NEST Modeling Language:
A modeling language for spiking neuron and synapse models for NEST

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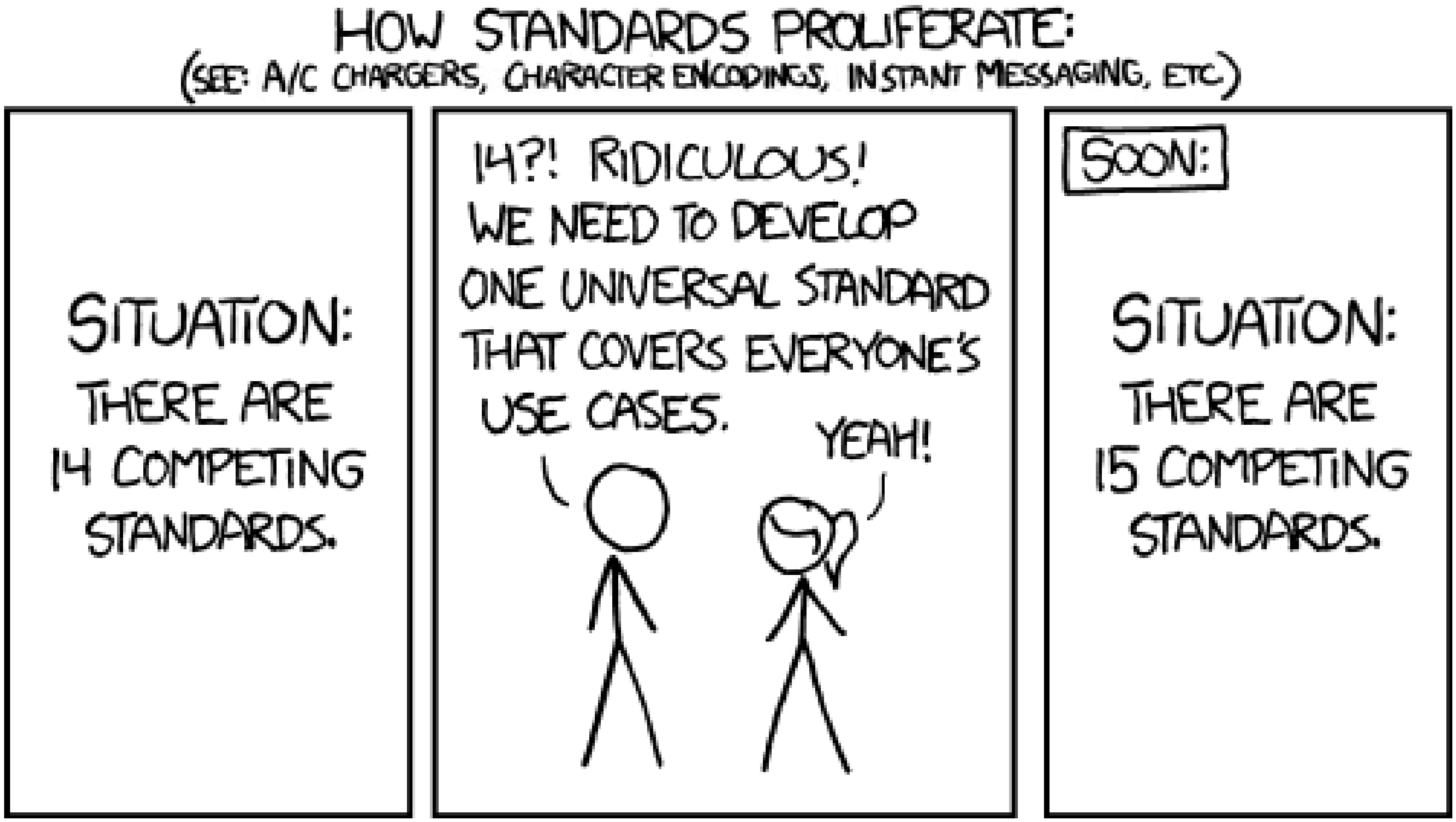
AN INITIATIVE OF

Wait, yet another modeling language?



