JÜLICH
FORSCHUNGSZENTRUM

N M B U
Norwegian University
of Life Sciences

LFPy and hybrid scheme for local field potentials:

CNS 2014 Tutorial T4:
Modeling and analysis of extracellular potentials

July 18 2014 | Espen Hagen, e.hagen@fz-juelich.de

Collaborations

LFPy:

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- Szymon Łęski
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- Klas H. Pettersen
- Gaute T. Einevoll

Hybrid LFP model:

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- Markus Diesmann
- Sonja Grün
- Gaute T. Einevoll

Topics

- Why model extracellular potentials?
- Forward modeling scheme (brief repetition)
- LFPy:
  - Introduction
  - Requirements, installation
  - Class overview
  - Examples
- Hybrid LFP model:
  - Introduction
  - Components
  - Application with 2-population network
- Summary & Outlook

Why model extracellular potentials?

- Improve understanding of experimental measurements:
  - Extracellular action-potential shapes:
    - Gold et al. *J Neurophysiol* (2006)
    - Pettersen&Einevoll. *Biophys J* (2008)
  - Spiking component of LFP:
    - Schomburg et al. *J. Neurosci* (2012)
  - Spectral content of LFP:
    - Lindén et al. *J Comput Neurosci* (2010)
  - Reach of LFP:
    - Lindén et al. *Neuron* (2011)
    - Łęski et al. *PLOS Comput Biol* (2013)
  - Role of active membranes:
    - Reimann et al. *Neuron* (2013)

Why model extracellular potentials?

- Methods validation:
  - Spike sorting:
    - Franke et al. *Proc IEEE Eng Med Biol Soc* (2010)
    - Einevoll et al. *Curr Op Neurobiol* (2012),
    - Thorbergsson et al. *J Neurosci Methods* (2013)
  - CSD estimation:
    - Pettersen et al. *J Comput Neurosci* (2008),
    - Łęski et al. *Neuroinform* (2011)

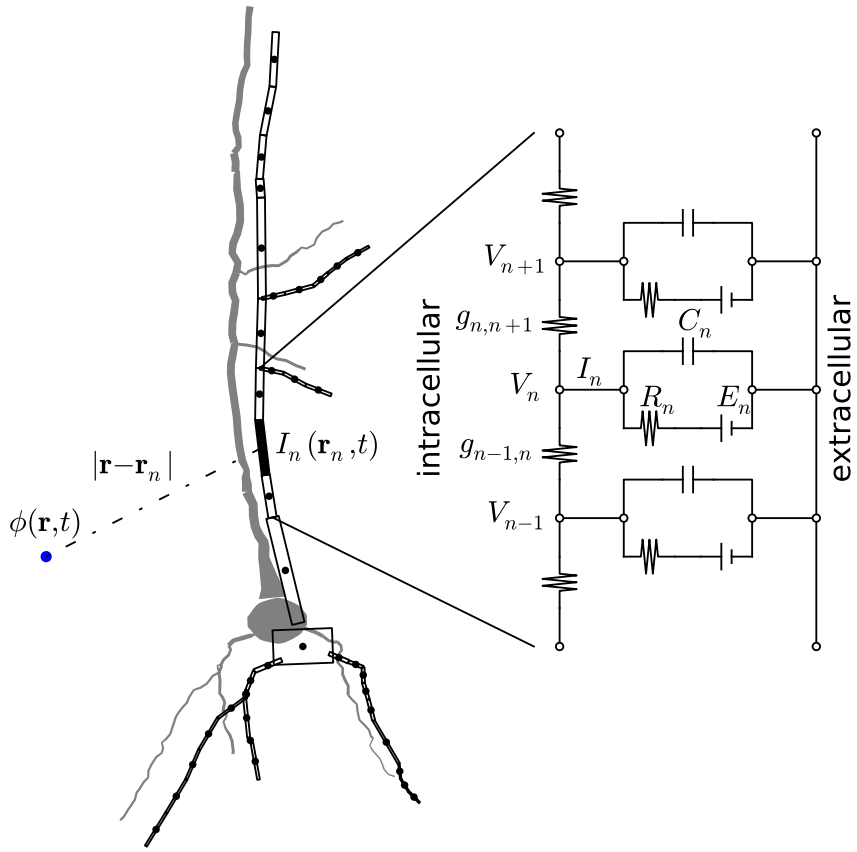
Forward modeling of extracellular potentials

Biophysical background:

- Poisson's equation in electrostatics

$$\nabla^2\phi = -\frac{\rho}{\sigma}$$

$\phi(\mathbf{r}, t)$ - electric potential
$\rho(\mathbf{r}, t)$ - current source density
$\sigma(\mathbf{r})$ - conductivity



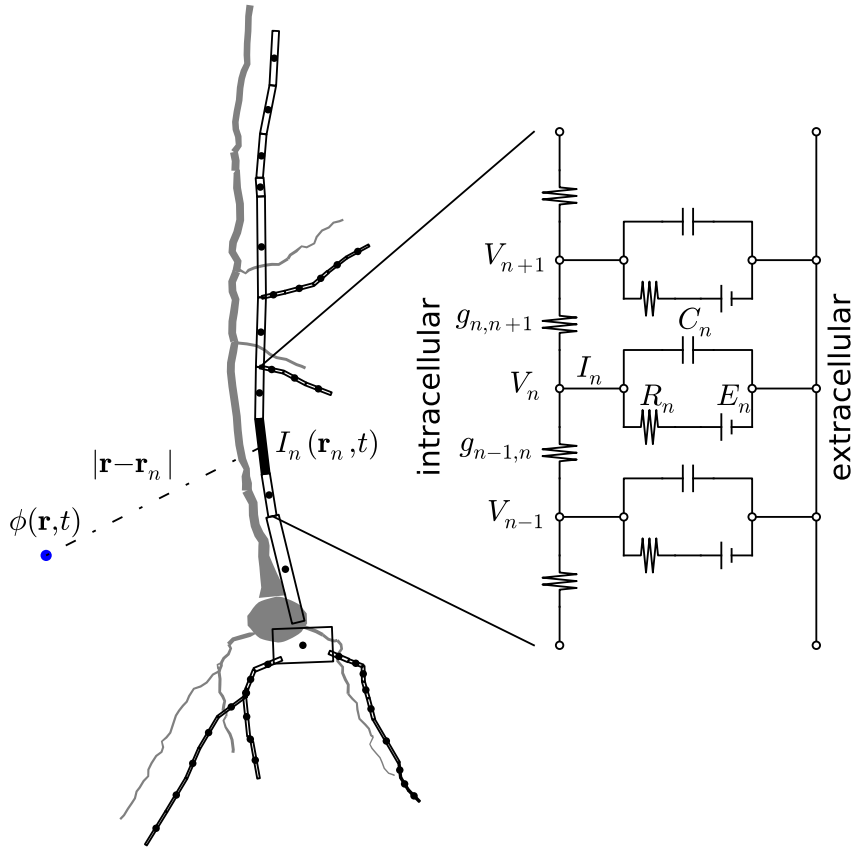
Forward modeling of extracellular potentials

Biophysical background:

- Assumptions:
  - Quasi-static approximation of Maxwell's equations
  - Extracellular medium:
    - linear
    - isotropic
    - homogeneous
    - ohmic

    (scalar, real σ)
- $\phi(r \to \infty) = 0$
- Point current source

$$\phi(\mathbf{r}, t) = \frac{1}{4\pi\sigma} \frac{I_0(t)}{|\mathbf{r} - \mathbf{r}_0|}$$



Forward modeling of extracellular potentials

Biophysical background:

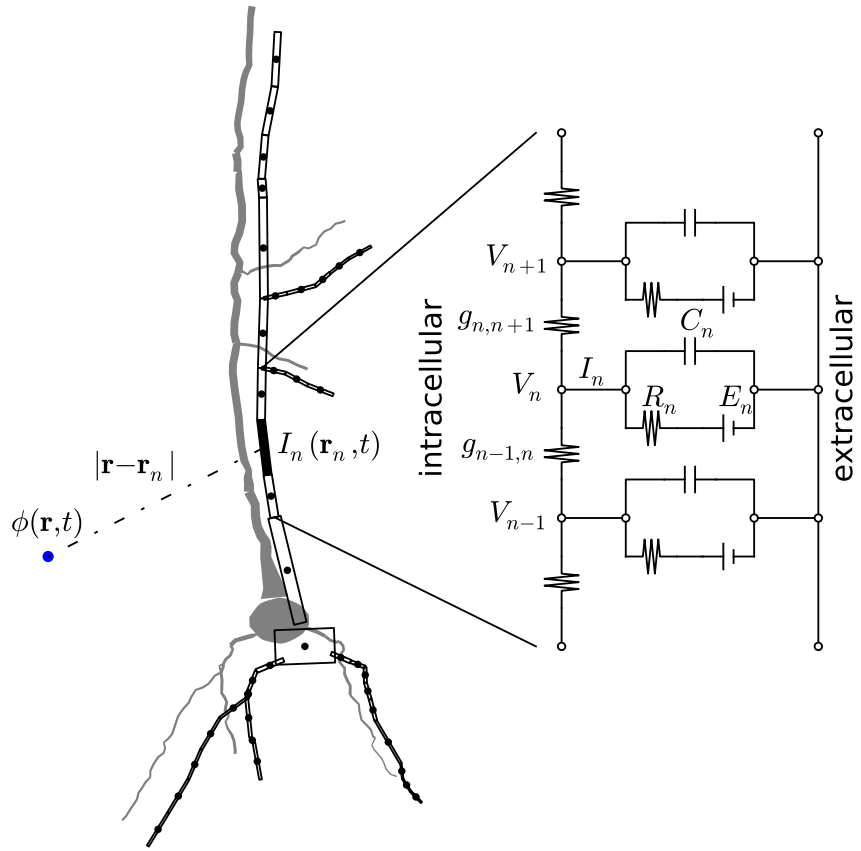
- Linear summation N point sources

$$\phi(\mathbf{r},t) = \frac{1}{4\pi\sigma}\sum_{n=1}^{N}\frac{I_n(t)}{|\mathbf{r}-\mathbf{r}_n|}$$

- Line-source equation

$$\phi(\mathbf{r},t) = \frac{1}{4\pi\sigma}\sum_{n=1}^{N} I_n(t)\int\frac{d\mathbf{r}_n}{|\mathbf{r}-\mathbf{r}_n|}$$

(Holt&Koch, *J Comput Neurosci* (1999))



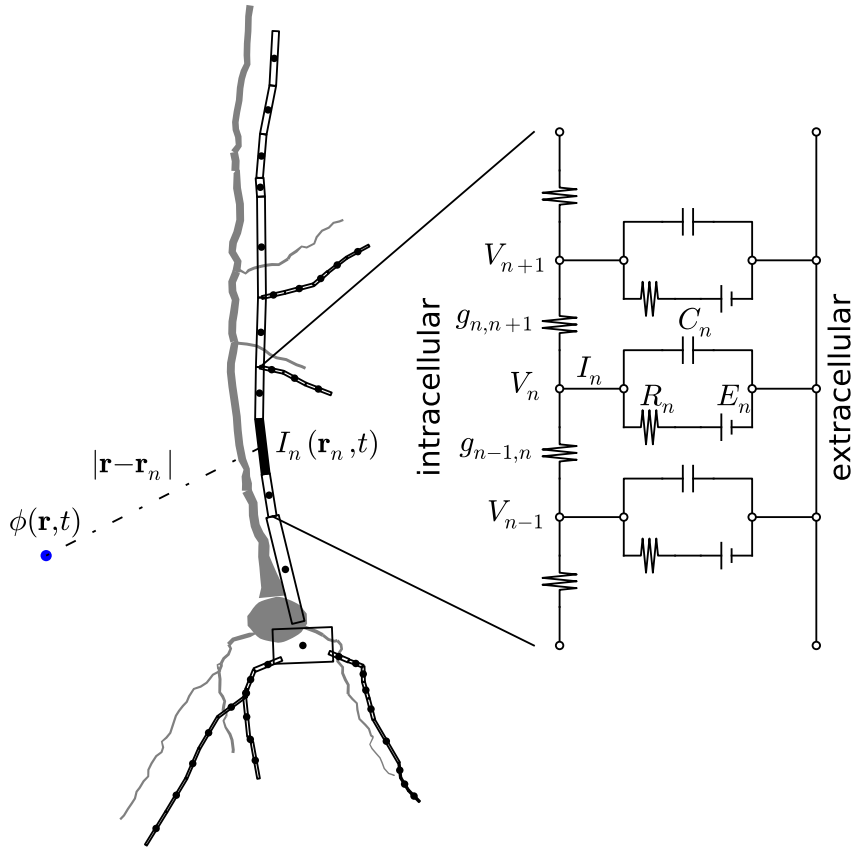
Forward modeling of extracellular potentials

Multi-compartment modeling:

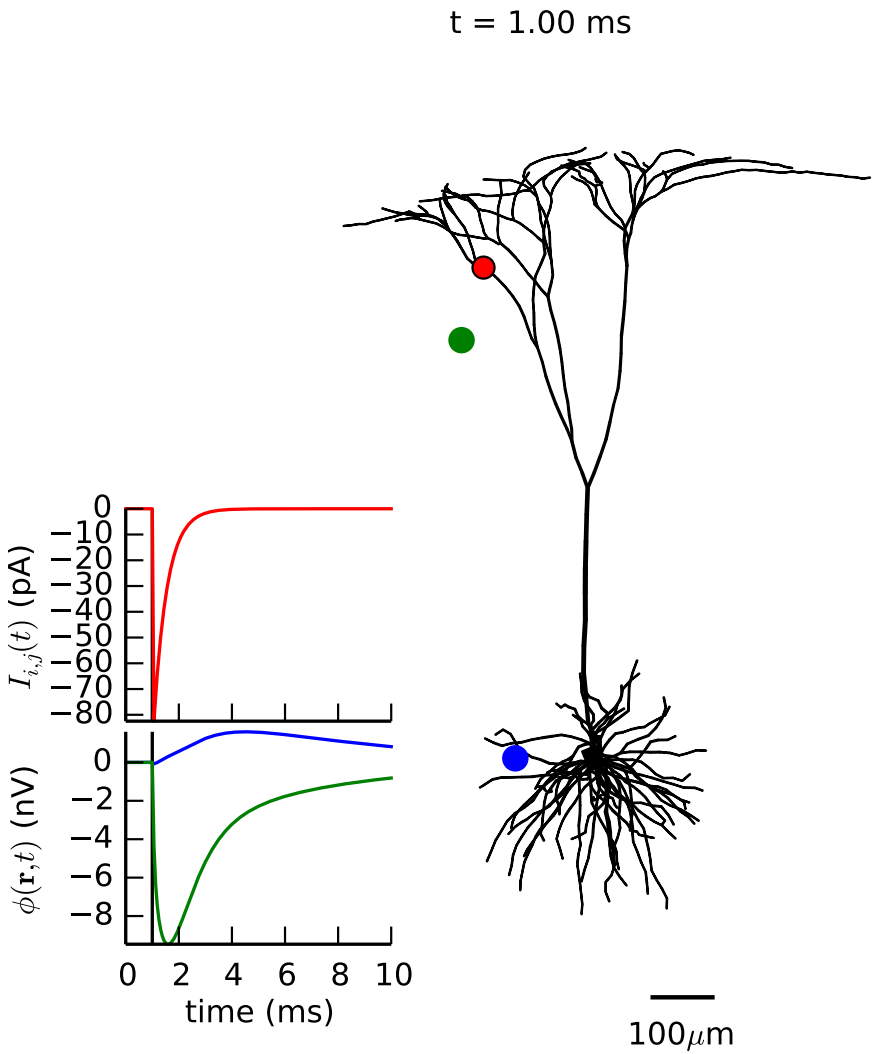
- Current balance intracellular node point, compartment n:

$$I_n = C_n \frac{dV_n}{dt} + \sum_j I_n^j = g_{n,n+1}(V_{n+1} - V_n) - g_{n-1,n}(V_n - V_{n-1})$$

- Simulated using NEURON (neuron.yale.edu, Hines et al. *Front Neuroinf* (2009))
- Extracellular potentials are computed from I_n

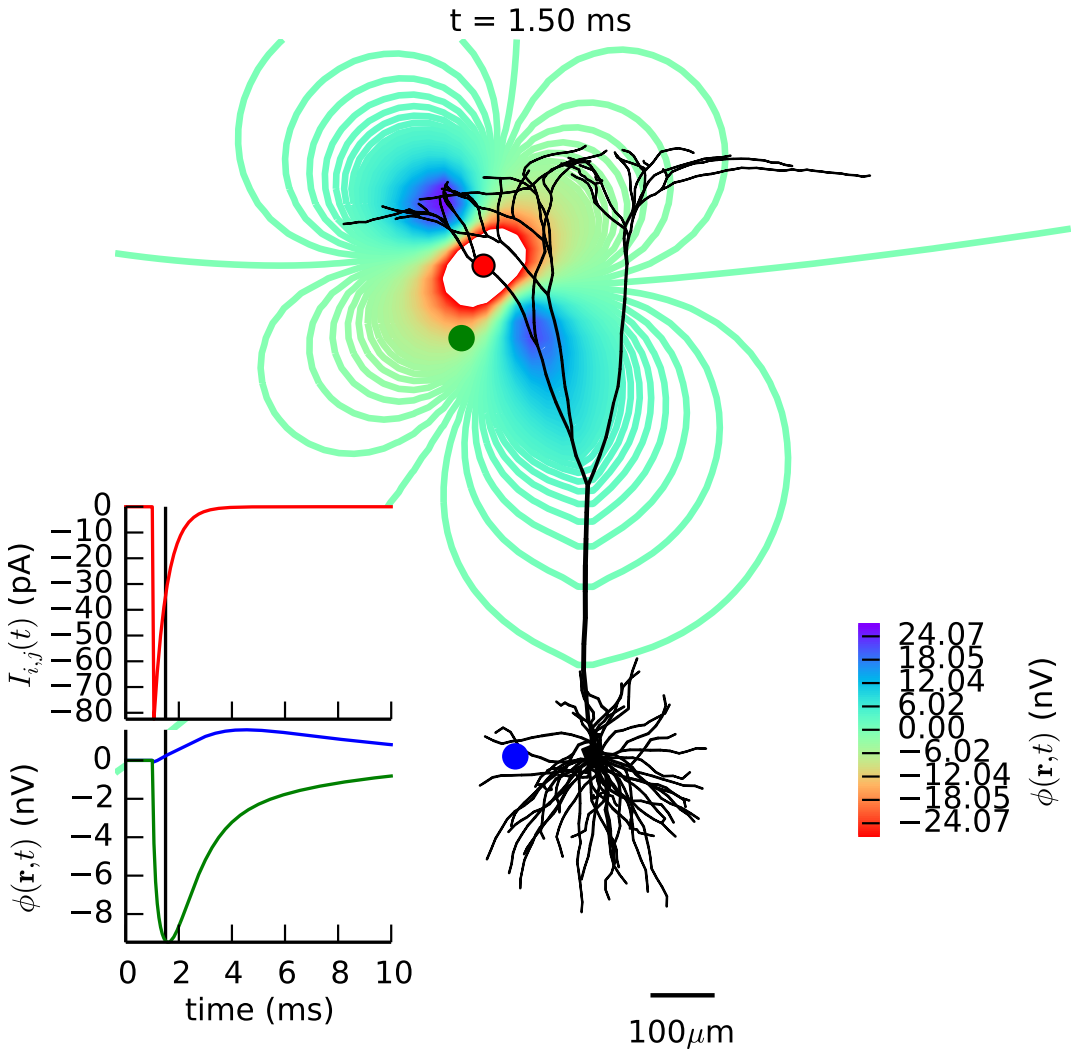


Forward modeling of extracellular potentials



Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials



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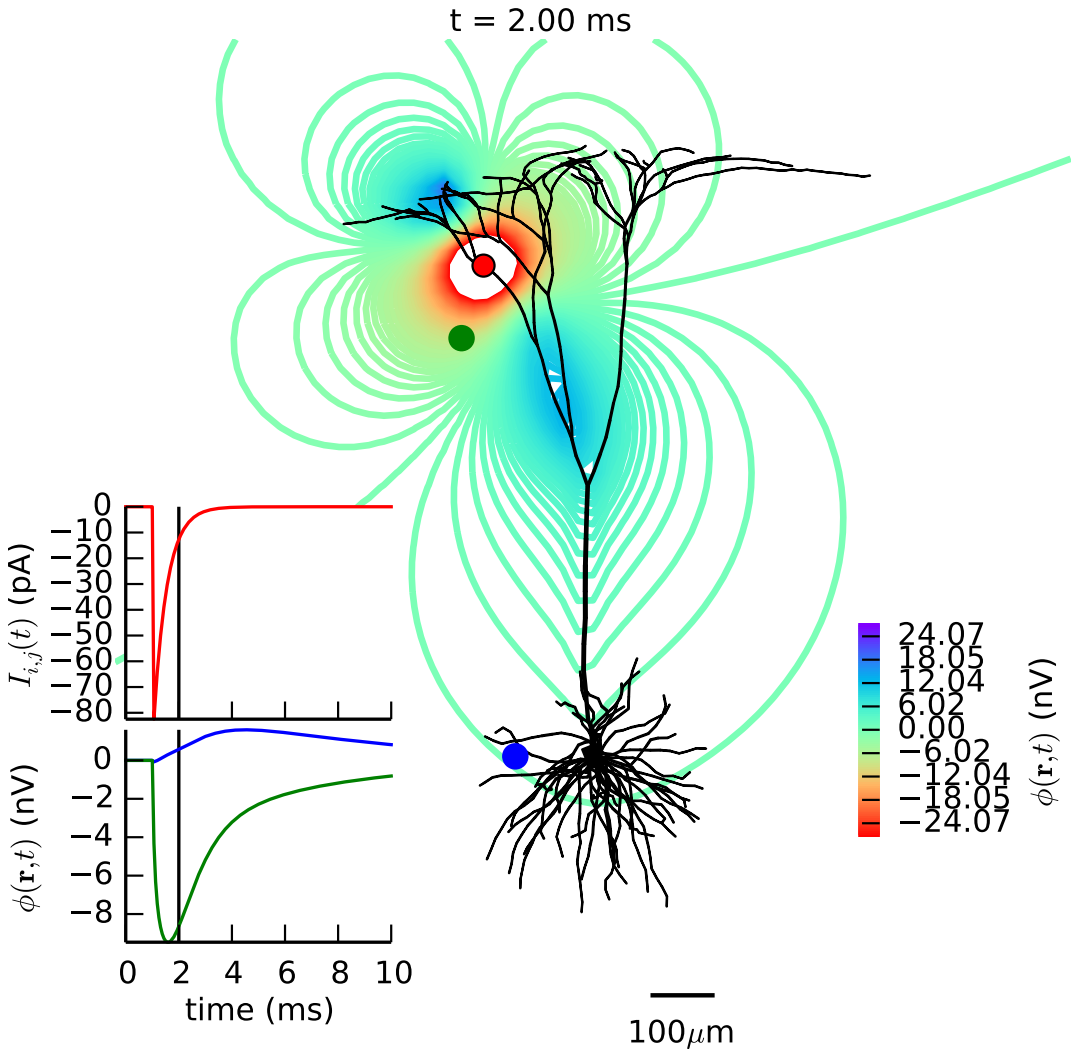
Forward modeling of extracellular potentials



