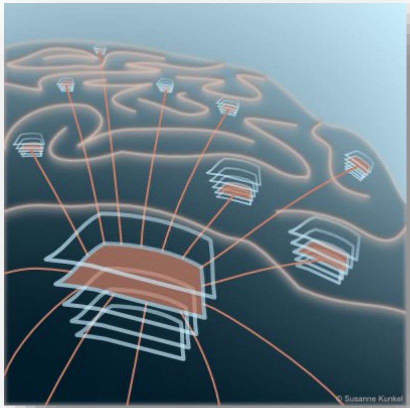

A full-scale spiking model of the local cortical network

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Medical Faculty, RWTH Aachen

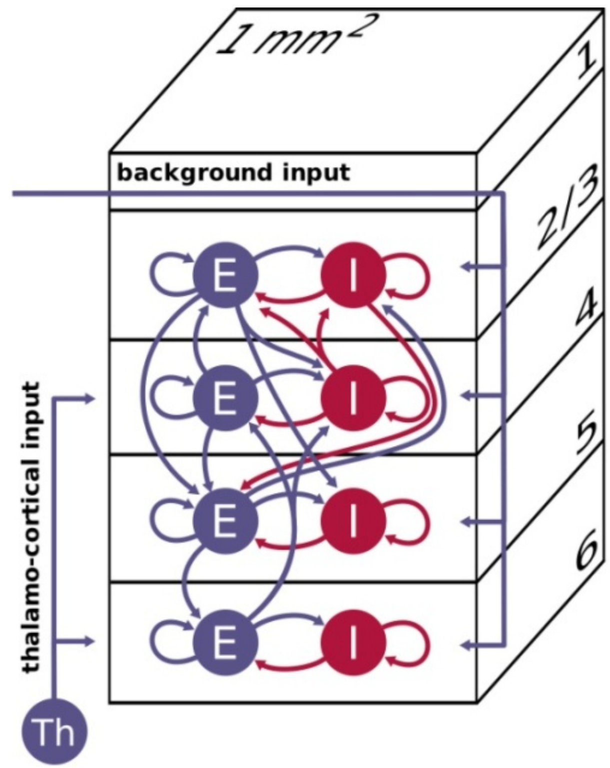
May 14th-16th 2014, Alghero

Outline

- construction of local cortical network model
- stationary state
- target specificity
- transients and a hypothesis
- critique of local network models
- necessity of brain-scale models
- enabling dissemination of the model

Minimal layered cortical network model

- extending the successful 2 population model
- understand impact of structure on observed dynamics
- explain cell type specific spike rates
- main work by Tobias C Potjans

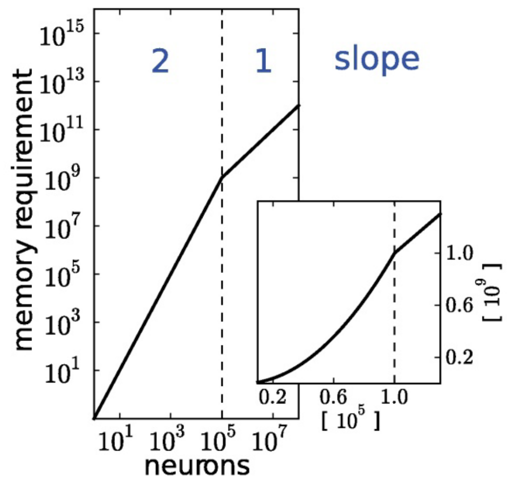


Potjans TC & Diesmann M (2014) The cell-type specific connectivity of the local cortical network explains prominent features of neuronal activity. *Cerebral Cortex* 24 (3): 785-806