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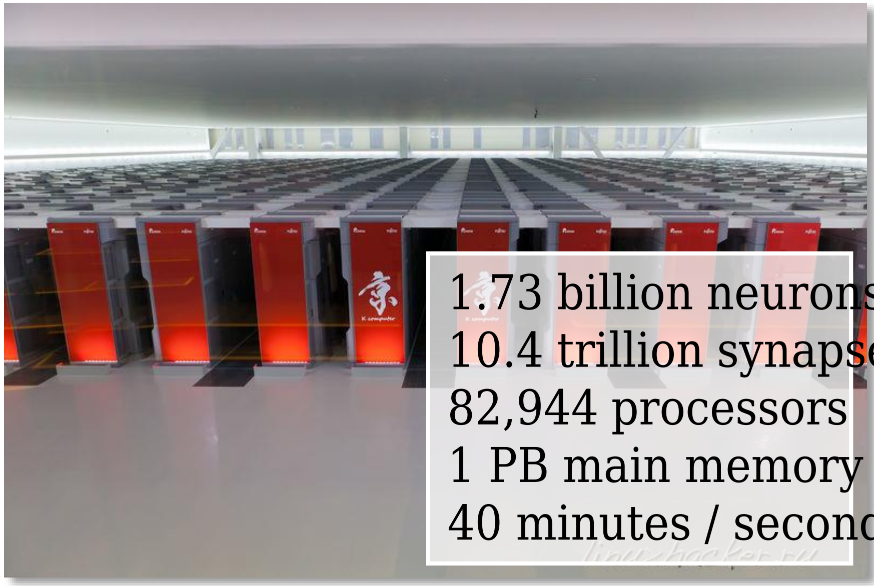
Wait, yet another modeling language?

The neural simulation tool NEST

- NEST is a hybrid parallel (OpenMP+MPI) simulator for spiking neural networks, written in C++, but with a Python frontend
- Neuron models are mainly point neurons and phenomenological synapse models (STDP, STP, neuromodulation)
- NEST supports large-scale models on the largest supercomputers
- Still the code also runs fine on laptops and workstations
- Get publication and source code on http://nest-simulator.org



The zoo of models

NEST 2.10.0 has 36 neuron models built in

- 19 are simple integrate-and-fire models
- 2 are based on the Hodgkin&Huxley formalism
- 11 have alpha-shaped post-synaptic responses
- 10 use exponentially decaying post-synaptic responses
- 15 with current-based dynamics solved exactly
- 9 conductance-based neurons using different solvers
- plus some more exotic specimen

… and the situation gets worse each release
and each new modelling study

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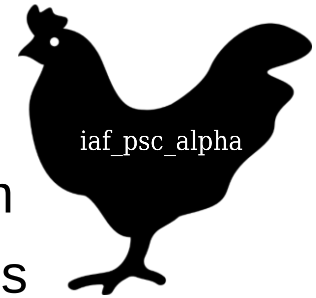