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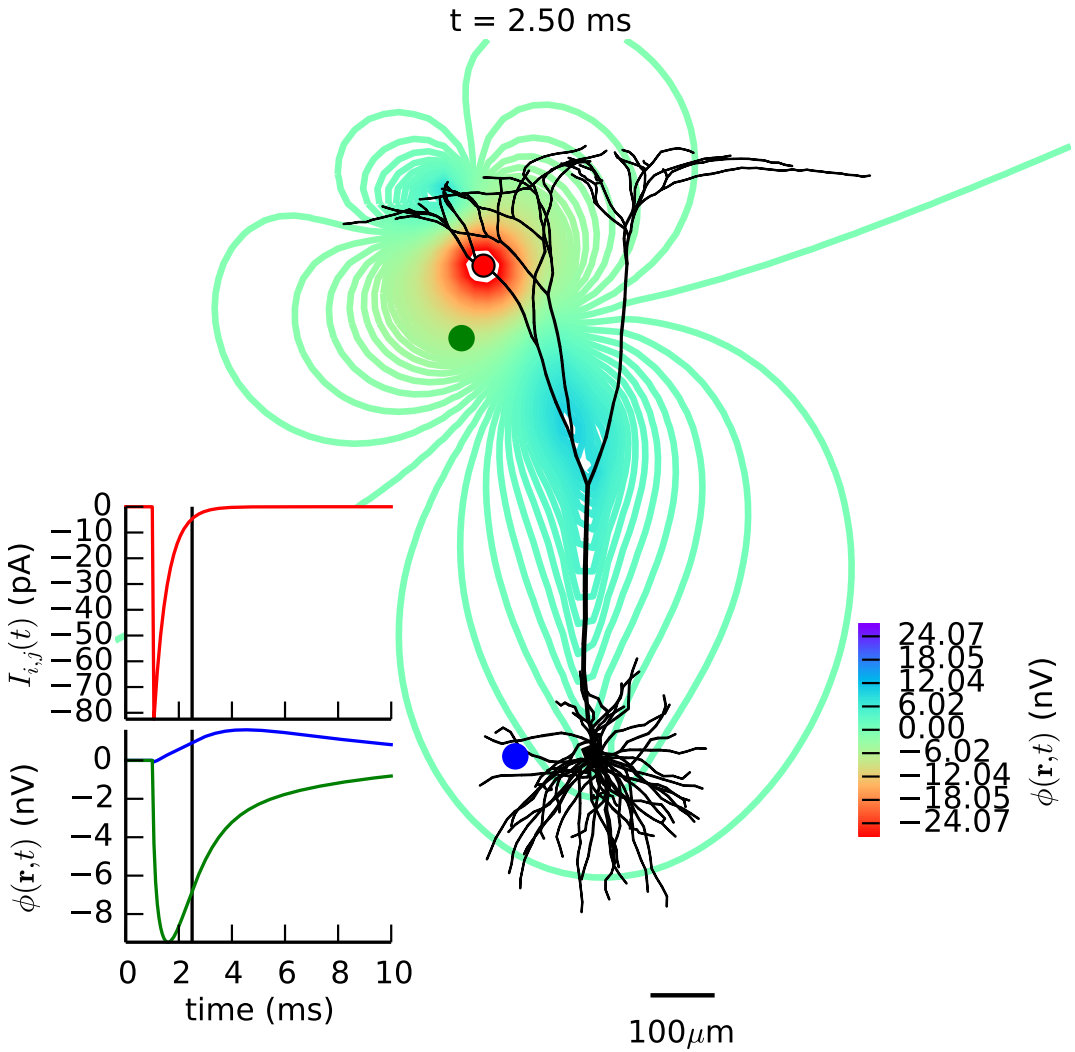

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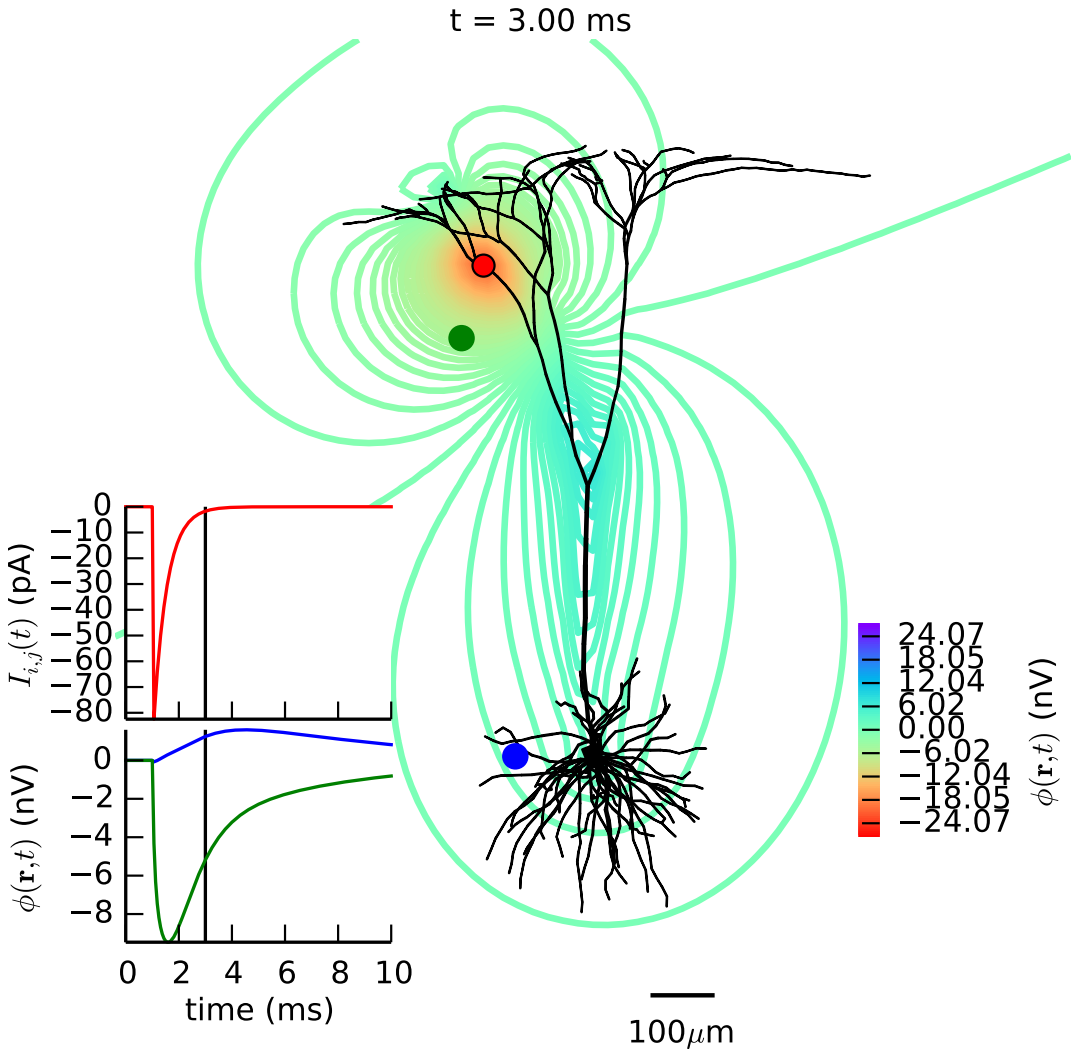

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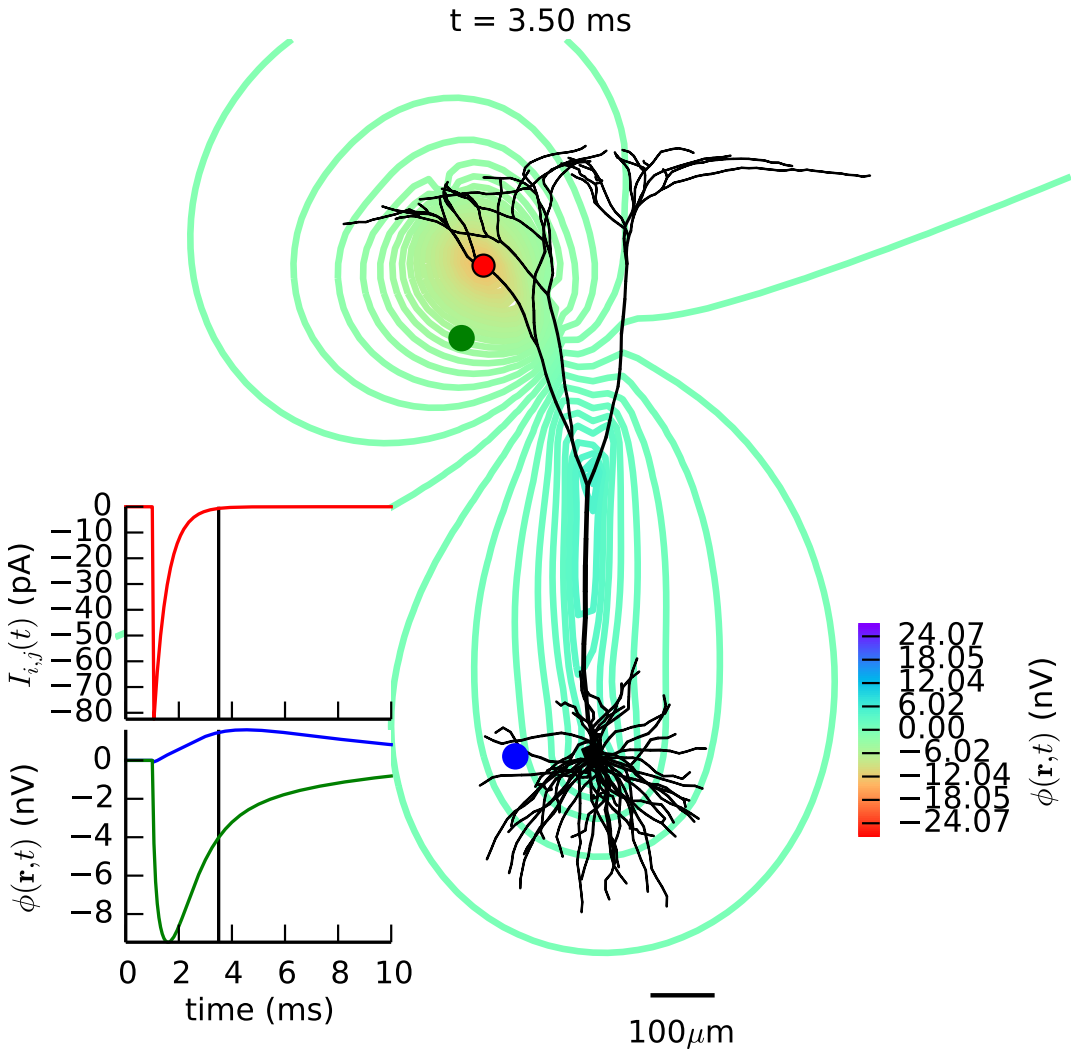

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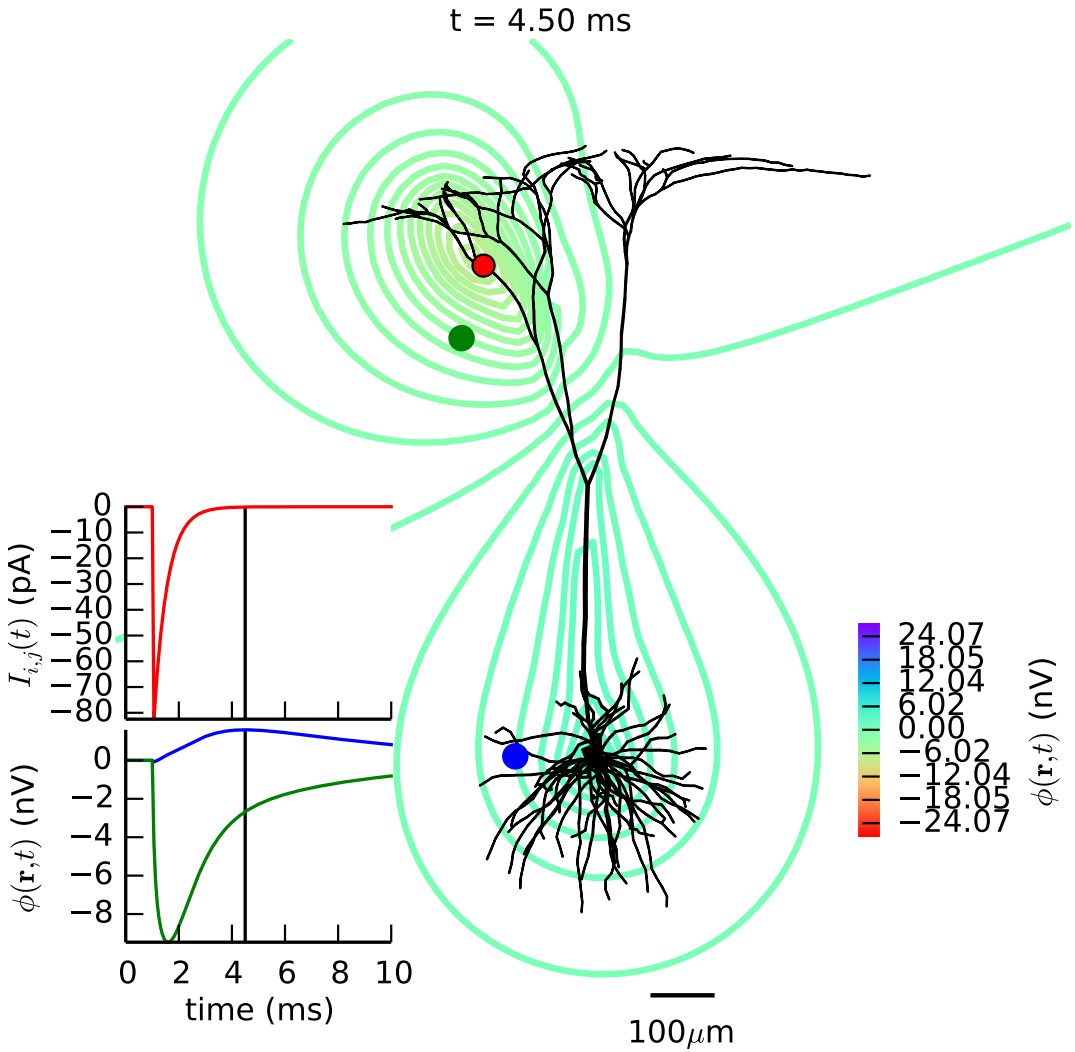

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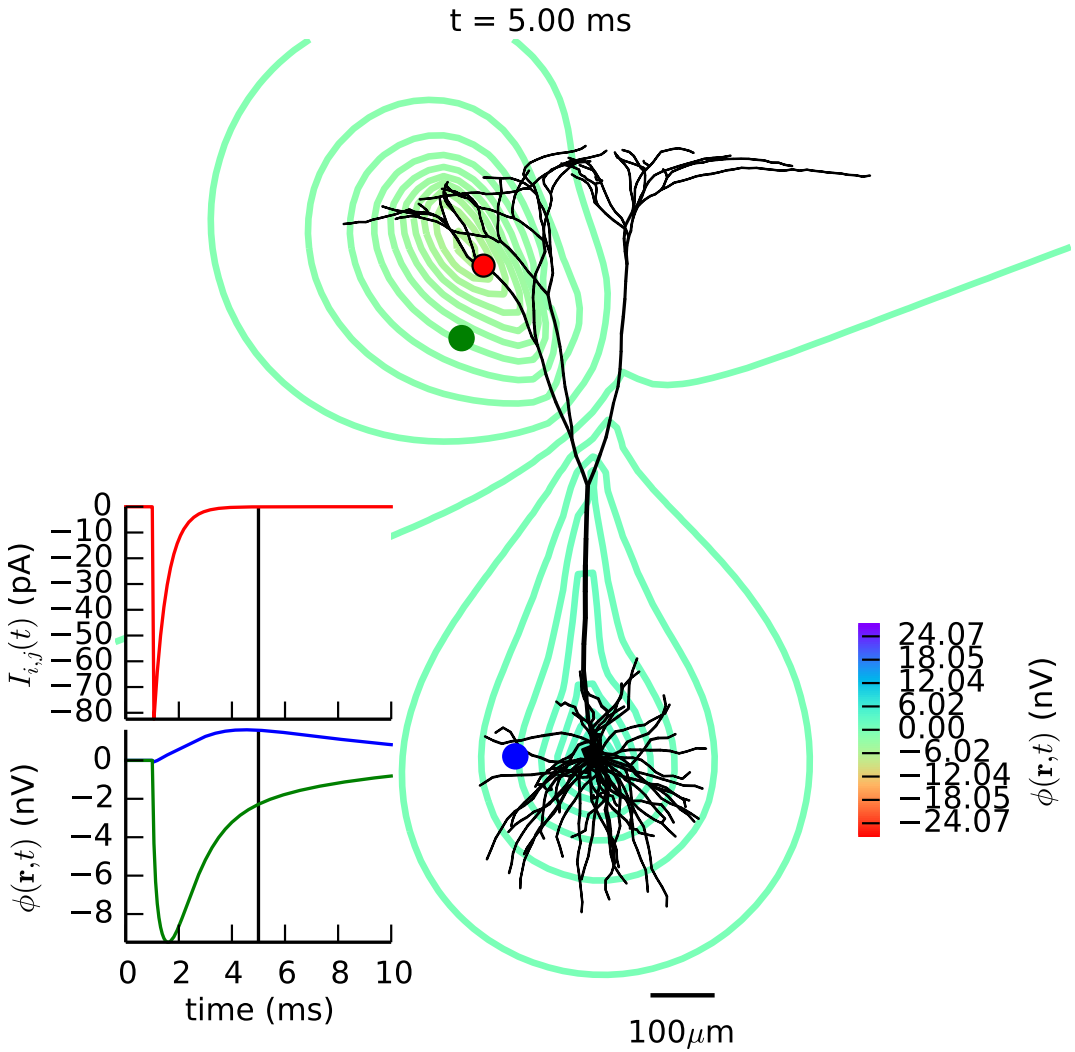

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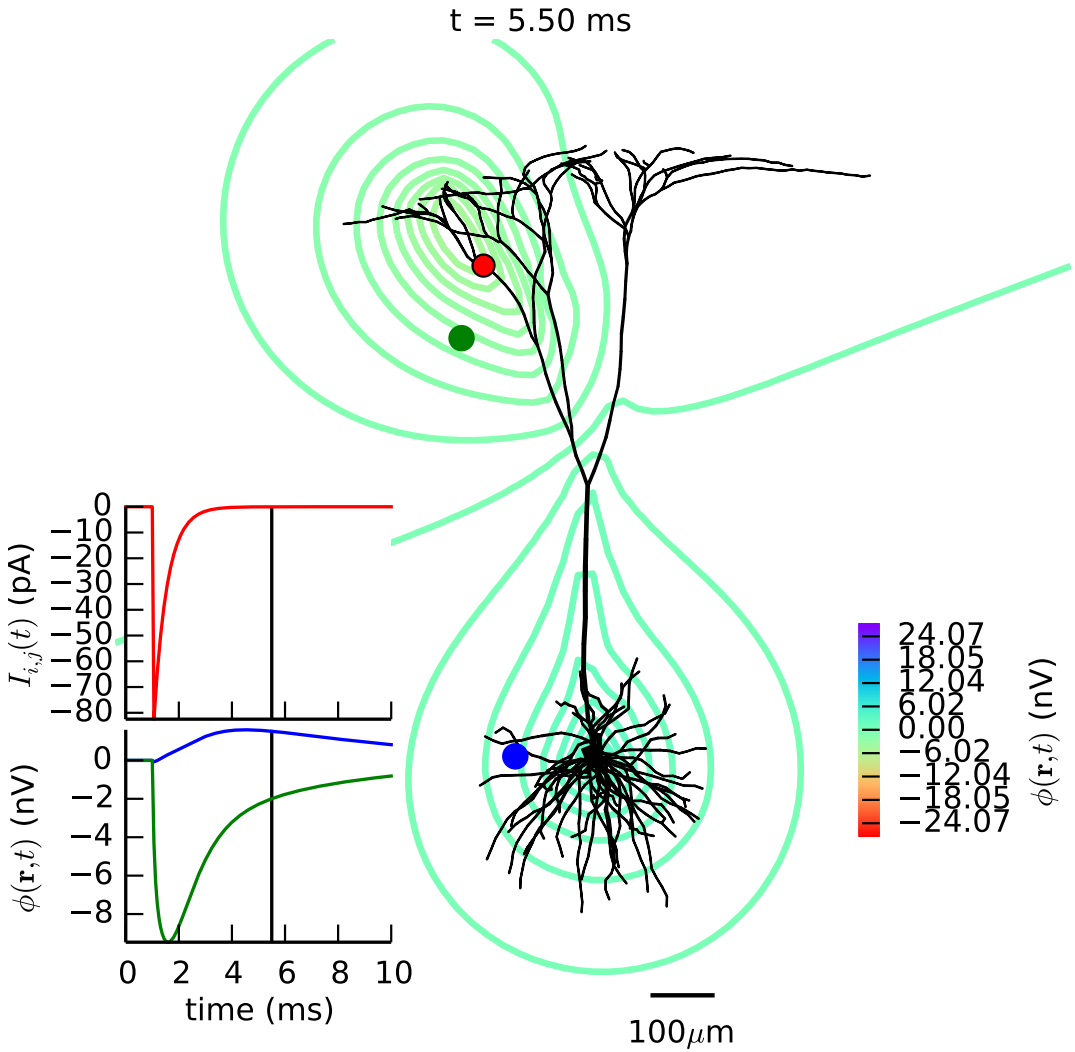
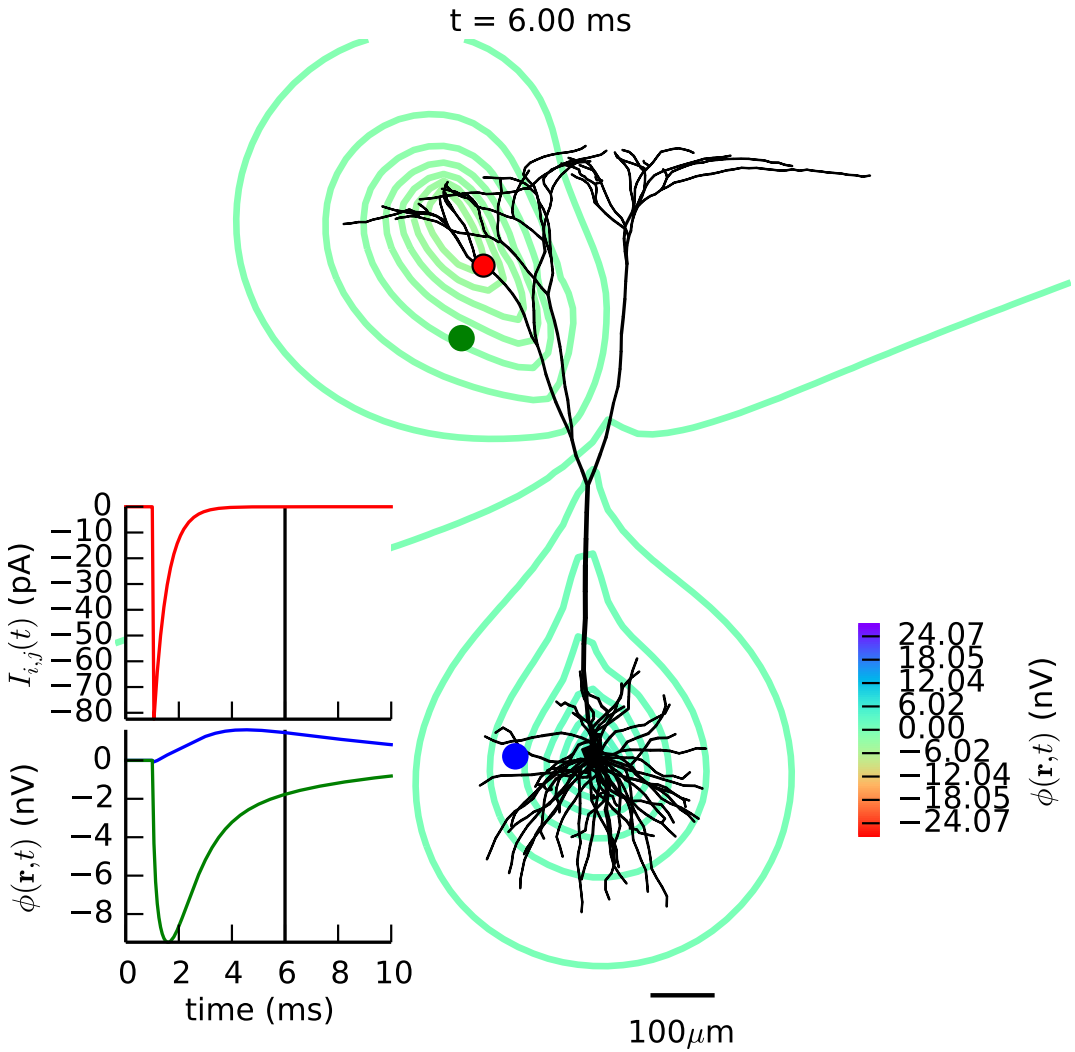
Forward modeling of extracellular potentials



