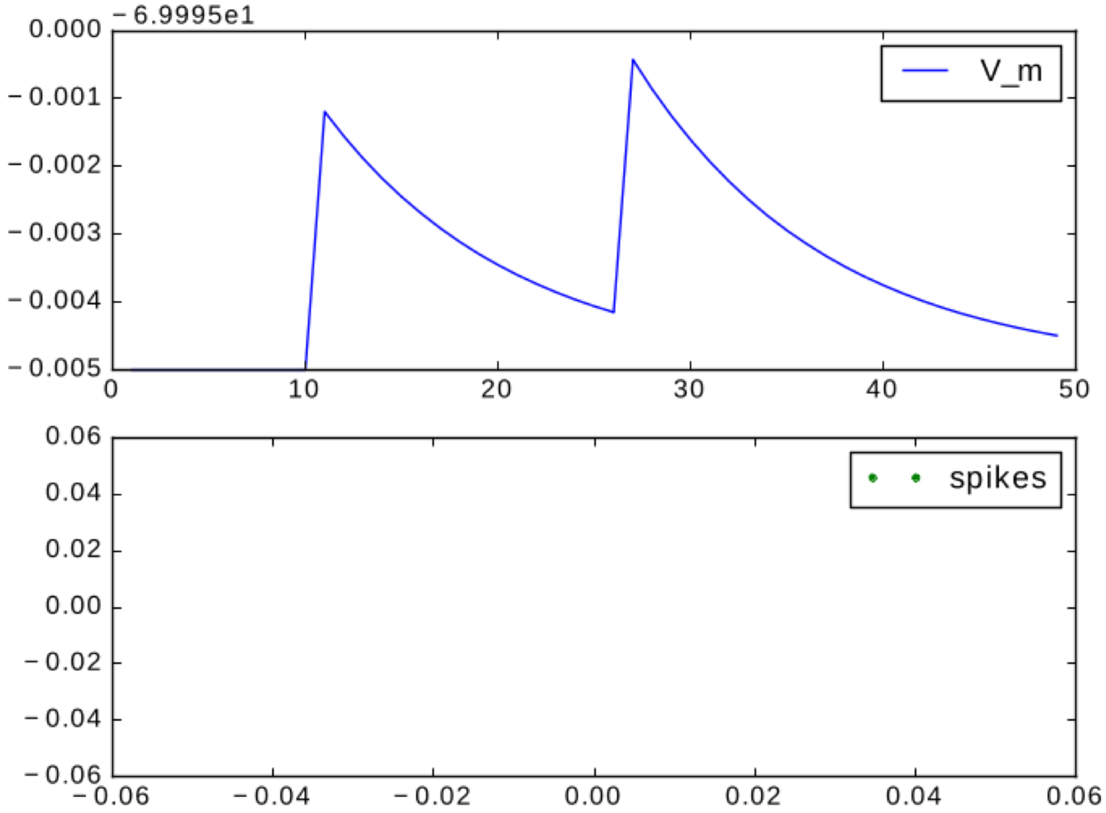
```
neuron rc_input:
  initial_values:
    V_m mV = E_L
  end

  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
```