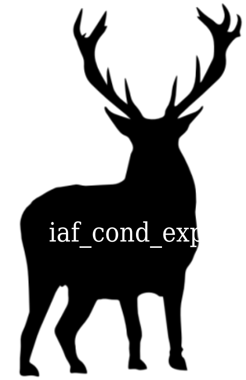

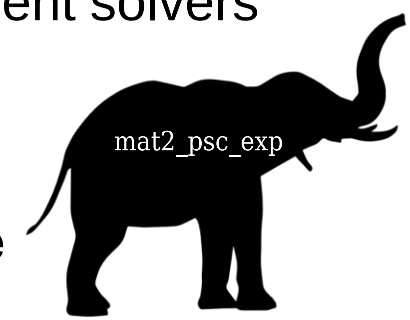

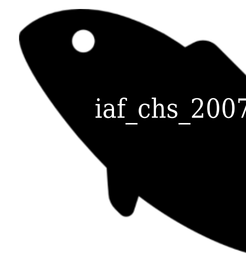

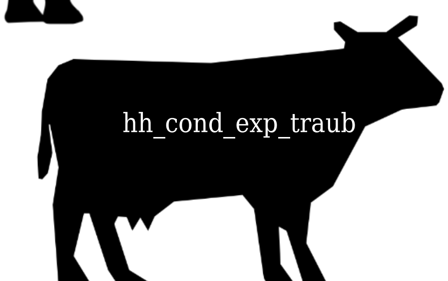

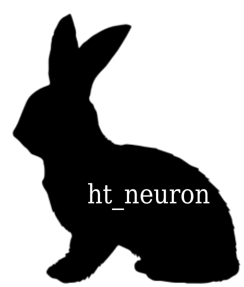

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Creating neuron models

```
void iaf_psc_alpha::update(Time const & origin, const long_t from, const long_t to)
{
  assert(to >= 0 && (delay) from < Scheduler::get_min_delay());
  assert(from < to);

  for ( long_t lag = from ; lag < to ; ++lag )
  {
    if ( S_.r_ == 0 )
    {
      // neuron not refractory
      S_.y3_ = V_.P30_*(S_.y0_ + P_.I_e_)
             + V_.P31_ex_ * S_.y1_ex_ + V_.P32_ex_ * S_.y2_ex_
             + V_.P31_in_ * S_.y1_in_ + V_.P32_in_ * S_.y2_in_
             + V_.expm1_tau_m_ * S_.y3_ + S_.y3_;

      // lower bound of membrane potential
      S_.y3_ = ( S_.y3_ < P_.LowerBound_ ? P_.LowerBound_ : S_.y3_);
    }
    else // neuron is absolute refractory
      --S_.r_;

    // alpha shape EPSCs
    S_.y2_ex_  = V_.P21_ex_ * S_.y1_ex_ + V_.P22_ex_ * S_.y2_ex_;
    S_.y1_ex_ *= V_.P11_ex_;

    // Apply spikes delivered in this step; spikes arriving at T+1 have
    // an immediate effect on the state of the neuron
    V_.weighted_spikes_ex_ = B_.ex_spikes_.get_value(lag);
    S_.y1_ex_ += V_.EPSCInitialValue_ * V_.weighted_spikes_ex_;

    // alpha shape EPSCs
    S_.y2_in_  = V_.P21_in_ * S_.y1_in_ + V_.P22_in_ * S_.y2_in_;
    S_.y1_in_ *= V_.P11_in_;

    // Apply spikes delivered in this step; spikes arriving at T+1 have
    // an immediate effect on the state of the neuron
    V_.weighted_spikes_in_ = B_.in_spikes_.get_value(lag);
    S_.y1_in_ += V_.IPSCInitialValue_ * V_.weighted_spikes_in_;

    // threshold crossing
    if ( S_.y3_ >= P_.Theta_)
    {
      S_.r_  = V_.RefractoryCounts_;
      S_.y3_ = P_.V_reset_;
      // A supra-threshold membrane potential should never be observable.
      // The reset at the time of threshold crossing enables accurate integration
      // independent of the computation step size, see [2,3] for details.

      set_spiketime(Time::step(origin.get_steps()+lag+1));
      SpikeEvent se;
      network()->send(*this, se, lag);
    }

    // set new input current
    S_.y0_ = B_.currents_.get_value(lag);

    // log state data
    B_.logger_.record_data(origin.get_steps() + lag);
  }
}
```