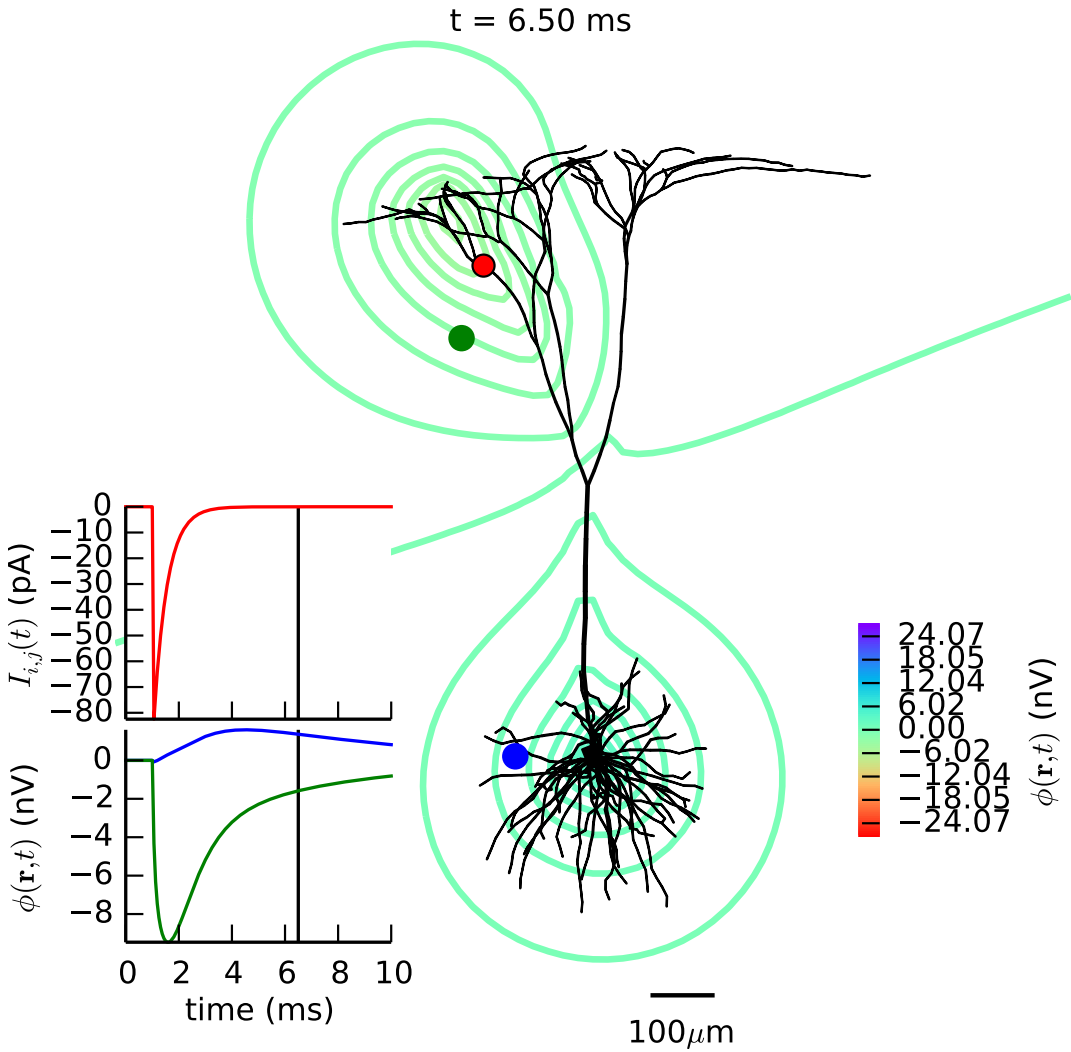
Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials



Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials

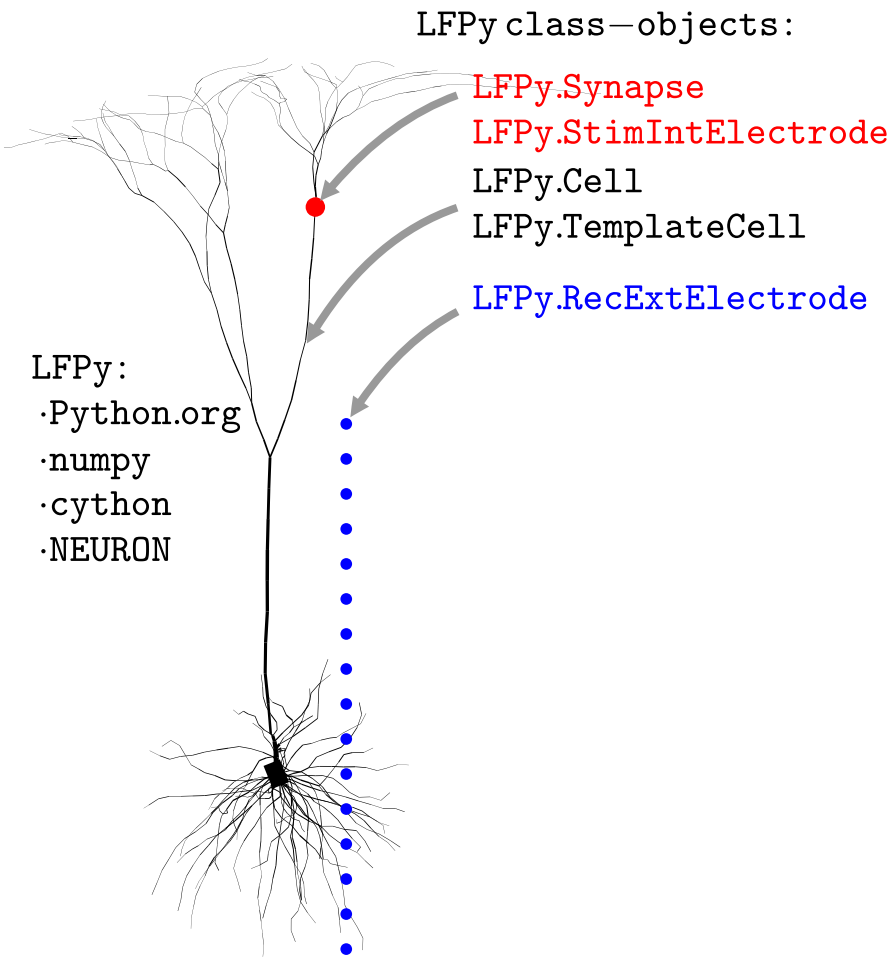


Passive propagation of synapse current input in passive cable model

LFPy - Introduction

Methods implementation:

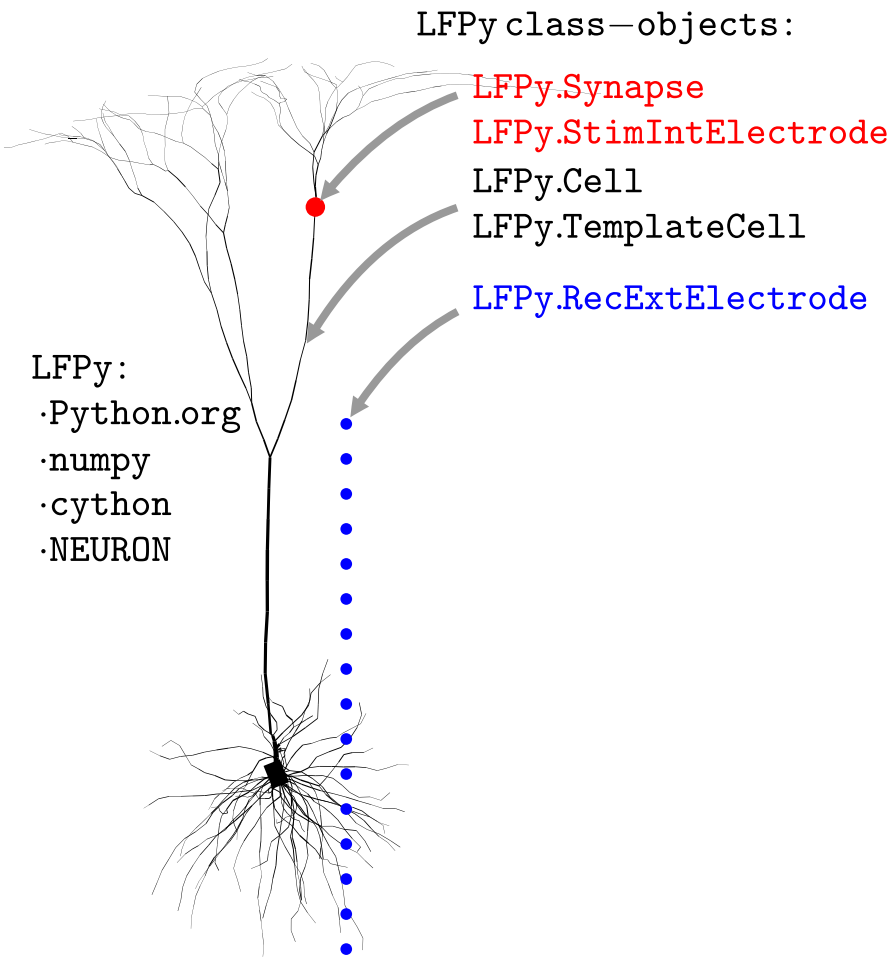
- Implemented in `Python`
- Uses `NEURON` under the hood
- Classes representing
  - cells
  - synapses
  - intracellular electrodes
  - extracellular electrodes
- Homepage w. documentation: http://compneuro.umb.no/LFPy/



LFPy - Introduction

Why Python?

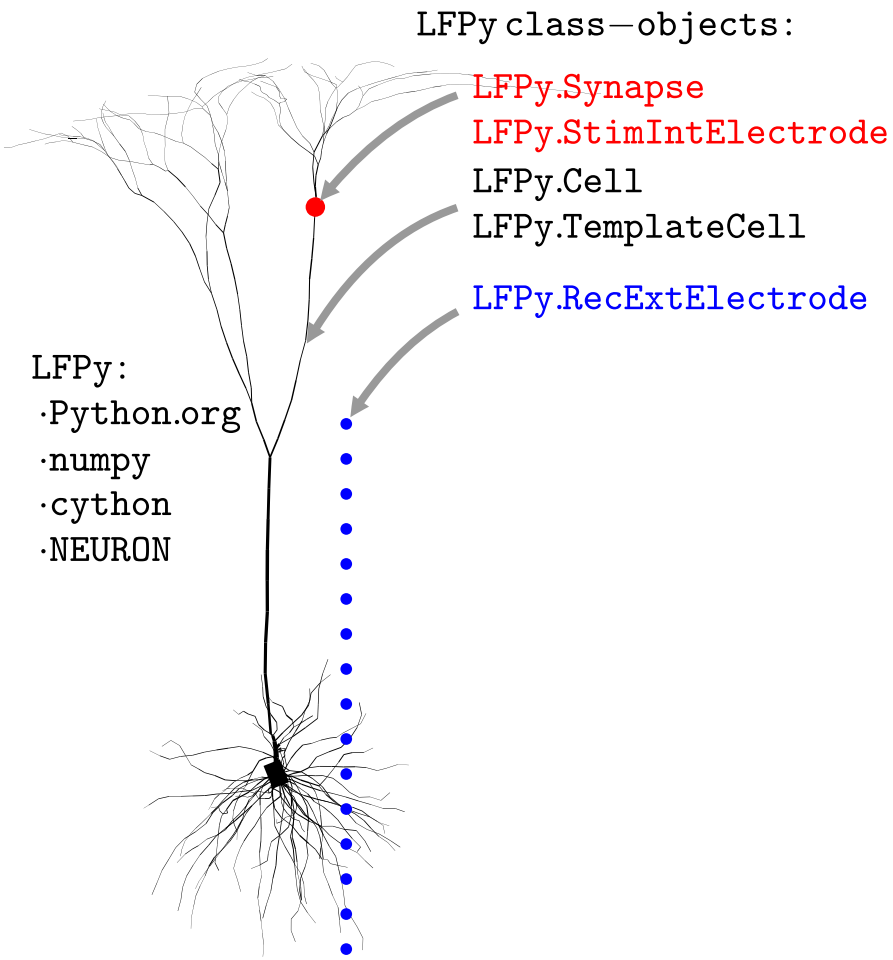
- Open source
- Easy, flexible coding
- Plethora of available packages for visualizations and analysis
- http://pypi.python.org:
  $\sim$ 46700 packages
- Interfacing other programming languages



LFPy - Requirements

Python dependencies:

- Hard:
  - `neuron`
  - `Cython`
  - `numpy`
  - `scipy`
  - `matplotlib`
- Soft:
  - `ipython (+notebook)`
  - `h5py`
  - `mpi4py`



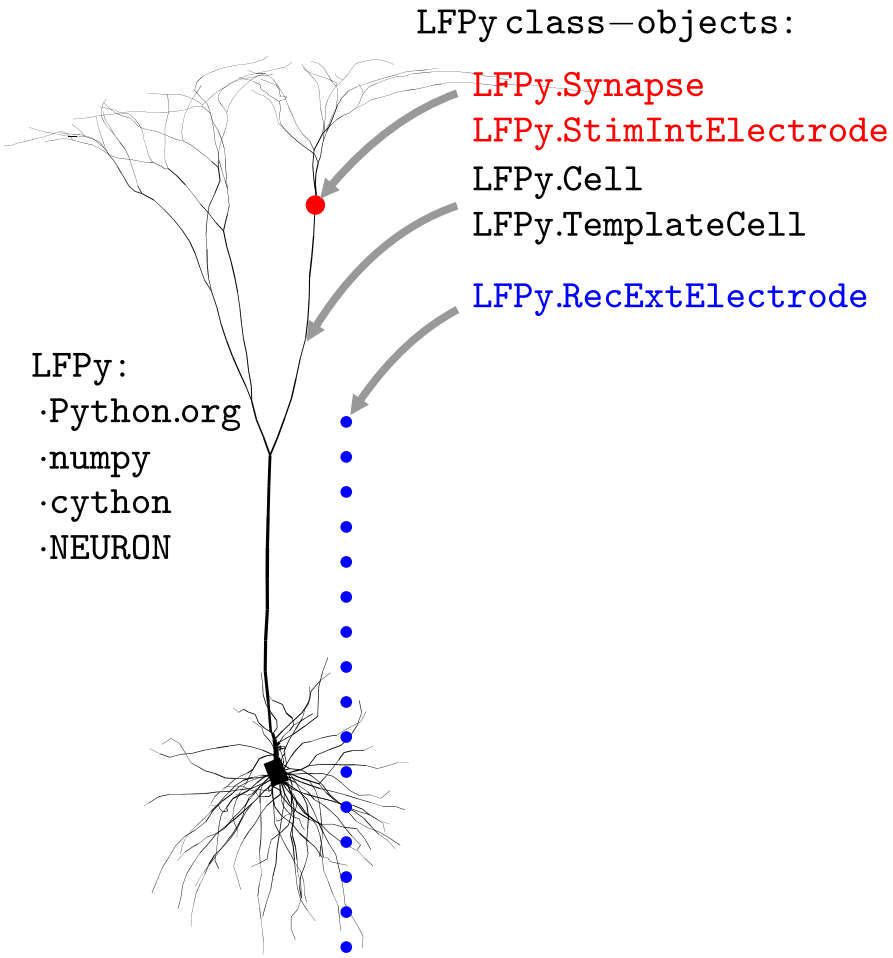
LFPy - Requirements

Python distributions:

- Anaconda
- Enthought Canopy
- Python(x,y)
- ...

LFPy platforms:

- *nix (Linux, Unix)
- OSX
- (Windows)



LFPy - Installation

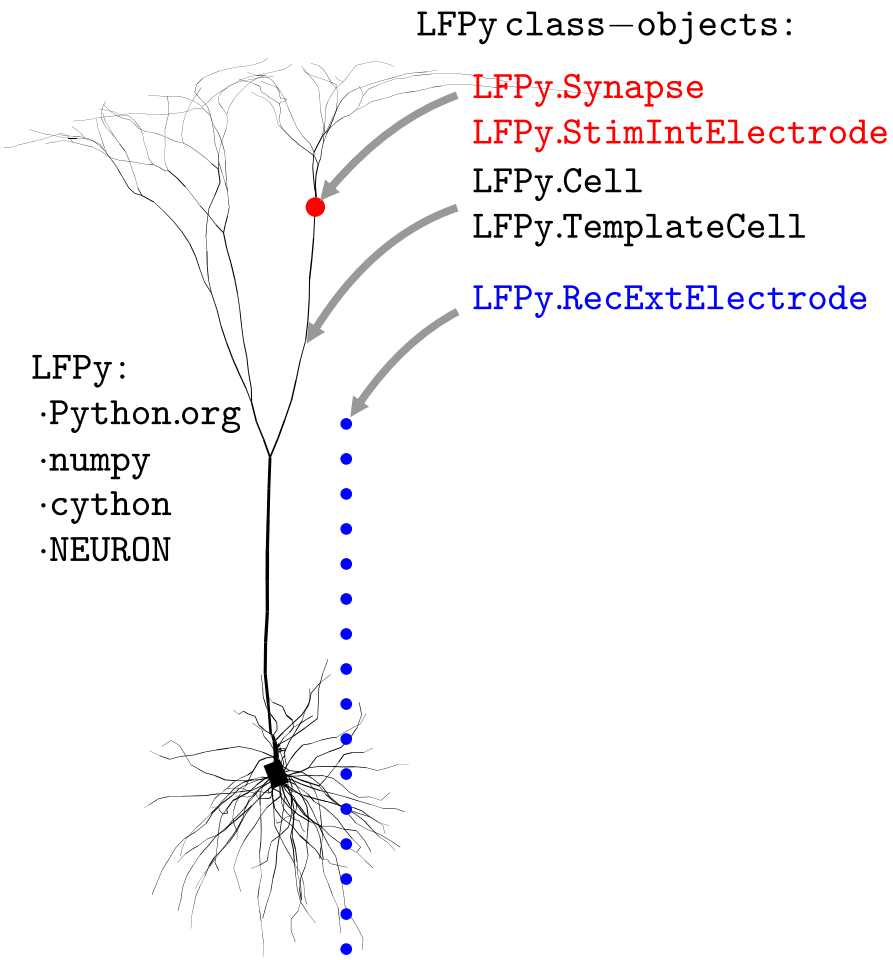
Installation:

Easy method:

- `pip install LFPy --user`
- `easy_install LFPy --user`

From source:

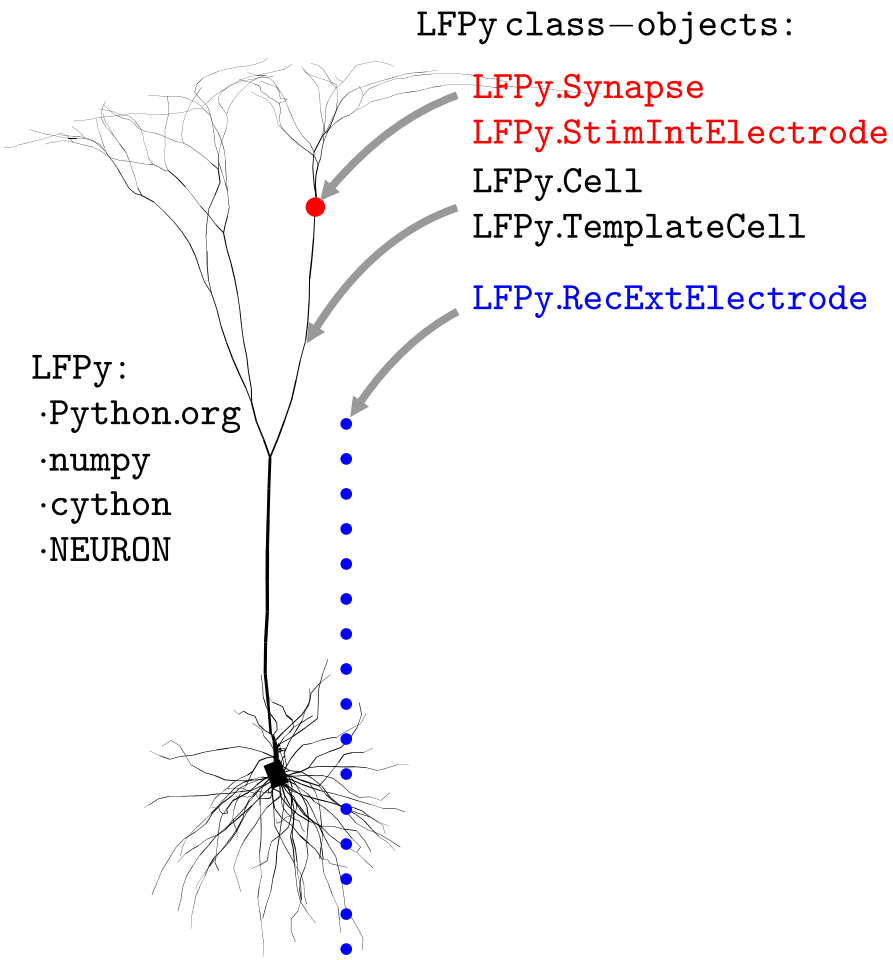
- `cd /PATH/TO/LFPy`
- `python setup.py install --user`