NESTML
<<rc_input>>



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

NEST
<<Runtime>>



Synaptic response

NESTML
<<rc_alpha>>

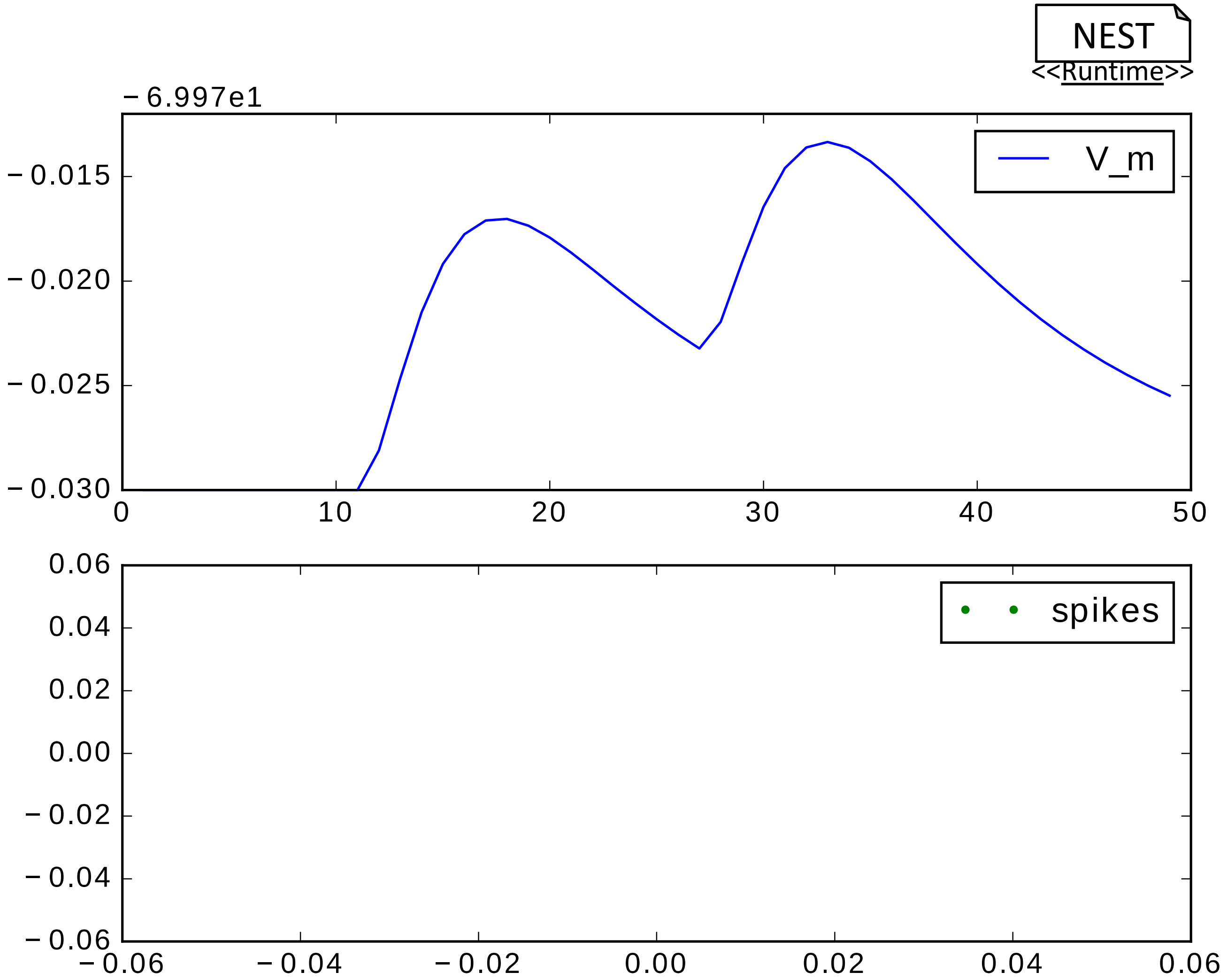
```
neuron rc_alpha_response:
  initial_values:
    V_m mV = E_L
    I_a pA = 0 pA
    I_a' pA/ms = e/tau_syn * pA
  end


  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
```

ODEs of order *n* require all initial values of the derivatives from 0 to *n*-1

$$\sum_{t_i \le t, i \in \mathbb{N}} \sum_{w \in W} w \cdot I_{\mathrm{a}}(t_i - t)$$

$$= \sum_{t_i \le t, i \in \mathbb{N}} I_{\mathrm{a}}(t_i - t) \sum_{w \in W} w$$

Simulating `rc_alpha_response`



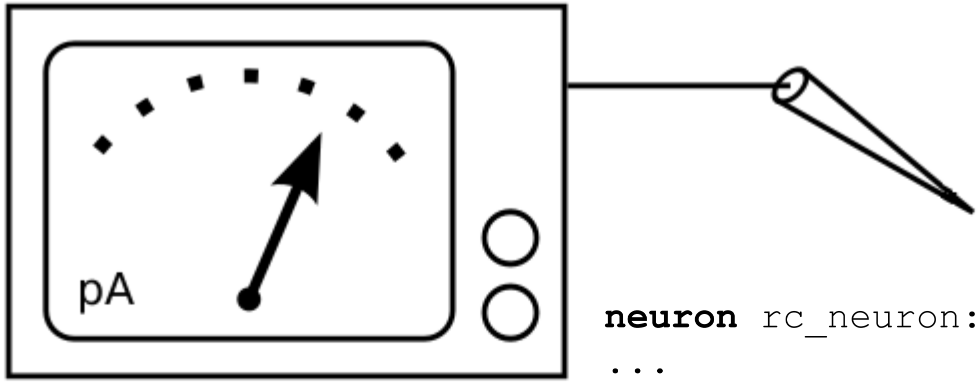
Shape notation

NESTML
<<rc_shape>>

initial values
computed automatically

```
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
```