1. Copy & paste
2. Modify parts of the code
3. Ideally adapt the comments ;-)
4. Add to Makefiles
5. Re-compile and test
6. Goto 2…

```
void nest::iaf_cond_alpha::update(Time const & origin, const long_t from, const long_t to)
{

  assert(to >= 0 && (delay) from < Scheduler::get_min_delay());
  assert(from < to);

  for ( long_t lag = from ; lag < to ; ++lag )
  {

    double t = 0.0;

    // numerical integration with adaptive step size control:
    // ------------------------------------------------------
    // gsl_odeiv_evolve_apply performs only a single numerical
    // integration step, starting from t and bounded by step;
    // the while-loop ensures integration over the whole simulation
    // step (0, step] if more than one integration step is needed due
    // to a small integration step size;
    // note that (t+IntegrationStep > step) leads to integration over
    // (t, step] and afterwards setting t to step, but it does not
    // enforce setting IntegrationStep to step-t; this is of advantage
    // for a consistent and efficient integration across subsequent
    // simulation intervals
    while ( t < B_.step_ )
    {
      const int status = gsl_odeiv_evolve_apply(B_.e_, B_.c_, B_.s_,
                         &B_.sys_,             // system of ODE
                         &t,                   // from t
                          B_.step_,            // to t <= step
                         &B_.IntegrationStep_, // integration step size
                          S_.y);               // neuronal state


      if ( status != GSL_SUCCESS )
        throw GSLSolverFailure(get_name(), status);
    }

    // refractoriness and spike generation
    if ( S_.r )
    {// neuron is absolute refractory
        --S_.r;
        S_.y[State_::V_M] = P_.V_reset;  // clamp potential
    }
    else
      // neuron is not absolute refractory
      if ( S_.y[State_::V_M] >= P_.V_th )
      {
     S_.r              = V_.RefractoryCounts;
     S_.y[State_::V_M] = P_.V_reset;

     // log spike with Archiving_Node
     set_spiketime(Time::step(origin.get_steps()+lag+1));

     SpikeEvent se;
     network()->send(*this, se, lag);
      }

    // add incoming spikes
    S_.y[State_::DG_EXC] += B_.spike_exc_.get_value(lag) * V_.PSConInit_E;
    S_.y[State_::DG_INH] += B_.spike_inh_.get_value(lag) * V_.PSConInit_I;

    // set new input current
    B_.I_stim_ = B_.currents_.get_value(lag);

    // log state data
    B_.logger_.record_data(origin.get_steps() + lag);
  }
}
```

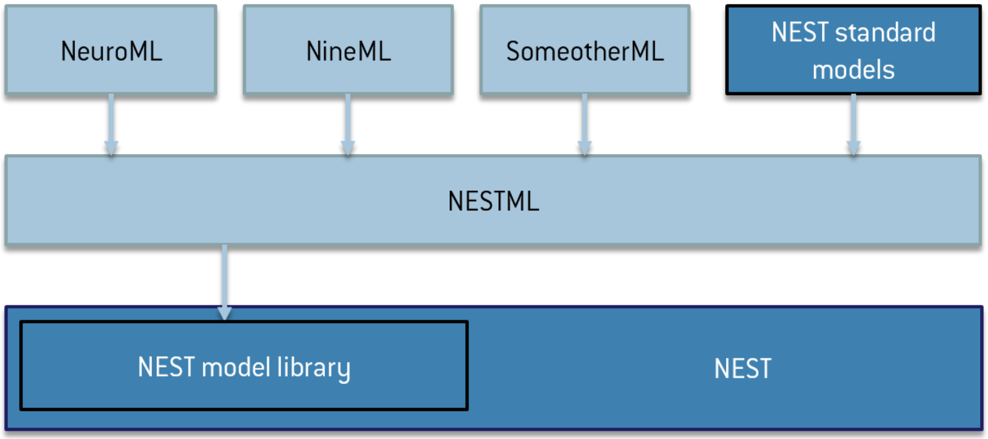
NESTML

The current process for model creation and the diversity leads to problems

- Copy & paste leads to errors and bad maintainability
- Implementation by non-programmers, often by trial and error

Basic NESTML features

- Semantic model checking and automatic choice of solver
- Automatic adaptation to new API versions
- Library for commonly used neuron dynamics and synaptic responses
- Ease of use



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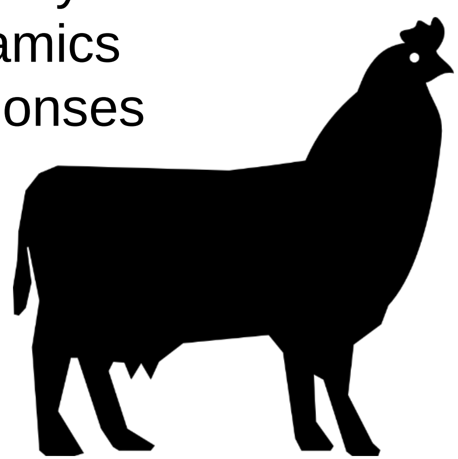