LFPy - Installation

Sources:

- Tar.gz-archive:
  http://compneuro.umb.no/LFPy/downloads/LFPy-1.0.tar.gz
- Subversion repository:
  `svn co http://bebiservice.umb.no/svn-public/LFPy-release/trunk LFPy`



LFPy - Installation

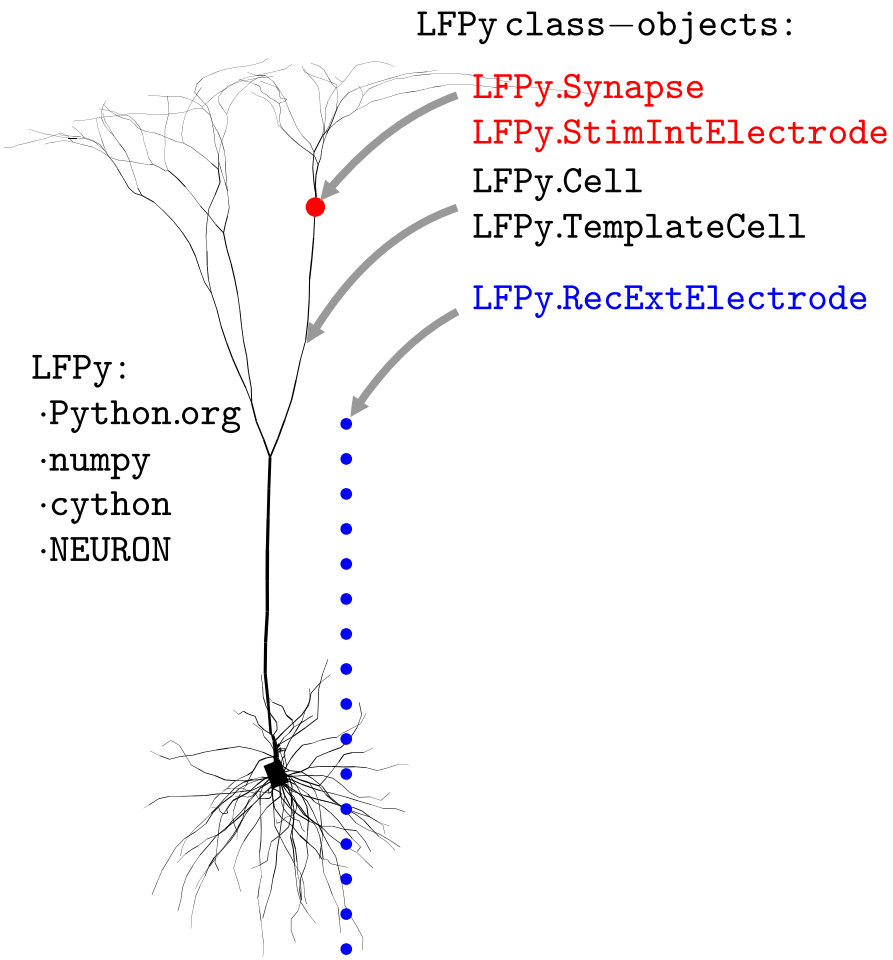
Test installation:

With `Python`:

- `python -c "import LFPy"`
  `NEURON -- Release 7.3`
  `(1089:ecf32eddfbc7)...`

With `NEURON`:

- `nrngui -python -c "import LPFy"`
  `NEURON -- Release 7.3`
  `(1089:ecf32eddfbc7)...`



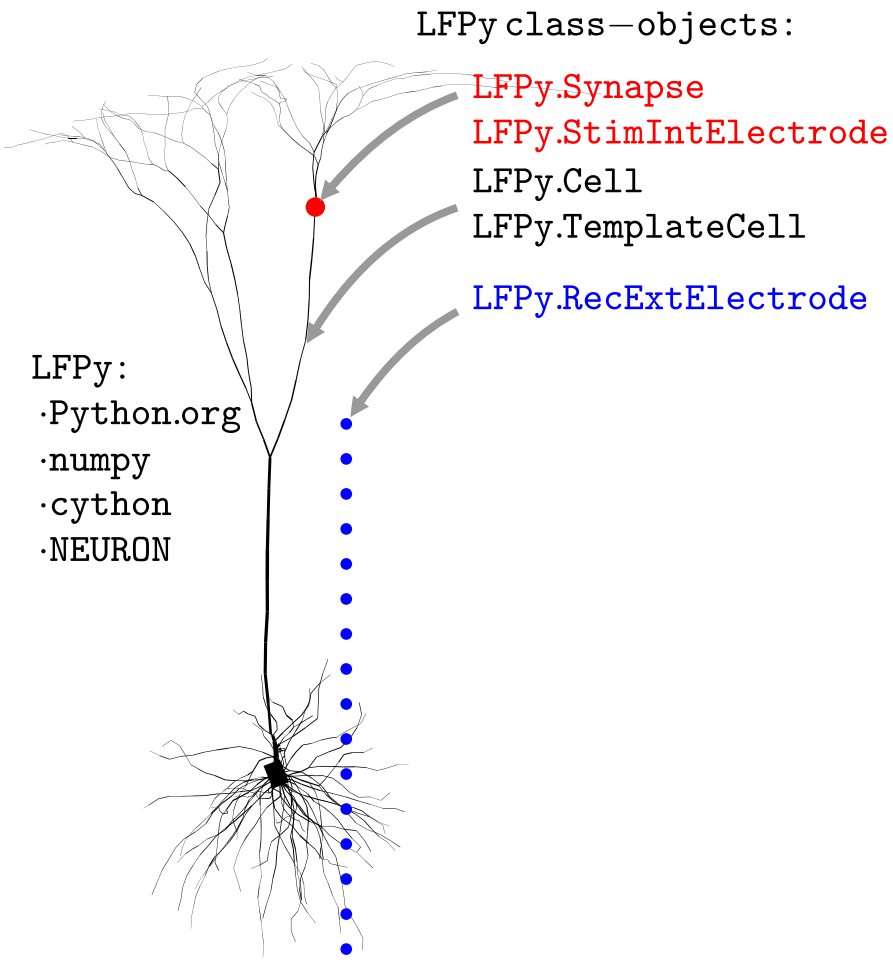
LFPy - Class overview

Main `LFPy` classes:

- `Cell`
- `Synapse`
- `RecExtElectrode`

Auxilliary classes and functions:

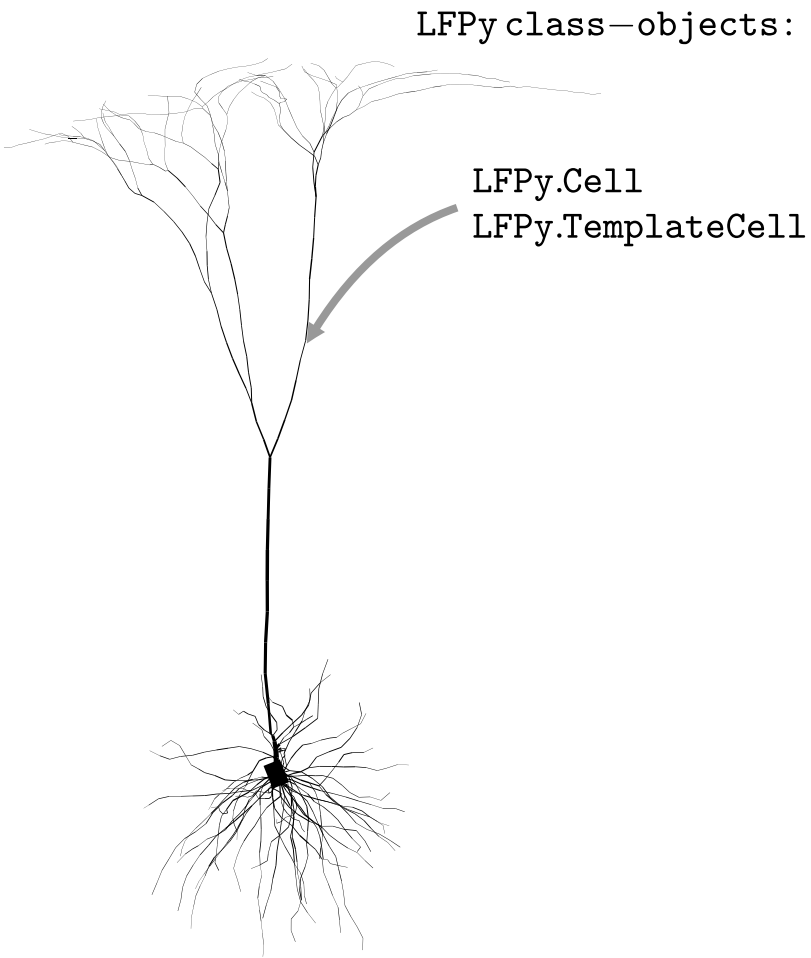
- `TemplateCell`
- `StimIntElectrode`
- `lfpcalc.calc_lfp.*`
- `inputgenerators.*`
- `tools.*`



LFPy - Class overview

`LFPy.Cell`:

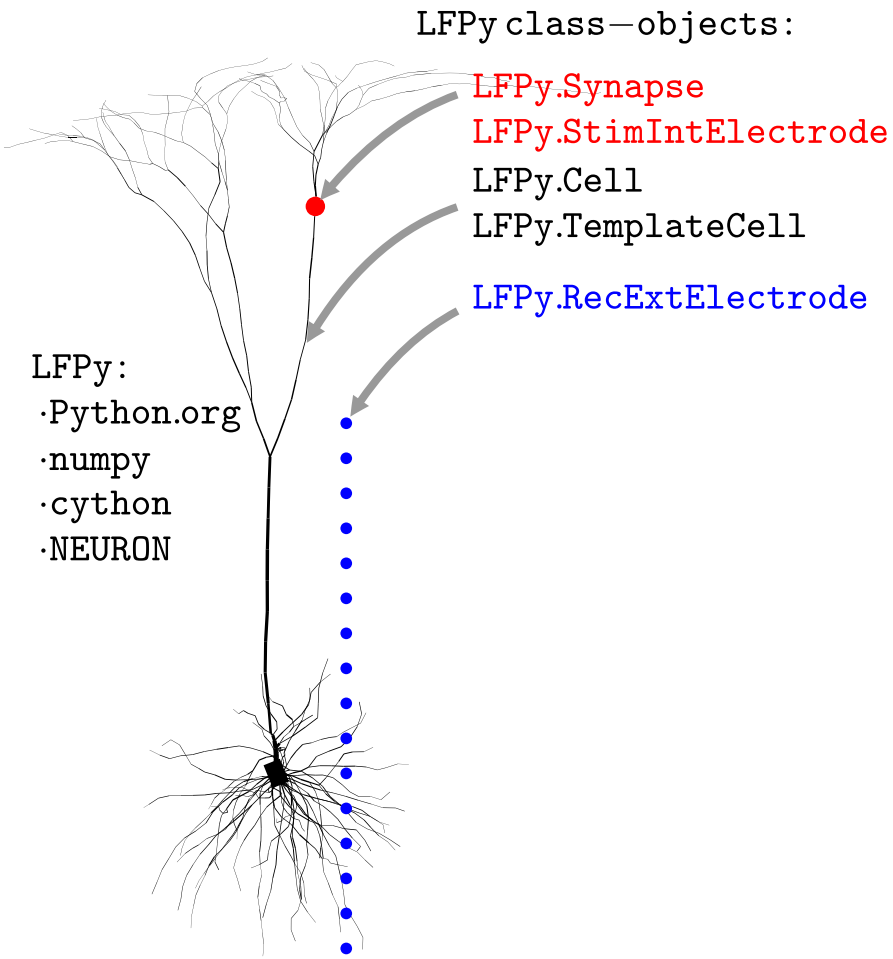
- Uses `NEURON` under the hood
- Sets neuron properties:
  - neuron geometry
  - membrane mechanisms ('pas', 'hh',...)
  - number of compartments ('d_lambda' rule; Hines&Carnevale. *Neuroscientist* (2001))
  - Sets cell location and rotation
- Simulation control
  - duration
  - record variables



LFPy - Class overview

LFPy.Cell:

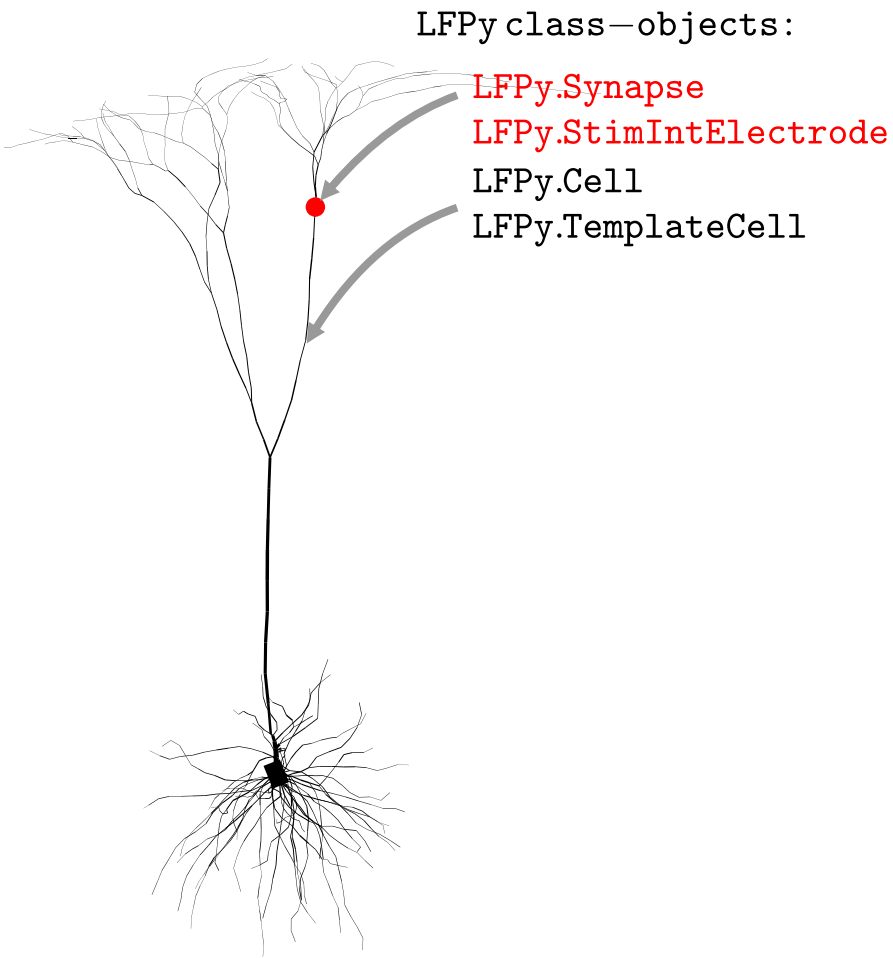
```
# Define cell parameters
cell_parameters = dict(
    morphology='j4a.hoc',
    rm = 30000.,
    cm = 1.,
    Ra = 150.,
    v_init = -65.,
    e_pas = -65.,
    tstopms = 100.)

# Create cell
cell = LFPy.Cell(
          **cell_parameters)
# Position and align cell
cell.set_pos(0., 0. ,0.)
cell.set_rotation(x=4.99,
          y=-4.33, z=3.14)
```



LFPy - Class overview

`LFPy.Synapse`:

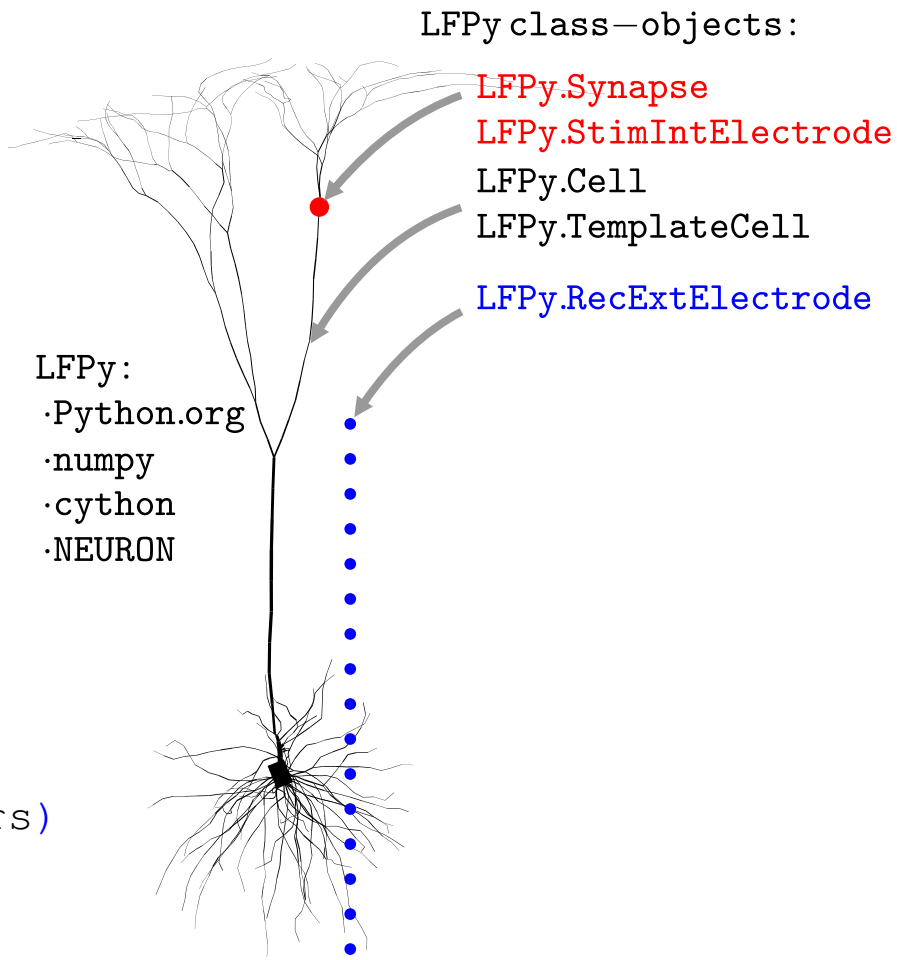
- Attach synapse-objects onto cell objects
- Keyword arguments:
  - `cell`-object
  - compartment index (`idx`)
  - synapse type (`Exp2syn`)
  - mechanism arguments (`e, tau, weight,...`)
- Feed in activation times
- Set up as `NetStim-NetCon` object pairs (see `NEURON` documentation)



LFPy - Class overview

LFPy.Synapse:

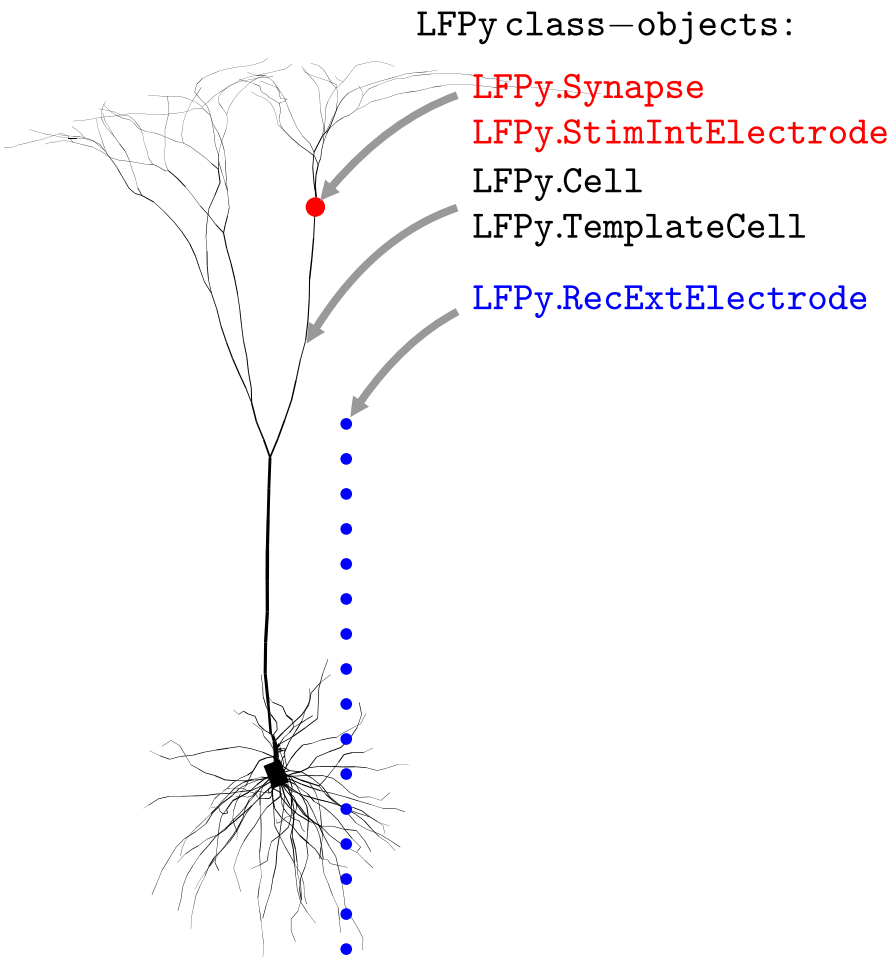
```
# Define synapse parameters
synapse_parameters = dict(
    idx = cell.get_closest_idx(
                x=-200.,
                y=0.,
                z=800.),
    syntype = 'ExpSyn',
    e = 0.,
    tau = 5.,
    weight = .001,
    record_current = True,)

# Create synapse, set activation time
syn = LFPy.Synapse(cell,
                   **synapse_parameters)
syn.set_spike_times(np.array([20.]))
```



LFPy - Class overview

`LFPy.RecExtElectrode`:

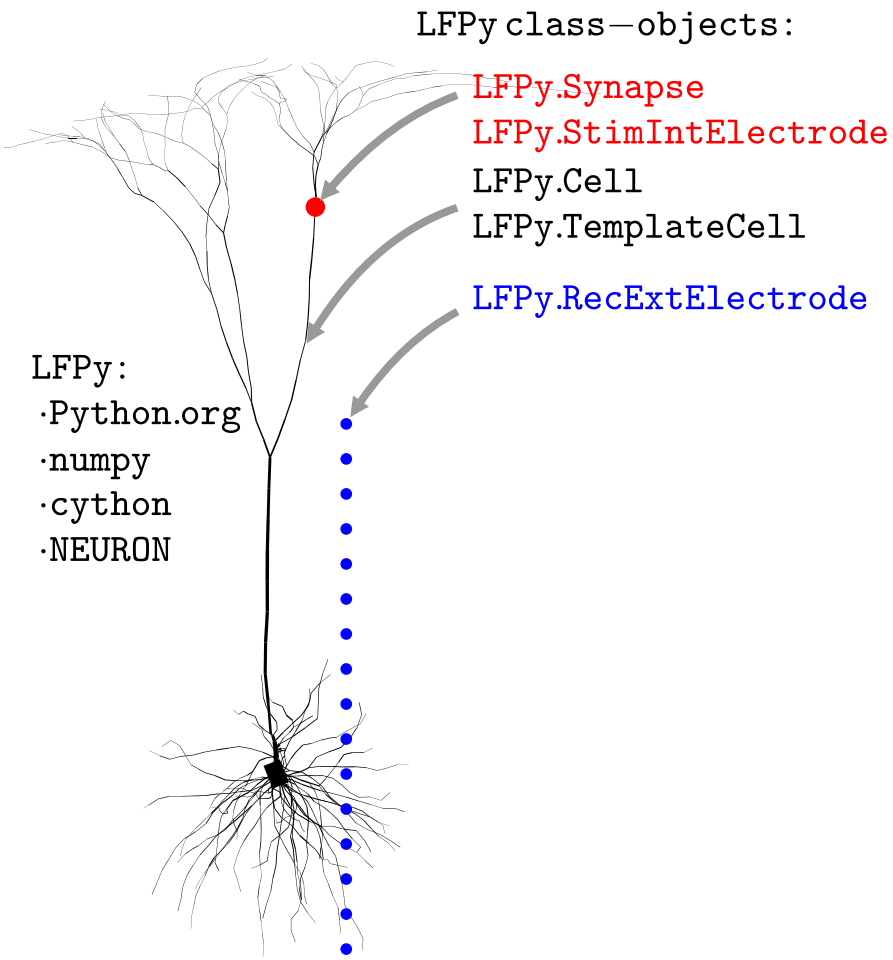
- Extracellular recording devices
- Main arguments:
  - `LFPy.Cell` objects (geometry, currents)
  - contact point coordinates
  - extracellular conductivity
  - method (point/line-sources)
- Optional:
  - radius and surface normal vectors of contacts
  - *n*-point surface area averaged potential



LFPy - Class overview

LFPy.RecExtElectrode:

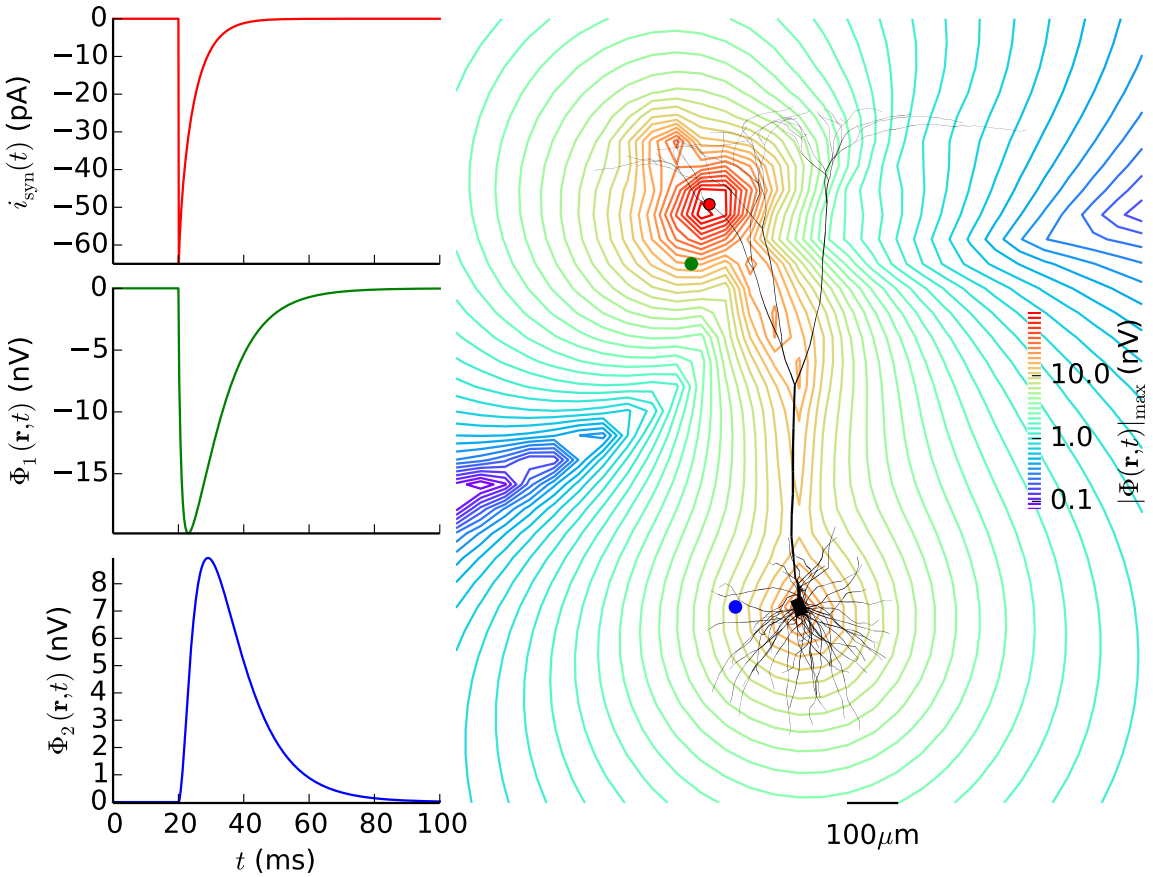
```
# Run simulation, record currents
cell.simulate(rec_imem=True,
              rec_isyn=True)
# Define electrode parameters
electrode_parameters = {
    'sigma' : 0.3,
    'x' : [-130., -220.],
    'y' : [   0.,    0.],
    'z' : [   0.,  700.],
}
# Create electrode object
electrode = LFPy.RecExtElectrode(
            cell,
            **electrode_parameters)
# Calculate LFPs
electrode.calc_lfp()
```



LFPy - Examples

`/path/to/LFPy/examples/example1.py`

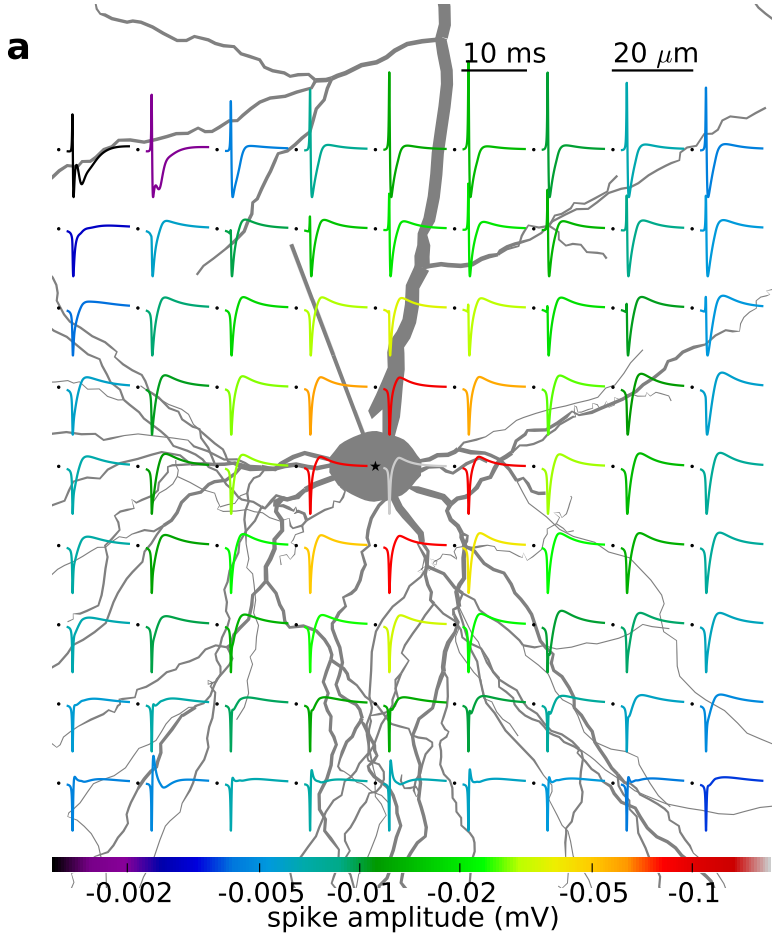
Apical synapse response, passive cable model

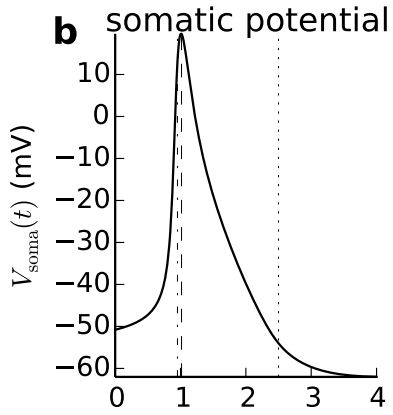


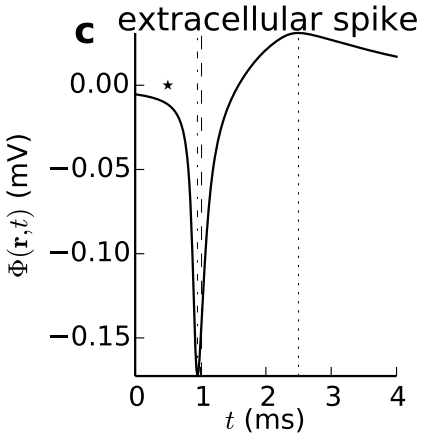
LFPy - Examples

`/path/to/LFPy/examples/example2.py`

Layer 5b action potential (Hay et al. 2011), `LFPy.TemplateCell`



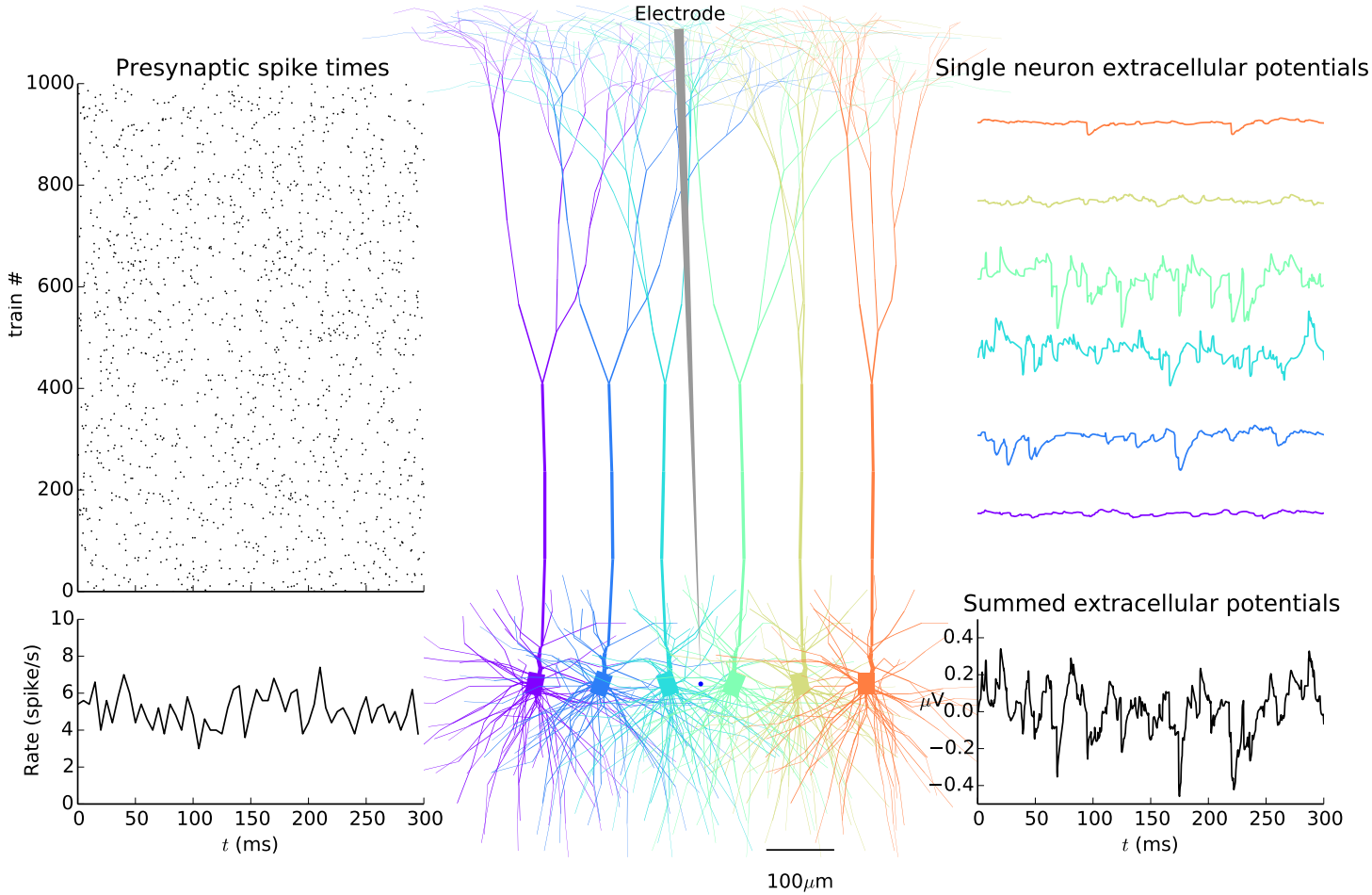




LFPy - Examples

`/path/to/LFPy/examples/example3.py`

Extracellular potentials of small model population, shared input



LFPy - Further reading

frontiers in
NEUROINFORMATICS

ORIGINAL RESEARCH ARTICLE
published: 16 January 2014
doi: 10.3389/fninf.2013.00041

LFPy: a tool for biophysical simulation of extracellular potentials generated by detailed model neurons

Henrik Lindén[1,2†], Espen Hagen[1†], Szymon Łęski[1,3], Eivind S. Norheim[1], Klas H. Pettersen[1,4] and Gaute T. Einevoll[1*]

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Electrical extracellular recordings, i.e., recordings of the electrical potentials in the extracellular medium between cells, have been a main work-horse in electrophysiology for almost a century. The high-frequency part of the signal ($\gtrsim$500 Hz), i.e., the *multi-unit activity (MUA)*, contains information about the firing of action potentials in surrounding neurons, while the low-frequency part, the *local field potential (LFP)*, contains information about how these neurons integrate synaptic inputs. As the recorded extracellular signals arise from multiple neural processes, their interpretation is typically ambiguous and

hybridLFPy - Introduction

Extracellular potentials from electrophysiology

- Low-frequency part; the local field potential (LFP, $f \lesssim 100$ Hz)
  - Highly ambiguous, difficult to analyze
  - Large number of contributing sources
  - Reflect integration of synaptic inputs, synchrony, ...
- High-frequency part ($f \gtrsim 500$ Hz)
  - Contain information of spiking activity
  - Single-unit activity (spikes)
  - Multi-unit activity (MUA)
  - Fewer contributing sources

hybridLFPy - Introduction

Extracellular potentials from electrophysiology

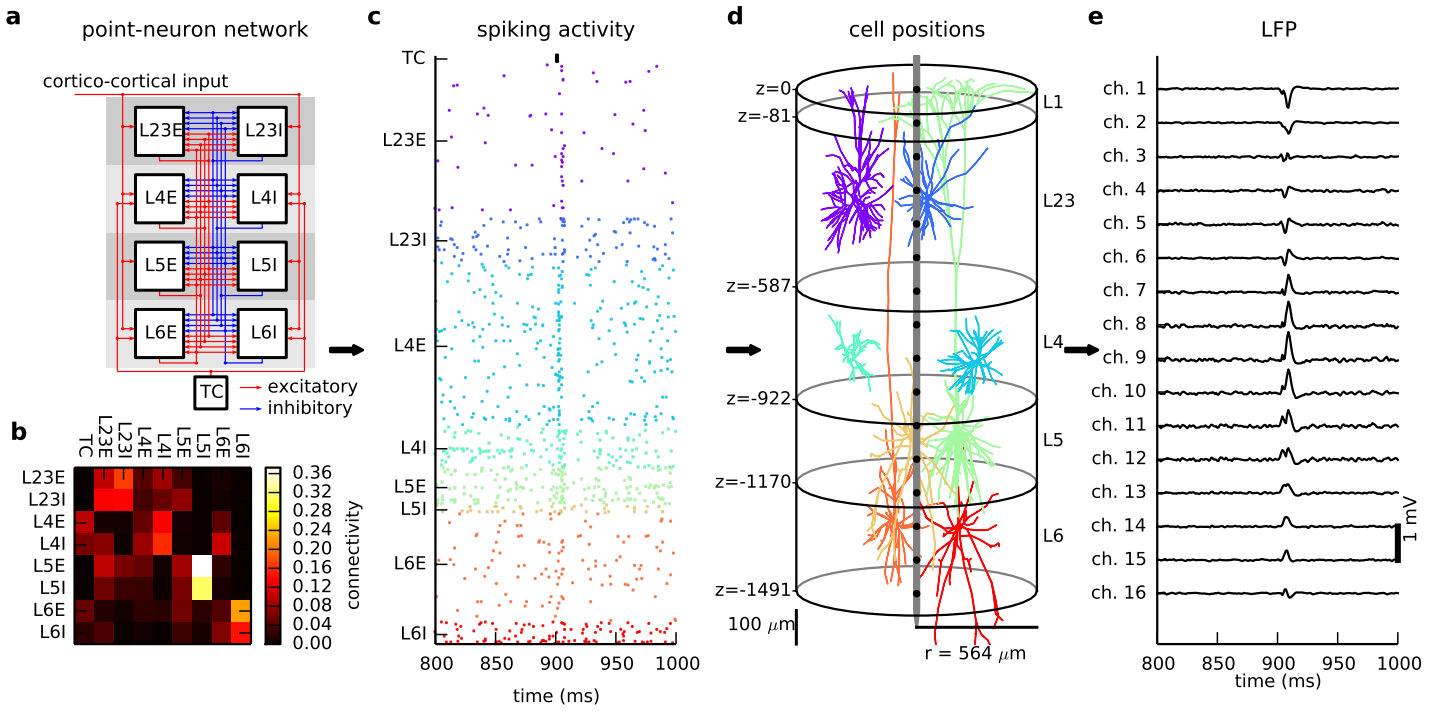
- Point-neuron network models:
  - accurate predictions of population spiking activity
  - efficient, easy to constrain (cf. tutorial T8)
  - poor predictors of extracellular signals (e.g., LFP)
- Biophysically detailed network models
  - demanding to implement
  - difficult to constrain
  - computationally expensive
  - extracellular signal predictions rare

hybridLFPy - Introduction

Extracellular potentials from electrophysiology

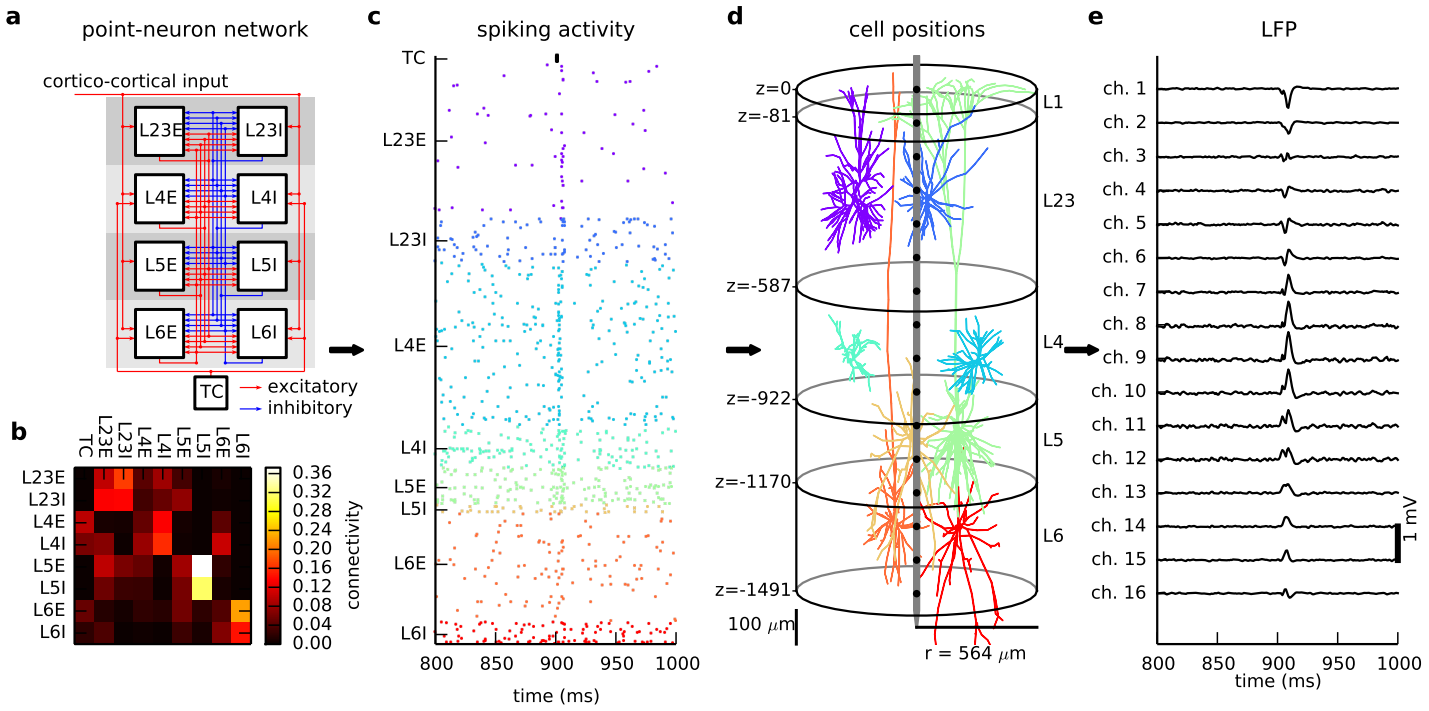
- Here: Hybrid scheme interfacing point-neuron network models with biophysically justified forward modelling scheme for extracellular potentials
  - LFP, CSD
  - (EEG, MEG, VSDi, ...)
- Benefits of hybrid scheme:
  - relate network spiking activity to LFPs
  - introduce spatial features (morphology, connectivity)
  - simplified, passive membrane model
  - preserve network features (cell count, synapse model ...)
  - massive parallelism not necessary

hybridLFPy - Introduction



- Point-neuron network, Potjans&Diesmann, *Cereb Cortex* (2014) (http://www.opensourcebrain.org; NEST tutorial T8; P92)

hybridLFPy - Introduction



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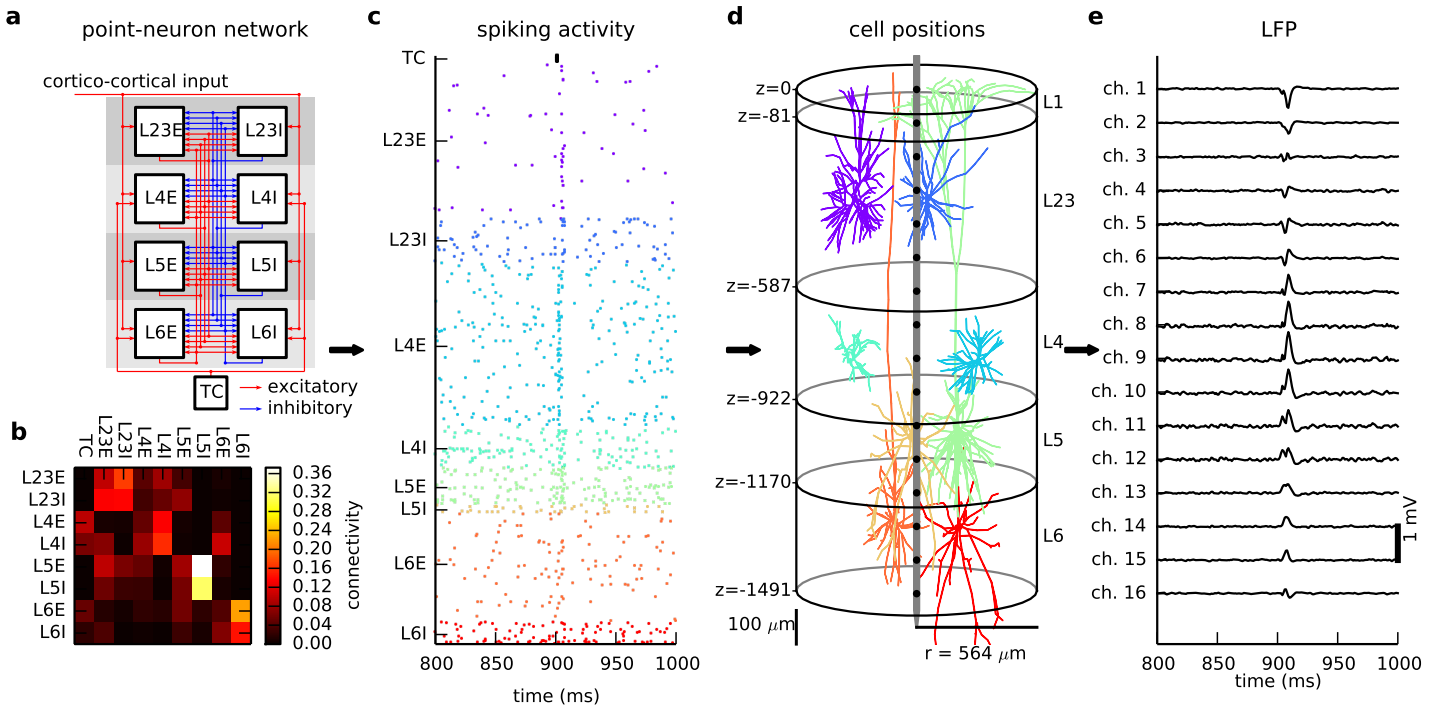