Injecting currents



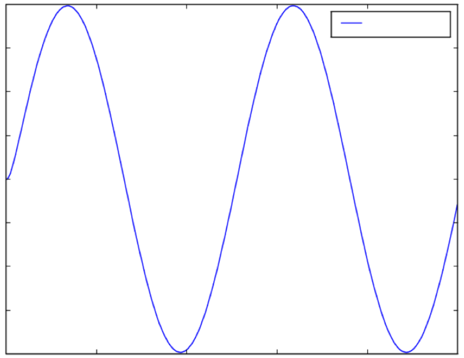
DC Generator

PyNEST

```
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
```

NEST
<<Runtime>>



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
```

Practical exercise: Izhikevich model

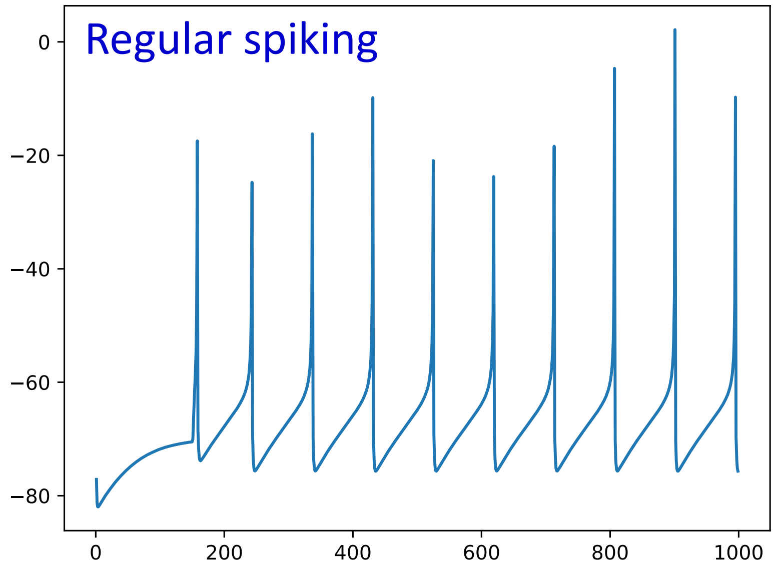
- Izhikevich: simple model for spiking neurons

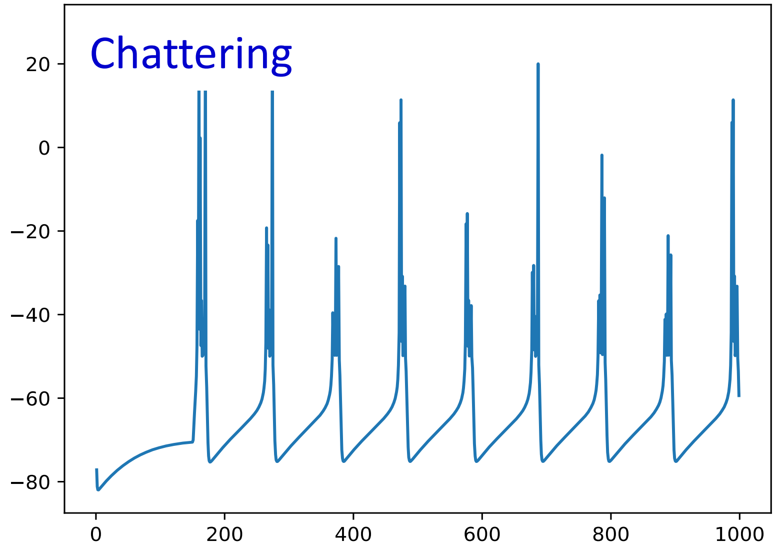
$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

$$\text{if } v \geq 30mV \text{ then } \begin{cases} v = c \\ u = u + d \end{cases}$$

- Tutorial task:
  1. Finish the model
  2. Change parameters to produce chattering behaviour

- See E. Izhikevich, IEEE Transactions on Neural Networks (2003) 14:1569-1572





Practical exercise: Izhikevich model

- Go to https://jupyter.cscs.ch/
- Under "Piz Daint node type", select "mc" (for multicore) and click "Spawn"
- On the welcome screen, scroll down and click the "Terminal" button
- `git clone https://github.com/jougs/HPAC_Training --depth=1 && pip3 install nestml --user && cp HPAC_Training/.jupyterhub.env ~`
- Restart the Jupyter server:
    - Go to File → Hub control panel → "Stop my server"
    - Click "Start my server" → "Launch server" and use the same details as in the first step
- Now, everything is installed and we are ready to go! Double click the "HPAC_Training" folder in the left panel, then open the "NESTML" folder and open the notebook "NESTML-izhikevich-tutorial"
- Step through the notebook and convince yourself that everything works. Change `izhikevich_solution.nestml` to `izhikevich_task.nestml`, and finish the model!