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Introductory Example:
An IaF PSC model with alpha shape

Fist class domain concepts

SI Units

Gaurds

```
neuron iaf_neuron:

  state:
    y0, y1, y2, V_m mV [V_m >= -99.0]
    # Membrane potential
    alias V_rel mV = V_m + E_L
  end

  function set_V_rel(v mV):
    V_m = v - E_L
  end

  parameter:
    # Capacity of the membrane.
    C_m        pF = 250 [C_m  > 0]
  end

  internal:
    h   ms   = resolution()
    P11 real = exp(-h / tau_syn)
    ...
    P32 real = 1 / C_m * (P33 - P11)
                / (-1/tau_m - -1/tau_syn)
  end

     input:
       spikeInh    <- inhibitory spike
       spikeExc    <- excitatory spike
       currentBuffer <- current
     end

     output: spike

     dynamics timestep(t ms):
       if r == 0: # not refractory
         V_m = P30 * (y0 + I_e) + P31 *
               y1 + P32 * y2 + P33 * V_m
       else:
         r = r - 1
       end
       # alpha shape PSCs
       V_m = P21 * y1 + P22 * y2
       y1 = y1 * P11
       y0 = currentBuffer.getSum(t);
     end

   end
```

Major Building blocks Blocks 1/2

- State block
  - Variables describing the neuron's state
  - `alias` to express a dependency (also in another block possible)

```
state:
  V_m mV [V_m >= -99.0]
  # Membrane potential
  alias V_rel mV = V_m + E_L
end
```

- Parameter block
  - Values adjustable during instantiation
  - Guard checks

```
parameter:
  # Capacity of the membrane.
  C_m       pF = 250 [C_m  > 0]
end
```

- Internal
  - Capture helper variables

```
internal:
  h   ms   = resolution()
  P11 real = exp(-h / tau_syn)
  ...
  P32 real = 1 / C_m * (P33 - P11)
         / (-1/tau_m - -1/tau_syn)
end
```

Major Building blocks Blocks 2/2

- Neuron's dynamic is modelled in a predefined dynamics function
  - timestamp, event based

```
dynamics timestep(t ms):
  if r == 0: # not refractory
    V_m = P30 * (y0 + I_e) ...
  else:
   r = r - 1
  end
end
```

- Auxiliary helper functions

```
function set_V_rel(v mV):
  V_m = v - E_L
end
```

- Buffers:
  - First-order language concept
  - Semantic checks

```
input:
  spikeInh   <- inhibitory spike
  spikeExc   <- excitatory spike
  cur <- current
end

output: spike
```

- ODE Blocks
  - Dynamics can be defined declaratively

```
ODE:
  G := E/tau_syn) * t * exp(-1/tau_syn*t)
  d/dt V := -1/Tau * V + 1/C_m * G + I_e + cur
end
```

An IaF PSC model with alpha shape ODE Approach

```
neuron iaf_neuron:
  internal:
    h    ms   = resolution()
    P11 real = exp(-h / tau_syn)
    ...
    P32 real = 1 / C_m * (P33 - P11)
                / (-1/tau_m - -1/tau_syn)
  end

  dynamics timestep(t ms):
    if r == 0: # not refractory
      V_m = P30 * (y0 + I_e) + P31 *
            z1 + P32 * y2 + P33 * y3
    else:
      r = r - 1
    end
    # alpha shape PSCs
    V_m = P21 * y1 + P22 * V_m
    y1 = y1 * P11

  end

end
```

```
neuron iaf_neuron_ode:
 internal:
   h    ms   = resolution()
 end

 dynamics timestep(t ms):
   if r == 0: # not refractory
     ODE:
       G := E/tau_syn) * t * exp(-1/tau_syn*t)
       d/dt V:=-1/Tau * V + 1/C_m * G + I_e +cur

     end
   else:
     r = r - 1
   end
   ...
 end
 ...
end
```