- Point-neuron network, Potjans&Diesmann, *Cereb Cortex* (2014) (http://www.opensourcebrain.org; NEST tutorial T8; P92)
  - Network spikes -> Synaptic activation times
  - Cell-type and layer specific connectivity

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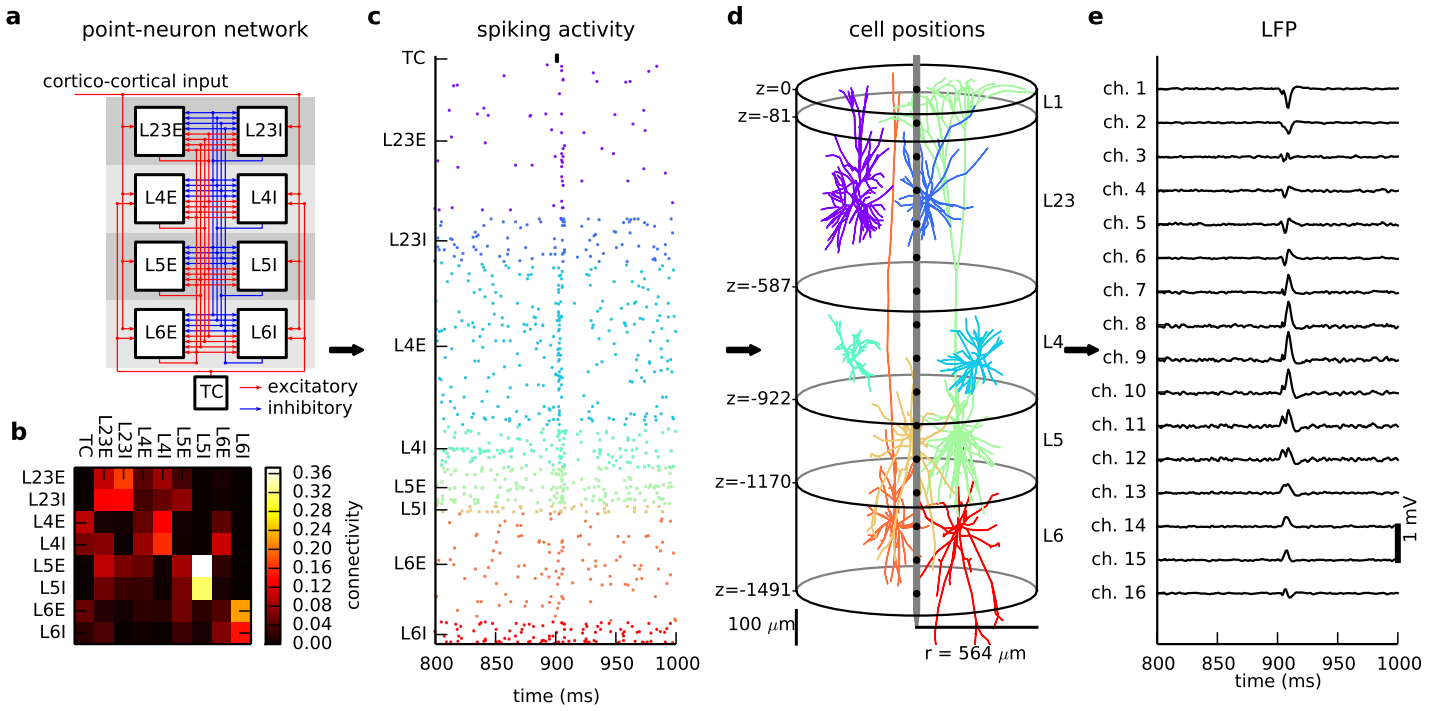
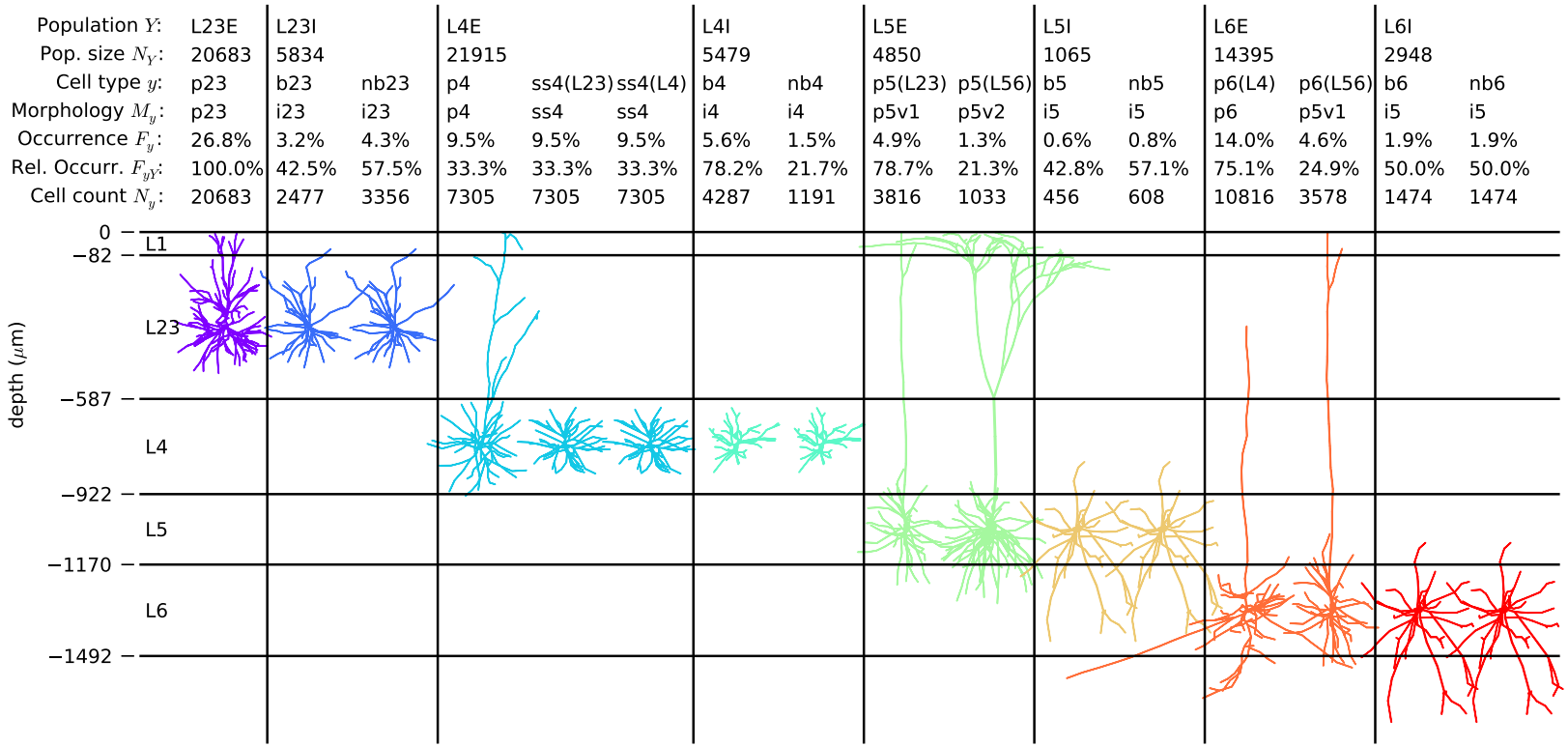


- Point-neuron network, Potjans&Diesmann, *Cereb Cortex* (2014) (http://www.opensourcebrain.org; NEST tutorial T8; P92)
  - Network spikes -> Synaptic activation times
  - Cell-type and layer specific connectivity
  - Multi-compartment neurons: “antennas” for LFP generation

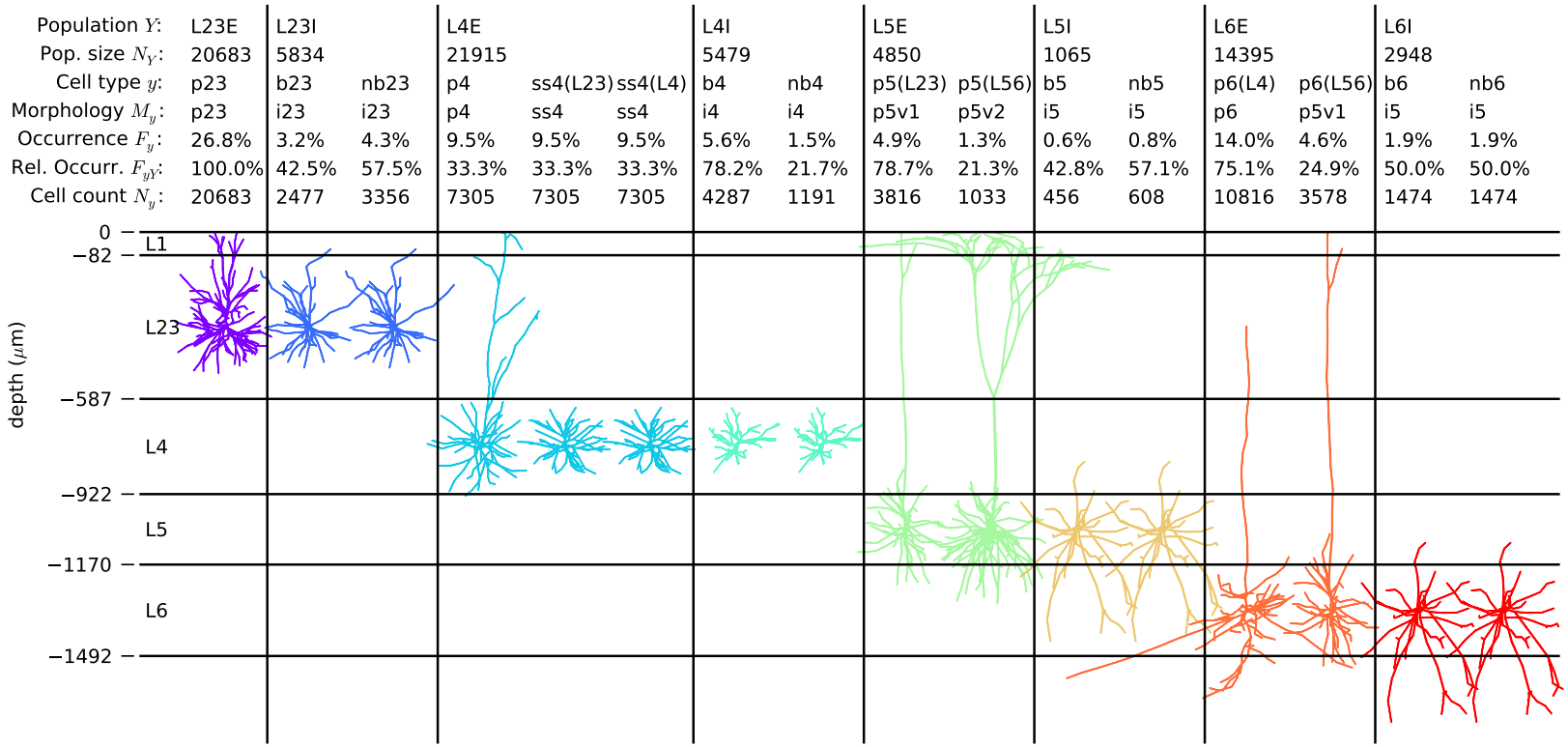
hybridLFPy: Cell-types in cortical column model



Morphologies and layer boundaries: [Stepanyants et al. *Cereb Cortex* (2008)]

- Reconstructions from cat (visual/somatosensory cortices)
- Limited data availability: reuse files across cell types

hybridLFPy: Cell-types in cortical column model

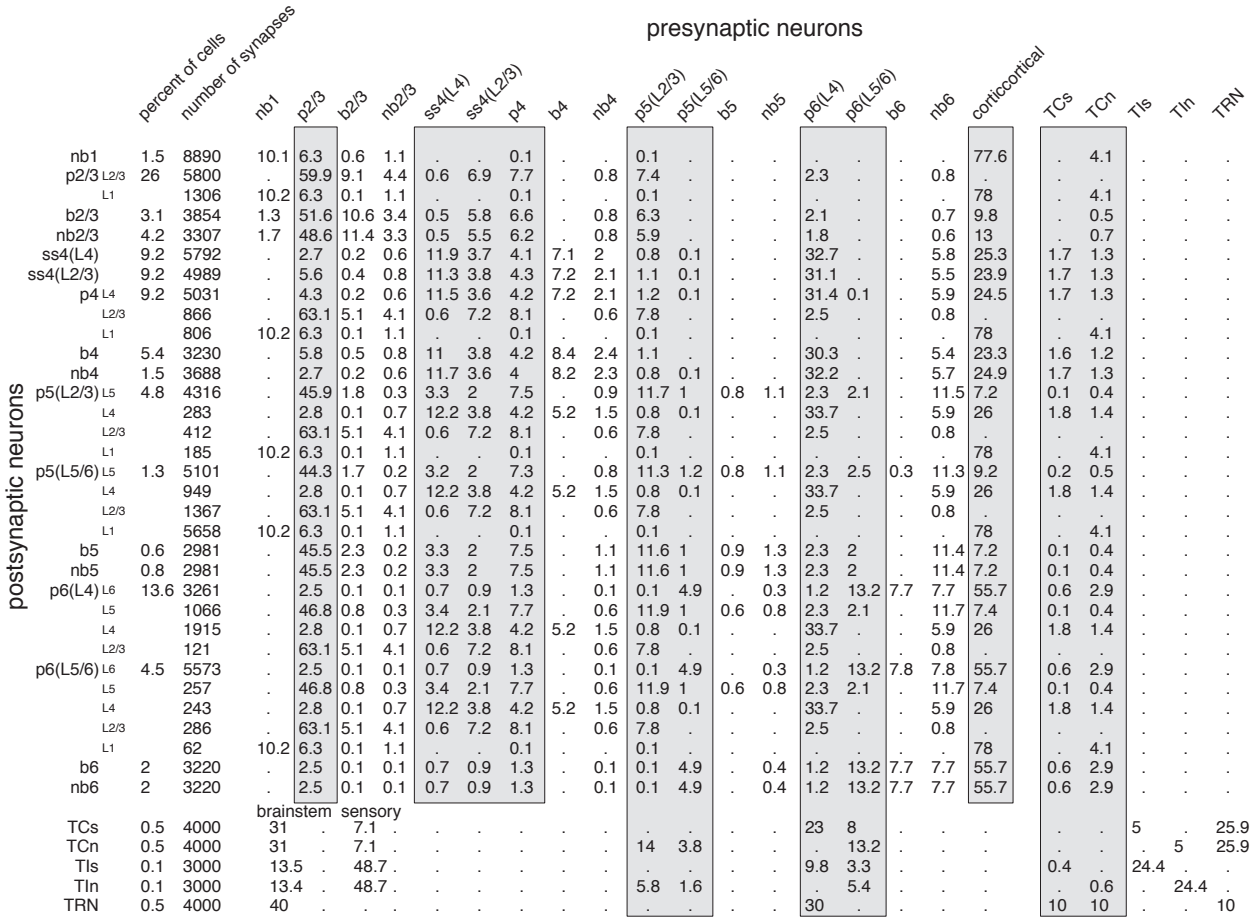


Extrapolation from anatomical data:

- Cell-type specific connectivity: 16 cell types
- Layer specificity of connections

[Binzegger et al. (2004)]

hybridLFPy: Cell-type and layer-specific connectivity



postsynaptic neurons	percent of cells	number of synapses	presynaptic neurons: nb1	p2/3	b2/3	nb2/3	ss4(L4)	ss4(L2/3)	p4	b4	nb4	p5(L2/3)	p5(L5/6)	b5	nb5	p6(L4)	p6(L5/6)	b6	nb6	corticocortical	TCs	TCn	TIs	TIn	TRN
nb1	1.5	8890	10.1	6.3	0.6	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	77.6	.	4.1	.	.	.
p2/3 L2/3	26	5800	.	59.9	9.1	4.4	0.6	6.9	7.7	.	0.8	7.4	.	.	.	2.3	.	.	0.8	.	.	.	.	.	.
L1		1306	10.2	6.3	0.1	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	78	.	4.1	.	.	.
b2/3	3.1	3854	1.3	51.6	10.6	3.4	0.5	5.8	6.6	.	0.8	6.3	.	.	.	2.1	.	.	0.7	9.8	.	0.5	.	.	.
nb2/3	4.2	3307	1.7	48.6	11.4	3.3	0.5	5.5	6.2	.	0.8	5.9	.	.	.	1.8	.	.	0.6	13	.	0.7	.	.	.
ss4(L4)	9.2	5792	.	2.7	0.2	0.6	11.9	3.7	4.1	7.1	2	0.8	0.1	.	.	32.7	.	.	5.8	25.3	1.7	1.3	.	.	.
ss4(L2/3)	9.2	4989	.	5.6	0.4	0.8	11.3	3.8	4.3	7.2	2.1	1.1	0.1	.	.	31.1	.	.	5.5	23.9	1.7	1.3	.	.	.
p4 L4	9.2	5031	.	4.3	0.2	0.6	11.5	3.6	4.2	7.2	2.1	1.2	0.1	.	.	31.4	0.1	.	5.9	24.5	1.7	1.3	.	.	.
L2/3		866	.	63.1	5.1	4.1	0.6	7.2	8.1	.	0.6	7.8	.	.	.	2.5	.	.	0.8	.	.	.	.	.	.
L1		806	10.2	6.3	0.1	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	78	.	4.1	.	.	.
b4	5.4	3230	.	5.8	0.5	0.8	11	3.8	4.2	8.4	2.4	1.1	.	.	.	30.3	.	.	5.4	23.3	1.6	1.2	.	.	.
nb4	1.5	3688	.	2.7	0.2	0.6	11.7	3.6	4	8.2	2.3	0.8	0.1	.	.	32.2	.	.	5.7	24.9	1.7	1.3	.	.	.
p5(L2/3) L5	4.8	4316	.	45.9	1.8	0.3	3.3	2	7.5	.	0.9	11.7	1	0.8	1.1	2.3	2.1	.	11.5	7.2	0.1	0.4	.	.	.
L4		283	.	2.8	0.1	0.7	12.2	3.8	4.2	5.2	1.5	0.8	0.1	.	.	33.7	.	.	5.9	26	1.8	1.4	.	.	.
L2/3		412	.	63.1	5.1	4.1	0.6	7.2	8.1	.	0.6	7.8	.	.	.	2.5	.	.	0.8	.	.	.	.	.	.
L1		185	10.2	6.3	0.1	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	78	.	4.1	.	.	.
p5(L5/6) L5	1.3	5101	.	44.3	1.7	0.2	3.2	2	7.3	.	0.8	11.3	1.2	0.8	1.1	2.3	2.5	0.3	11.3	9.2	0.2	0.5	.	.	.
L4		949	.	2.8	0.1	0.7	12.2	3.8	4.2	5.2	1.5	0.8	0.1	.	.	33.7	.	.	5.9	26	1.8	1.4	.	.	.
L2/3		1367	.	63.1	5.1	4.1	0.6	7.2	8.1	.	0.6	7.8	.	.	.	2.5	.	.	0.8	.	.	.	.	.	.
L1		5658	10.2	6.3	0.1	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	78	.	4.1	.	.	.
b5	0.6	2981	.	45.5	2.3	0.2	3.3	2	7.5	.	1.1	11.6	1	0.9	1.3	2.3	2	.	11.4	7.2	0.1	0.4	.	.	.
nb5	0.8	2981	.	45.5	2.3	0.2	3.3	2	7.5	.	1.1	11.6	1	0.9	1.3	2.3	2	.	11.4	7.2	0.1	0.4	.	.	.
p6(L4) L6	13.6	3261	.	2.5	0.1	0.1	0.7	0.9	1.3	.	0.1	0.1	4.9	.	0.3	1.2	13.2	7.7	7.7	55.7	0.6	2.9	.	.	.
L5		1066	.	46.8	0.8	0.3	3.4	2.1	7.7	.	0.6	11.9	1	0.6	0.8	2.3	2.1	.	11.7	7.4	0.1	0.4	.	.	.
L4		1915	.	2.8	0.1	0.7	12.2	3.8	4.2	5.2	1.5	0.8	0.1	.	.	33.7	.	.	5.9	26	1.8	1.4	.	.	.
L2/3		121	.	63.1	5.1	4.1	0.6	7.2	8.1	.	0.6	7.8	.	.	.	2.5	.	.	0.8	.	.	.	.	.	.
p6(L5/6) L6	4.5	5573	.	2.5	0.1	0.1	0.7	0.9	1.3	.	0.1	0.1	4.9	.	0.3	1.2	13.2	7.8	7.8	55.7	0.6	2.9	.	.	.
L5		257	.	46.8	0.8	0.3	3.4	2.1	7.7	.	0.6	11.9	1	0.6	0.8	2.3	2.1	.	11.7	7.4	0.1	0.4	.	.	.
L4		243	.	2.8	0.1	0.7	12.2	3.8	4.2	5.2	1.5	0.8	0.1	.	.	33.7	.	.	5.9	26	1.8	1.4	.	.	.
L2/3		286	.	63.1	5.1	4.1	0.6	7.2	8.1	.	0.6	7.8	.	.	.	2.5	.	.	0.8	.	.	.	.	.	.
L1		62	10.2	6.3	0.1	1.1	.	.	0.1	.	.	0.1	.	.	.	.	.	.	.	78	.	4.1	.	.	.
b6	2	3220	.	2.5	0.1	0.1	0.7	0.9	1.3	.	0.1	0.1	4.9	.	0.4	1.2	13.2	7.7	7.7	55.7	0.6	2.9	.	.	.
nb6	2	3220	.	2.5	0.1	0.1	0.7	0.9	1.3	.	0.1	0.1	4.9	.	0.4	1.2	13.2	7.7	7.7	55.7	0.6	2.9	.	.	.
			brainstem	sensory																					
TCs	0.5	4000	31	.	7.1	.	.	.	.	.	.	.	.	.	.	23	8	.	.	.	.	.	5	.	25.9
TCn	0.5	4000	31	.	7.1	.	.	.	.	.	.	14	3.8	.	.	.	13.2	.	.	.	.	.	.	5	25.9
TIs	0.1	3000	13.5	.	48.7	.	.	.	.	.	.	.	.	.	.	9.8	3.3	.	.	.	0.4	.	24.4	.	.
TIn	0.1	3000	13.4	.	48.7	.	.	.	.	.	.	5.8	1.6	.	.	.	5.4	.	.	.	.	0.6	.	24.4	.
TRN	0.5	4000	40	.	.	.	.	.	.	.	.	.	.	.	.	30	.	.	.	.	10	10	.	.	10

Binzegger et al. *J Neurosci* (2004)

hybridLFPy - Package overview

- `hybridLFPy` Python package:
  - Homepage: http://github.com/espenhgn/hybridLFPy
  - Main classes and functions:
    - `hybridLFPy.CachedNetwork`
    - `hybridLFPy.Population`
    - `hybridLFPy.Postprocess`
    - `hybridLFPy.setup_file_dest`
  - Example files - `/path/to/hybridLFPy/examples`
    - Network model: `/brunel_alpha_nest.py`
    - Hybrid model application: `/example_brunel.py`
  - Python dependencies: `LFPy, nest, mpi4py, h5py, sqlite3, NeuroTools`

hybridLFPy - Package overview

hybridLFPy 0.1 documentation »

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Welcome to hybridLFPy's documentation!

Module **hybridLFPy**

hybridLFPy ¶

Provides methods for estimating extracellular potentials of simplified spiking neuron network models.

This software comes with no warranties.

How to use the documentation

Documentation is available in two forms:

1. Docstrings provided with the code, e.g., as hybridLFPy? within IPython
2. Autogenerated sphinx-built output, compiled using

```
sphinx-build -b html docs documentation
```

in the root folder of the package sources

Available classes

CachedNetwork
: Offline interface between network spike events and used by class Population

CachedNoiseNetwork
: Creation of Poisson spiketrains of a plastative network model, interfaces class Population

CachedFixedSpikesNetwork

hybridLFPy - Application with 2-population network

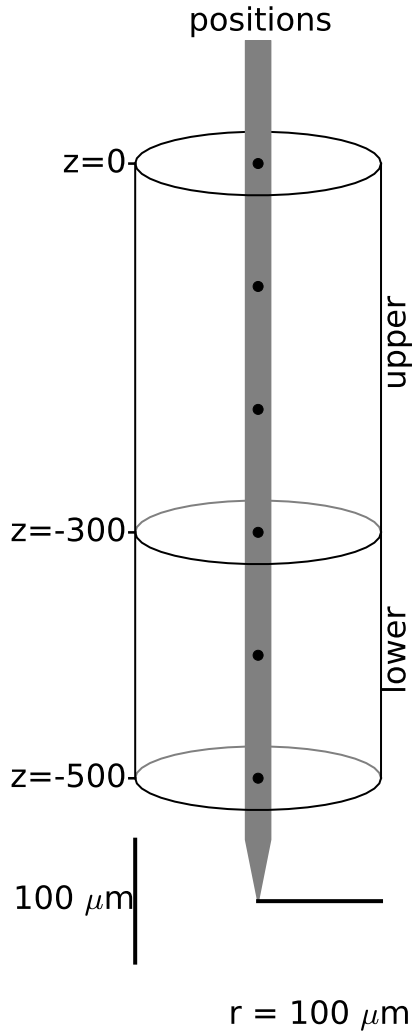
Network model

- Two-population E-I network (Brunel, *J Comput Neurosci* (2000))
  - leaky integrate-and-fire (LIF) neurons
  - current based synapses
  - alpha-shaped PSCs
  - adapted from PyNest example file:
    `nest-2.4.1/pynest/examples/brunel-alpha-nest.py`
- Modifications:
  - $N_{\mathrm{E}} + N_{\mathrm{I}} = 500$ neurons
  - $J = 1.$ mV
  - $g = -6.$
  - External Poisson spike generators removed
  - DC current input ($I_{\mathrm{DC}} \approx 300$ nA)
  - All spike events dumped to disk

hybridLFPy - Application with 2-population network

Model configuration

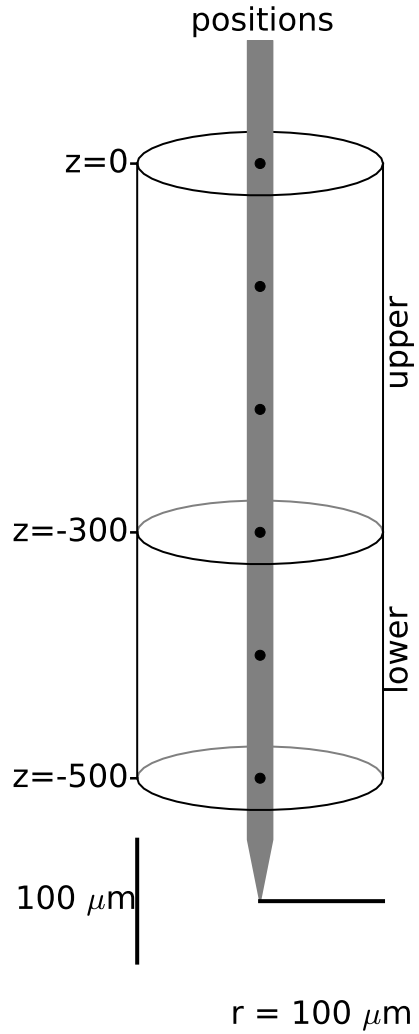
- "Layers":
  - upper $z \in [-300, 0]$ μm
  - lower $z \in [-500, -300]$ μm



hybridLFPy - Application with 2-population network

Model configuration

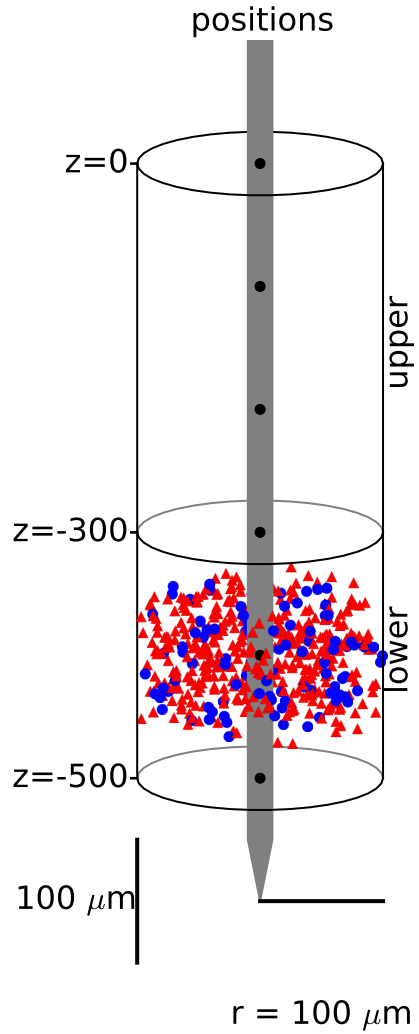
- "Layers":
  - upper $z \in [-300, 0]$ μm
  - lower $z \in [-500, -300]$ μm
- Measurements:
  - 6-channel laminar "electrode"
  - 100 μm between contacts
  - current-source density (CSD)
  - local field potentials (LFP)



hybridLFPy - Application with 2-population network

Model configuration

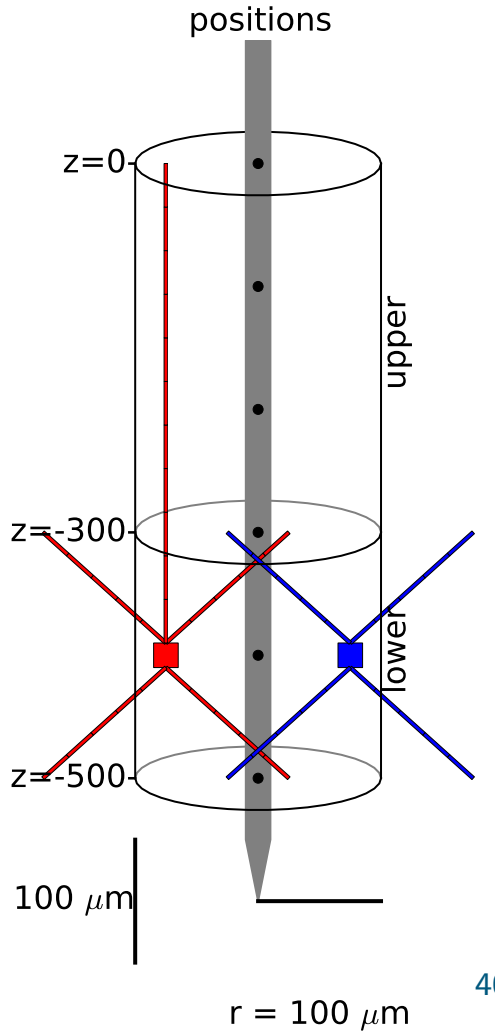
- "Layers":
  - upper $z \in [-300, 0]$ μm
  - lower $z \in [-500, -300]$ μm
- Measurements:
  - 6-channel laminar "electrode"
  - 100 μm between contacts
  - current-source density (CSD)
  - local field potentials (LFP)
- Random locations within cylinder
  - $z \in [-450, -350]$ μm
  - $R < 100$ μm



hybridLFPy - Application with 2-population network

Model configuration

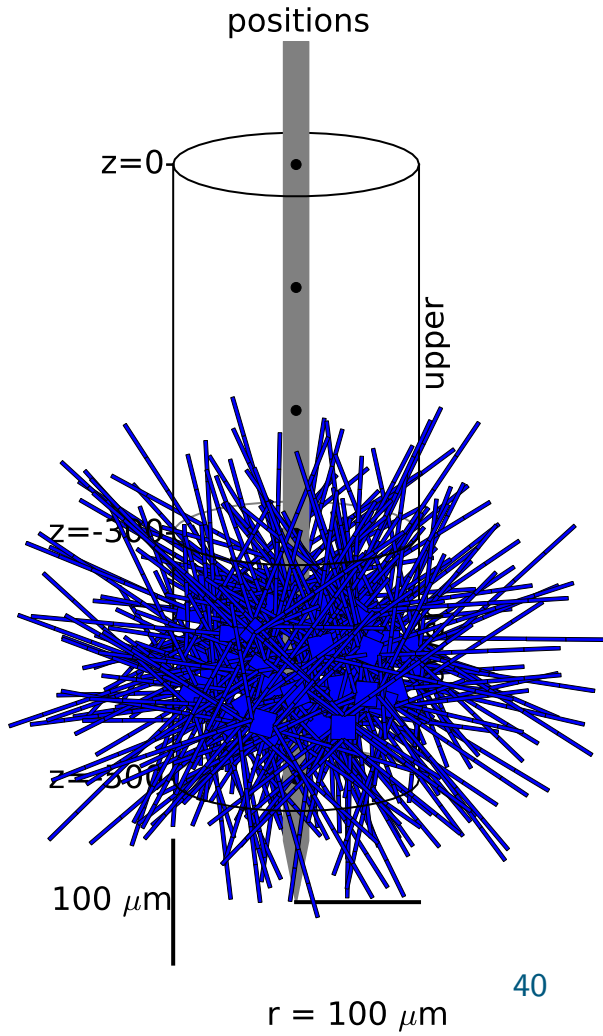
- Simplified morphologies:
  - “EX” - “pyramidal neuron”
  - “IN” - “interneuron”
  - passive cable models
  - membrane time constant of LIF neurons
  - spatially discretized into compartments



hybridLFPy - Application with 2-population network

Model configuration

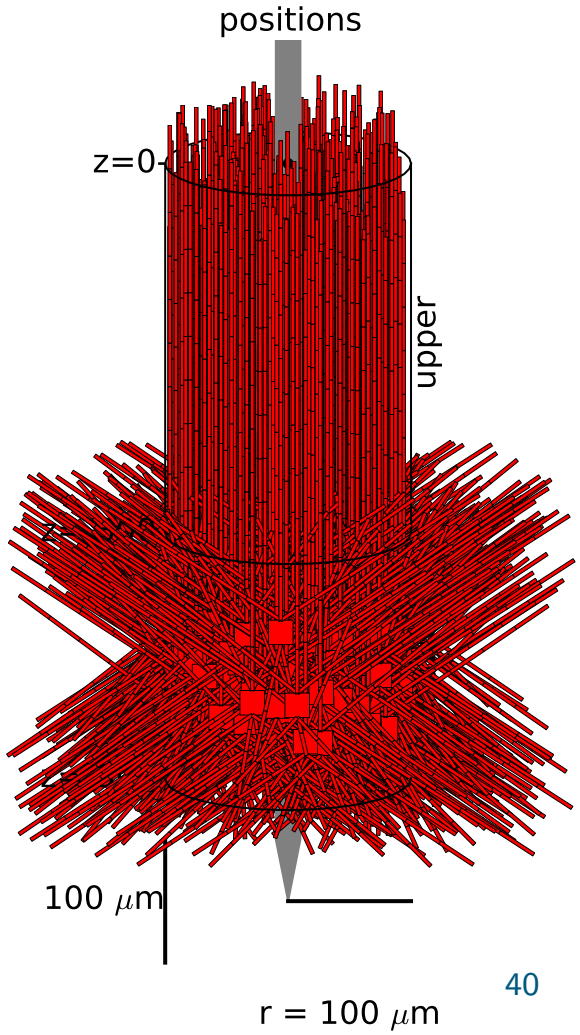
- Simplified morphologies:
  - “EX” - “pyramidal neuron”
  - “IN” - “interneuron”
  - passive cable models
  - membrane time constant of LIF neurons
  - spatially discretized into compartments
- IN - Random orientation



hybridLFPy - Application with 2-population network

Model configuration

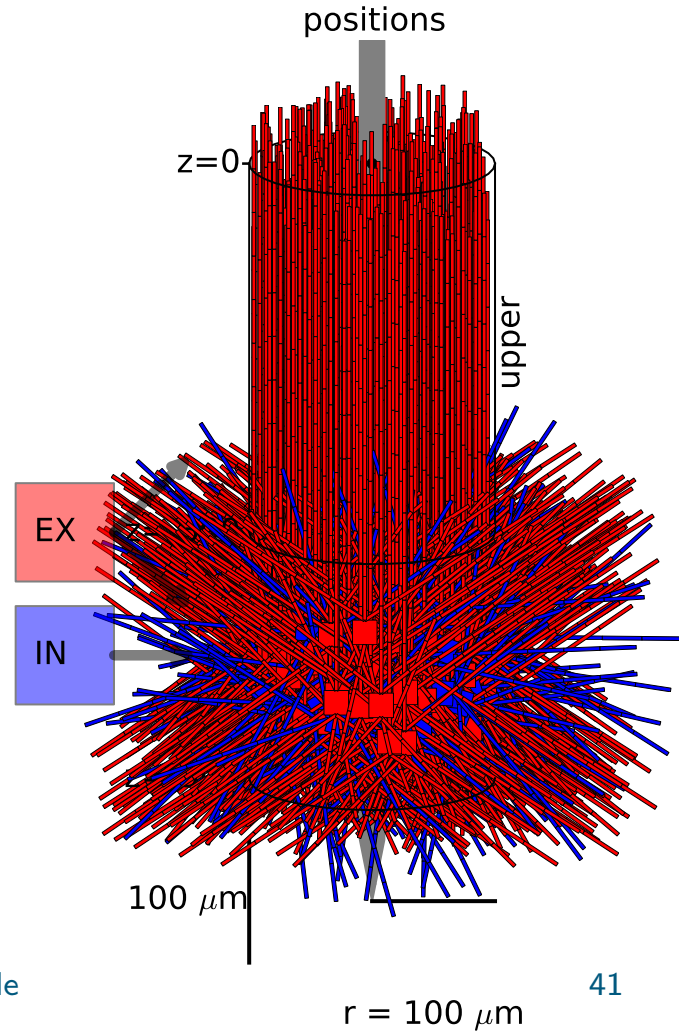
- Simplified morphologies:
  - "EX" - "pyramidal neuron"
  - "IN" - "interneuron"
  - passive cable models
  - membrane time constant of LIF neurons
  - spatially discretized into compartments
- IN - Random orientation
- EX - Vertically aligned apical stick



hybridLFPy - Application with 2-population network

Model configuration

- Connectivity:
  - In-degree inherited from network
  - EX - 50-50% distribution of excitatory input in upper/lower layer
  - EX - Inhibition only in lower layer
  - IN - All connections in lower layer
  - No inputs on soma
  - Within layers - conn.-prob. normalized by surface area
- Synapse model
  - inherited from network
  - `NEURON NMODL` language `examples/alphaisyn.mod`



hybridLFPy - Example implementation

`example_brunel.py` initialization:

```
#import necessary classes and functions
...
from hybridLFPy import PostProcess, Population, CachedNetwork
from hybridLFPy import setup_file_dest
from NeuroTools.parameters import ParameterSet
from mpi4py import MPI

#MPI Initialization
COMM = MPI.COMM_WORLD
SIZE = COMM.Get_size()
RANK = COMM.Get_rank()

#Parameters defined in pynest example script,
#brunel_alpha_nest.py, adapted from NEST v2.4.1 release:
import brunel_alpha_nest as BN
#note: will not execute model
```

hybridLFPy - Example implementation

File hierarchy:

- `simulation_output_example_brunel/`
  - `simscripts/`
  - `cells/`
  - `populations/`
  - `spiking_output_path/`
  - `figures/`

hybridLFPy - Example implementation

`example_brunel.py` file hierarchy:

```
PS = ParameterSet(dict()) #initialize
savefolder = 'simulation_output_example_brunel'
PS.update(
    #Main destination destination
    savefolder = savefolder,
    #copy of simulation files
    sim_scripts_path = os.path.join(savefolder, 'sim_scripts'),
    #single-cell output
    cells_path = os.path.join(savefolder, 'cells'),
    #destination compound signals
    populations_path = os.path.join(savefolder, 'populations'),
    #spike output from the network model
    spike_output_path = BN.spike_output_path,
    #figure destination
    figures_path = os.path.join(savefolder, 'figures')
))
#set up file destination, clear old results
setup_file_dest(PS, clearDestination=True)
```

hybridLFPy - Example implementation

`example_brunel.py`, parameter setup:

```
#population (and cell type) specific parameters
PS.update(dict(
    #population names
    X = ["EX", "IN"],
    #population-specific LFPy.Cell parameters
    cellParams = dict(
        #excitory cells
        EX = dict(
            morphology = 'morphologies/ex.hoc',
            v_init = BN.neuron_params['E_L'],
            rm = BN.neuron_params['tau_m'] * 1E3 / 1.,
            cm = 1.0, Ra = 150,
            e_pas = BN.neuron_params['E_L'],
            timeres_NEURON = BN.dt,
            timeres_python = BN.dt,
            tstopms = BN.simtime,),
        #inhibitory cells
        IN = dict(
            morphology = 'morphologies/in.hoc', ...))
```

hybridLFPy - Example implementation

`example_brunel.py`, parameter setup:

```
#population (and cell type) specific parameters
PS.update(dict(
    #cylindrical model populations
    populationParams = dict(
        EX = dict(
            number = BN.NE,
            radius = 100,
            z_min = -450,
            z_max = -350,
            min_cell_interdist = 1.,),
        IN = dict(number = BN.NI, ...),
    ),
    #set the boundaries between the
    #"upper" and "lower" layer:
    layerBoundaries = [[0.,   -300],
                       [-300, -500]]),
```

hybridLFPy - Example implementation

`example_brunel.py`, parameter setup:

```
#set the geometry of the virtual recording device
PS.update(dict(
    electrodeParams = dict(
            #contact locations:
            x = [0]*6,
            y = [0]*6,
            z = [x*-100. for x in range(6)],
            #extracellular conductivity:
            sigma = 0.3,
            #contact surface normals, radius, n-point averaging
            N = [[1, 0, 0]]*6,
            r = 5,
            n = 20,
            seedvalue = None,
            #dendrite line sources, soma as sphere source (Linden2014)
            method = 'som_as_point',
            #no somas within the constraints of the "electrode shank":
            r_z = [[-1E199, -600, -550, 1E99],[0, 0, 10, 10]],)))
```

hybridLFPy - Example implementation

`example_brunel.py`, parameter setup:

```
#layer- and population-specific
#connection parameters
PS.update(dict(
    #number of connections per layer per cell
    #from each presynaptic population
    k_yXL = dict(
        EX = [[int(0.5*BN.CE), 0],
              [int(0.5*BN.CE), BN.CI]],
        IN = [[0,      0],
              [BN.CE, BN.CI]],),

    #Connection weights (current amplitudes)
    J_yX = dict(
        EX = [BN.J_ex*1E-3, BN.J_in*1E-3],
        IN = [BN.J_ex*1E-3, BN.J_in*1E-3],),
```

hybridLFPy - Example implementation

`example_brunel.py`, parameter setup:

```
#set up synapse parameters as derived from the network
PS.update(dict(
    synParams = dict(
        EX = dict(
            section = ['apic', 'dend'],
            tau = BN.tauSyn,
            syntype = 'AlphaISyn'
        ),
        IN = dict(section = ['dend'], ...),),
    #fixed delays of network
    synDelayLoc = dict(
        EX = [BN.delay, BN.delay],
        IN = [BN.delay, BN.delay],
    ),
    #no distribution of delays
    synDelayScale = dict(
        EX = [None, None],
        IN = [None, None],),
```