Current equations

Membran potential

Model cross-referencing

Imports a component

Uses imported component

```
import PSPHelpers

neuron iaf_neuron:

  use PSPHelpers as PSP

  dynamics timestep(t ms):
    PSP.computePSPStep(t)
    # alpha shape PSCs
    y2 = P21 * y1 + P22 * y2
    y1 = y1 * P11
  end

  ...

end
```

```
component PSPHelpers:
  state:
    - y0, y1, y2, V_m mV [V_m >= -99
    alias V_rel mV = y3 + E_L
  end

  function computePSPStep(t ms):
    if r == 0: # not refractory
      y3 = P30 * (y0 + I_e) + P31 *
            y1 + P32 * y2 + P33 * y3
    else:
      r = r - 1
    end

  end
  ...
end
```

MontiCore Language Workbench

- Opensource and free github project
- Grammar based
- Definition of modular language fragments
- Assistance for analysis, transformations
- Generates: parsers, symbol tables, language processing infrastructure

- Composition of languages:
  - independent language development
  - composition of languages and tools
  - Language extension
  - Language inheritance (allows replacement)

- Quick definition of domain specific languages (DSLs)
  - by reusing existing languages
  - variability in syntax, context conditions, generation, semantics

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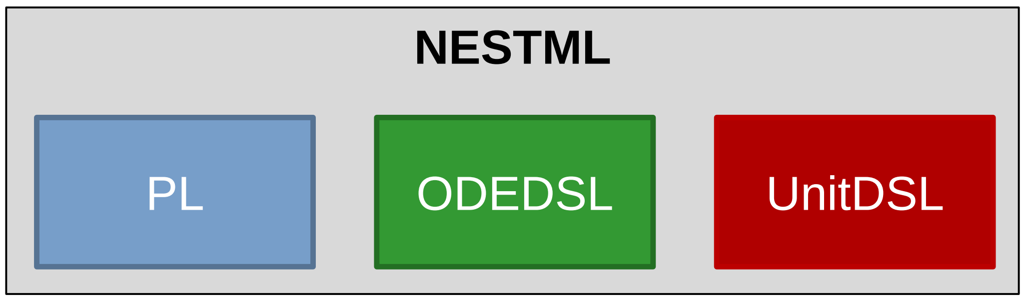
Language Architecture of NESTML

NESTML
Nest Modeling Language
Description of the neuron models



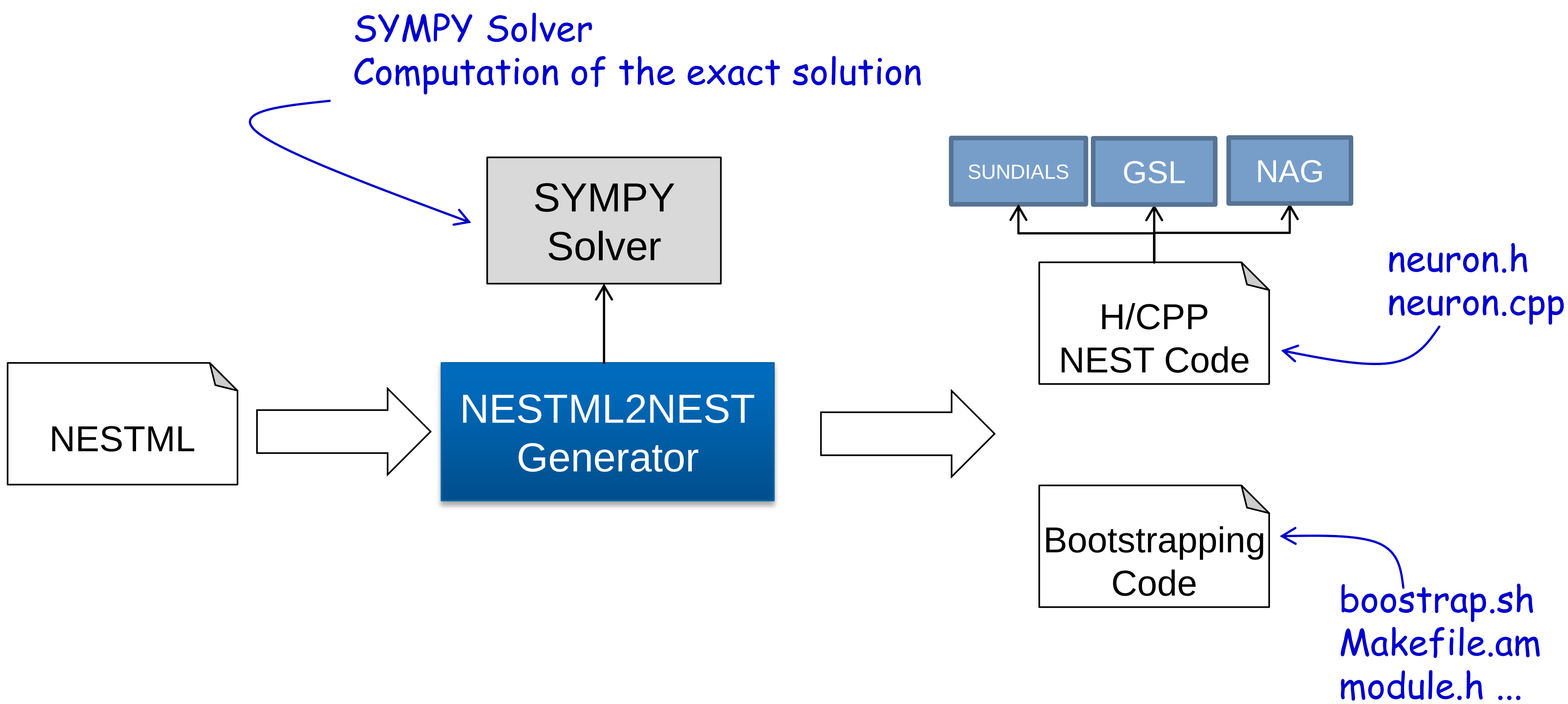
PL
Precedural Language:
Description of the imperative parts (e.g. definition of the dynamics function)

ODEDSL
Definition of
Ordinary Differential Equations

UnitDSL:
definition and automatic conversion of physical units

Generator Architecture for NEST

- Templated based code generation
  - Based on well founded mathematical theory
- Traceable model transformations
  - After transformations altered NESTML model is produced