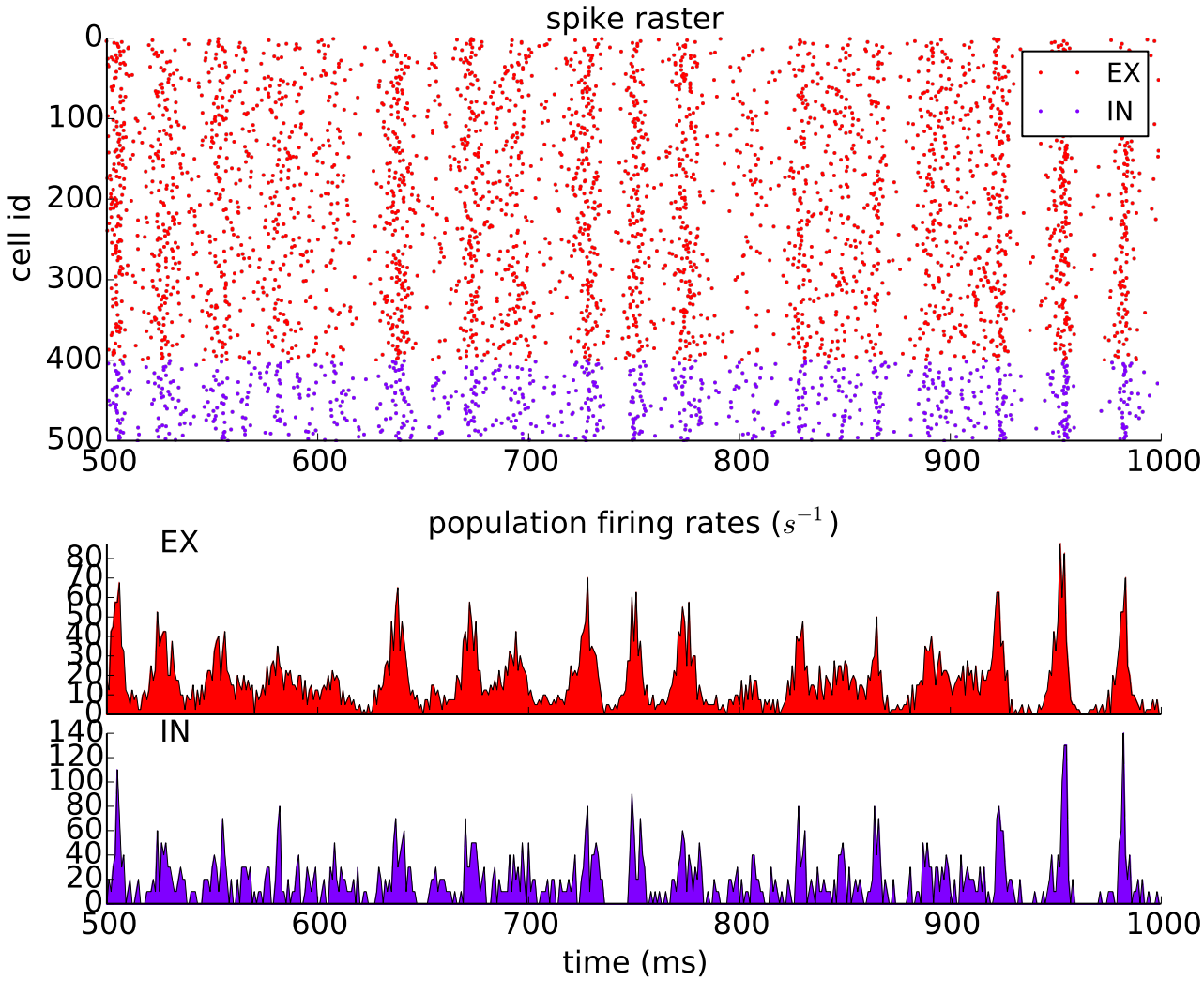
hybridLFPy - Example implementation

`example_brunel.py`, network spikes:

```
if RANK == 0:
#run network off-line
    os.system("python brunel_alpha_nest.py")
#sync MPI threads
COMM.Barrier()

#Create object representation with spiking activity of network
#output using sqlite3 under the hood. kwargs are derived from the brunel
#network instance.
networkSim = CachedNetwork(
    simtime = BN.simtime,
    dt = BN.dt,
    spike_output_path = PS.spike_output_path,
    label = BN.label,
    ext = 'gdf',
    N_X = np.array([BN.NE, BN.NI]),
    X = PS.X,
)
```

hybridLFPy - Application with 2-population network

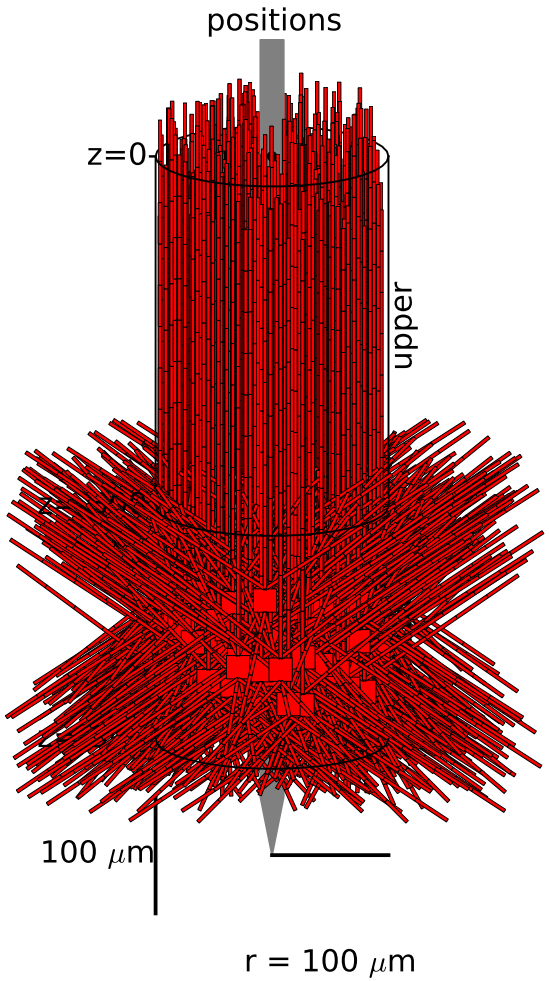


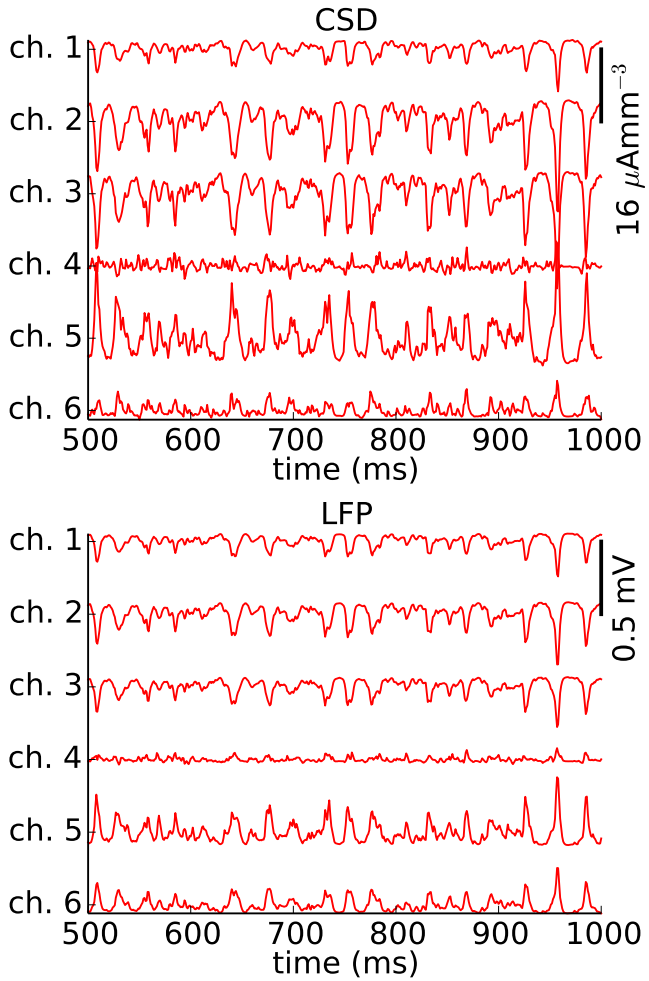
hybridLFPy - Example implementation

`example_brunel.py`, run single-cell simulations:

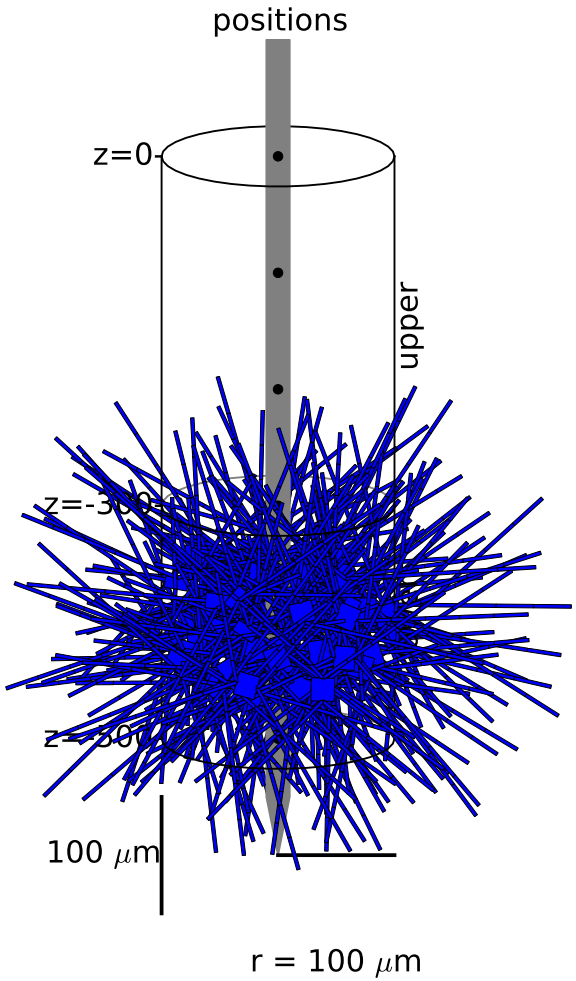
```
for i, Y in enumerate(PS.X):
    #create population:
    pop = Population(
            cellParams = PS.cellParams[Y],
            rand_rot_axis = PS.rand_rot_axis[Y],
            simulationParams = PS.simulationParams,
            populationParams = PS.populationParams[Y],
            layerBoundaries = PS.layerBoundaries,
            electrodeParams = PS.electrodeParams,
            ...
            networkSim = networkSim,
            k_yXL = PS.k_yXL[Y],
            synParams = PS.synParams[Y],
            synDelayLoc = PS.synDelayLoc[Y],
            synDelayScale = PS.synDelayScale[Y],
            J_yX = PS.J_yX[Y],)
    #run simulation and process single-cell data
    pop.run()
    pop.collect_data()
```

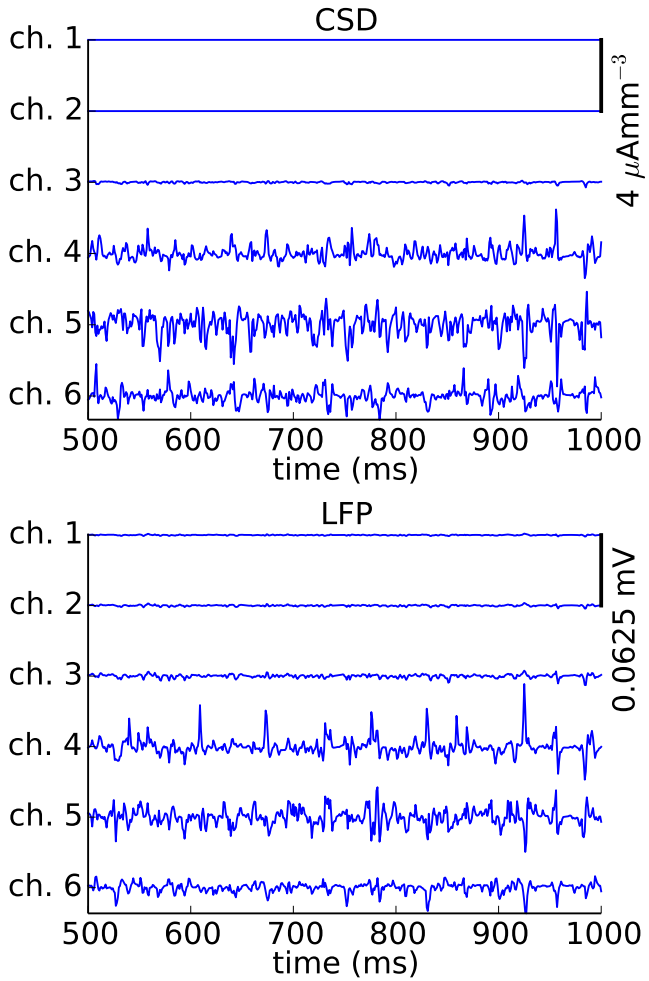
hybridLFPy - Application with 2-population network





hybridLFPy - Application with 2-population network



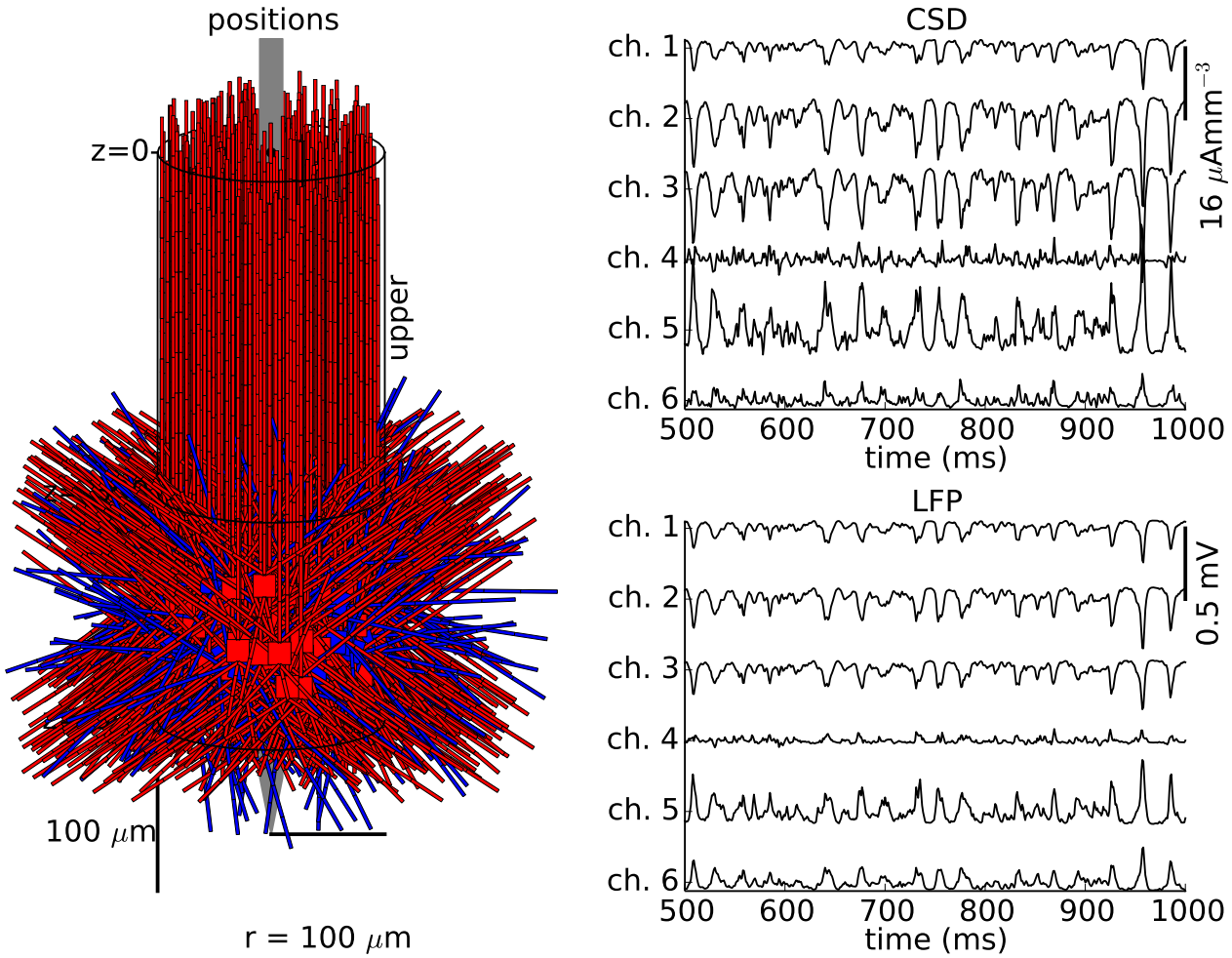


hybridLFPy - Example implementation

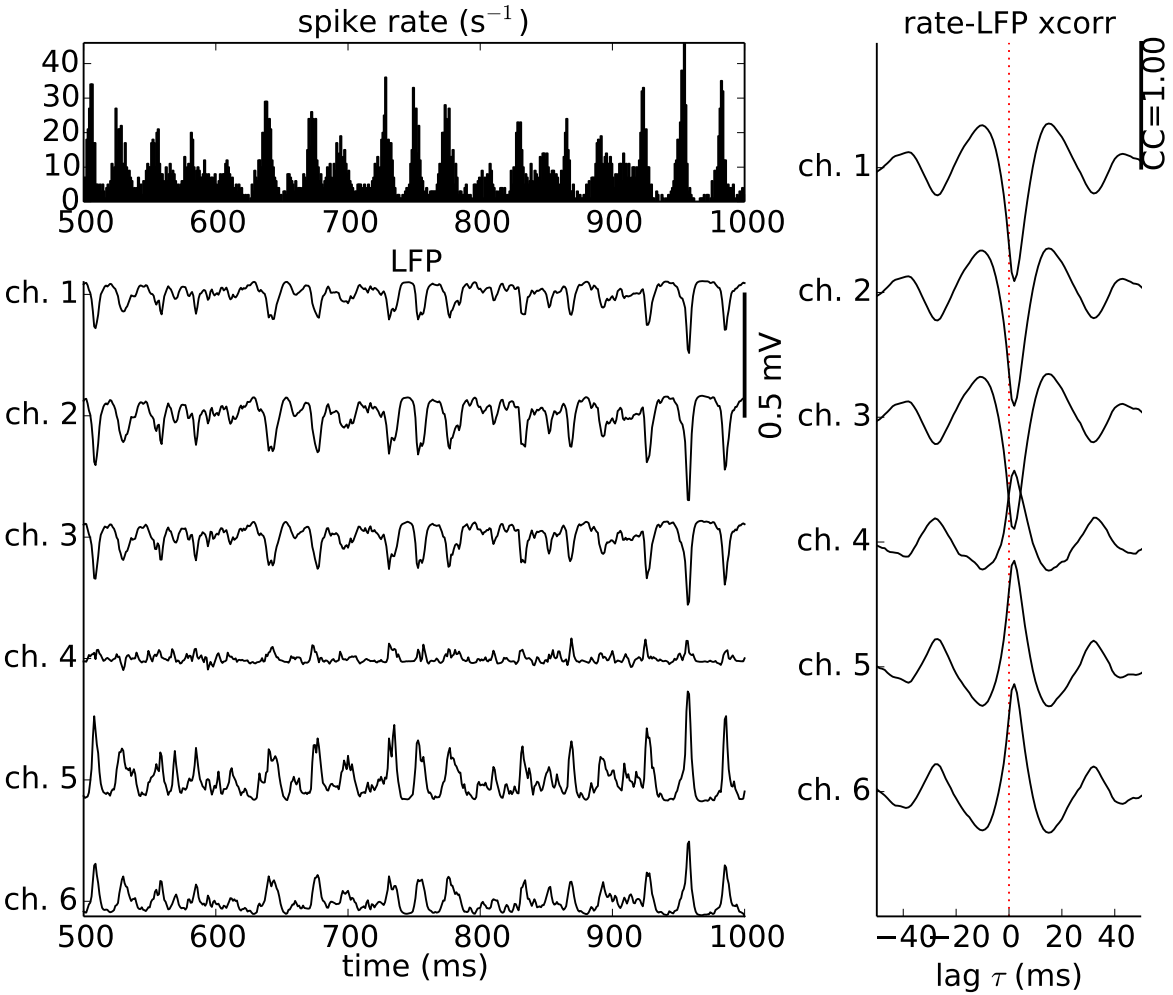
`example_brunel.py`, create compound signals:

```
#Postprocessing of population output,
#(superposition of population LFPs, CSDs)
postproc = PostProcess(y = PS.X,
                       dt_output = PS.dt_output,
                       savefolder = PS.savefolder,
                       mapping_Yy = PS.mapping_Yy,
                       )
#run procedure
postproc.run()
```

hybridLFPy - Application with 2-population network



hybridLFPy - Application with 2-population network



Summary & Outlook

- Forward modeling scheme:
  - derived using standard electrostatic theory
  - multi-compartmental neuron models
- `LFPy`; http://compneuro.umb.no/LFPy:
  - Extracellular potentials of single-neuron models
  - anisotripic extracellular medium
  - method of images (MoI) for inhomogeneous media
  - support parallel network implementations
- `hybridLFPy`; http://github.com/espenhgn/hybridLFPy:
  - LFP predictions of simplified network models
  - Main application: Potjans&Diesmann, *Cereb Cortex* (2014)
  - Multi-area model predictions
  - Network models with distance dependent connections
  - Verify simplified LFP prediction schemes

Talks & Posters

- P130: Modelling spatially realistic local field potentials in spiking neural networks. using the VERTEX simulation tool. Richard Tomsett et al.
- P131: Modelling local field potential features during network gamma oscillations Richard Tomsett et al.
- P174: Measurement of propagating waves from local field potentials and unit activity in the cortex of human and monkey. Lyle Muller et al.
- P214: Microscale impedance measurements suggest that ionic diffusion is implicated in generating extracellular potentials. Claude Bedard et al.
- P215: Cable equation formalism for neuronal magnetic fields. Alain Destexhe et al.

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Questions?