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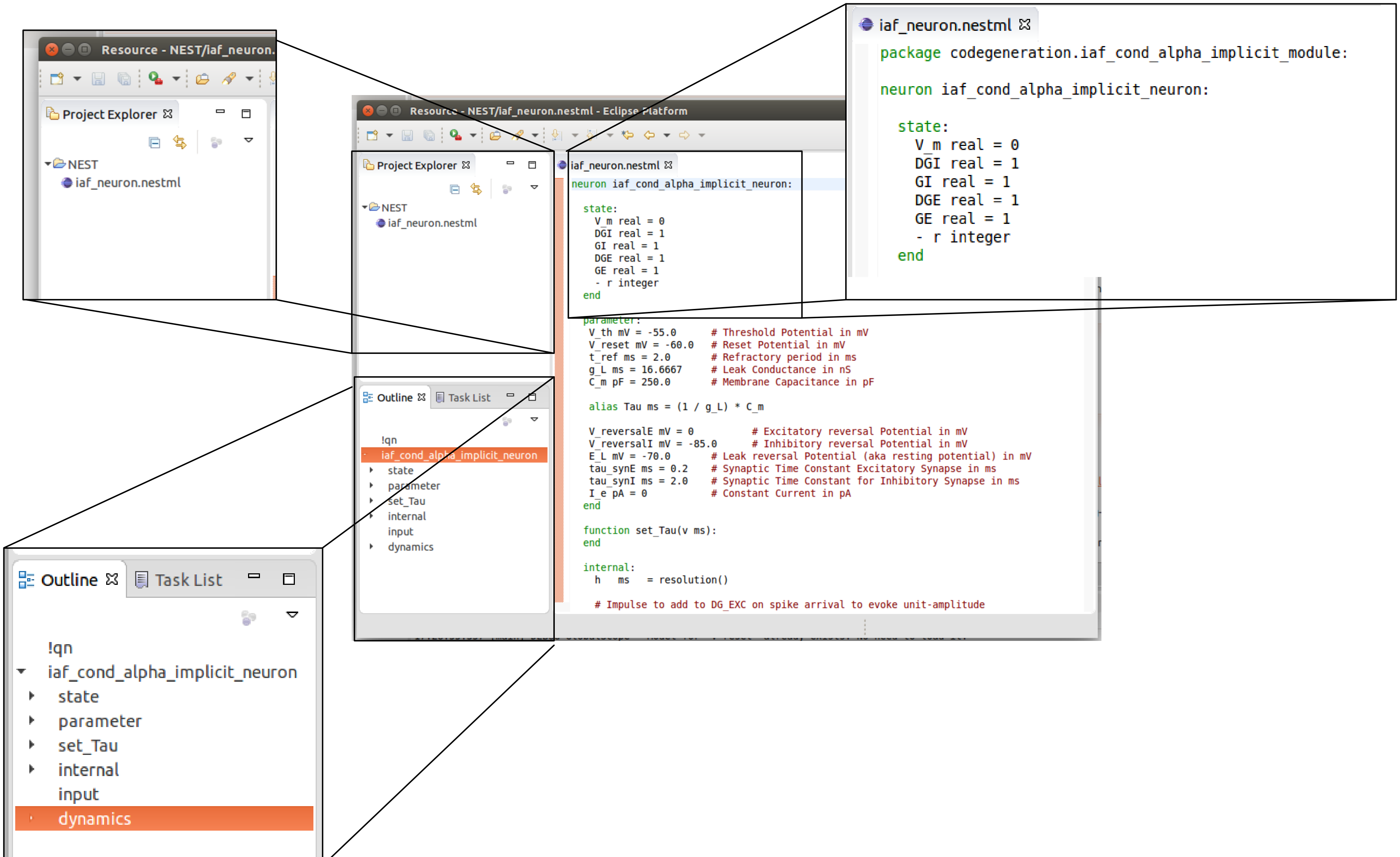
For Comfort: Editor in Eclipse for NESTML



Current State and Future Work

- Open-source github project

- First evaluation during a community workshop
  - Participant wrote NESTML models and ran them in NEST under 30 minutes
  - Also without preliminary experience with NEST or NESTML

- Publication: NESTML: a modeling language for spiking neurons
  - (to appear in spring 2016)

- Support for:
  - Explicit solvable models
    - E.g. PSC models in the NEST context
  - Numerical solvers
    - For now the GSL solver is already integrated

- New modeling concepts and optimisations
  - E.g. struct of arrays
  - Multi-compartment models

- Targeting new platforms
  - GPU
  - SpiNNaker

Backup

ODE Processing Workflow

NESTML

```
G ===(E/tau_syn) * t * exp(-1/tau_syn*t)
d/dt V === -1/Tau * V + 1/C_m * G
```

SymPy

For the ODE a SymPy-Solver is generated and executed.

Text

```
...
h*exp(-h/tau_in)# P10
exp(-h/tau_in)# P11
...
```

The matrix is parsed and a new NESTML Model with the solution matrix is created

NESTML

```
internal:
...
  P10 = h*exp(-h/tau_in)
  P11 = exp(-h/tau_in)
...
end
```

H/CPP
NEST Code

SI Units Specification

Größen-Name	Größen-Zeichen	Einheiten-Name	Einheiten-Zeichen
Länge	l	Meter	m
Masse	m	Kilogramm	kg
Zeit	t	Sekunde	s
Stromstärke	I	Ampere	A
Temperatur	T	Kelvin	K
Stoffmenge	n	Mol	mol
Lichtstärke	I_V	Candela	cd

- Every another unit is defined as a combination of base units:

$$Q = L^{\alpha} \cdot M^{\beta} \cdot T^{\gamma} \cdot I^{\delta} \cdot \Theta^{\varepsilon} \cdot N^{\zeta} \cdot J^{\eta}$$

- E.g. volt is defined as.

$$V = m^2 \cdot kg \cdot s^{-3} \cdot A^{-1} \cdot K^0 \cdot mol^0 \cdot cd^0$$