Feasibility and structural constraints

- connectivity $c = 0.1$
- synapses per neuron $= 10^4$

$\Rightarrow$ minimal network size $= 10^5$



network $N = 10^5$

- considered elementary unit
- corresponding to 1 mm^3

$\Rightarrow$ possible

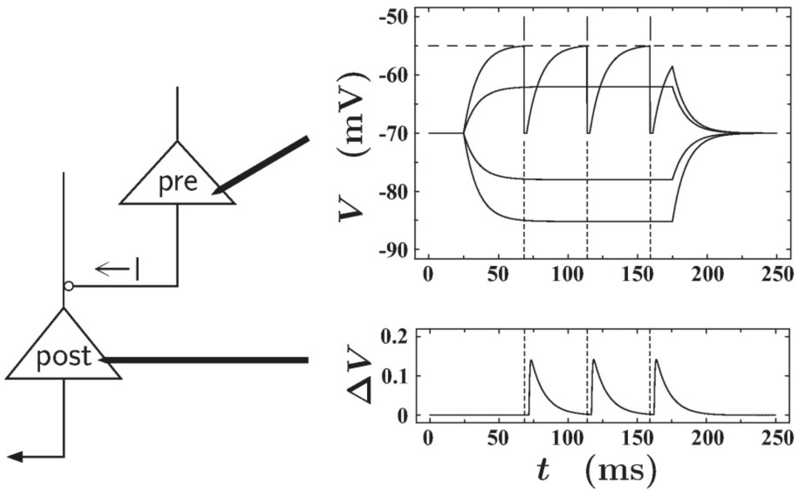
total number of synapses $= (cN) \cdot N$

Morrison, Mehring, Geisel, Aertsen, Diesmann (2005) *Neural Computation* 17:1776–1801

Morrison, Straube, Plesser, Diesmann (2007) *Neural Computation* 19:47–79

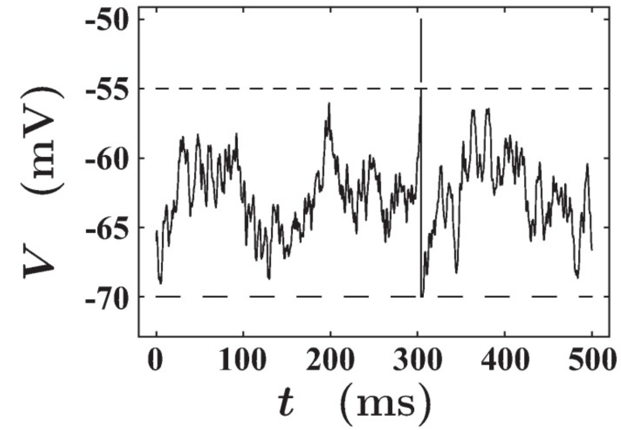
Fundamental interactions

in vitro



- current injection into pre-synaptic neuron causes excursions of membrane potential
- supra-threshold value causes spike transmitted to post-synaptic neuron
- post-synaptic neuron responds with small excursion of potential after delay
- inhibitory neurons (20%) cause negative excursion

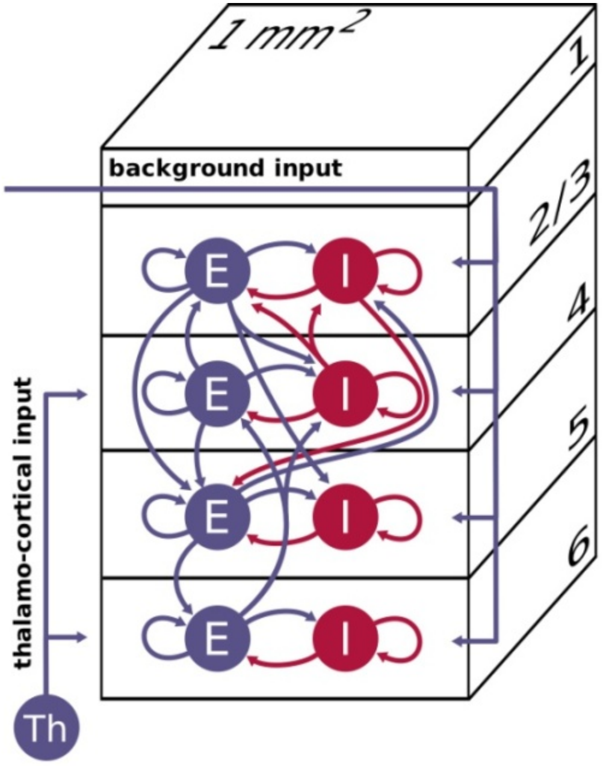
in vivo



- each neuron receives input from 10,000 other neurons
- causing large fluctuations of membrane potential
- emission rate of 1 to 10 spikes per second

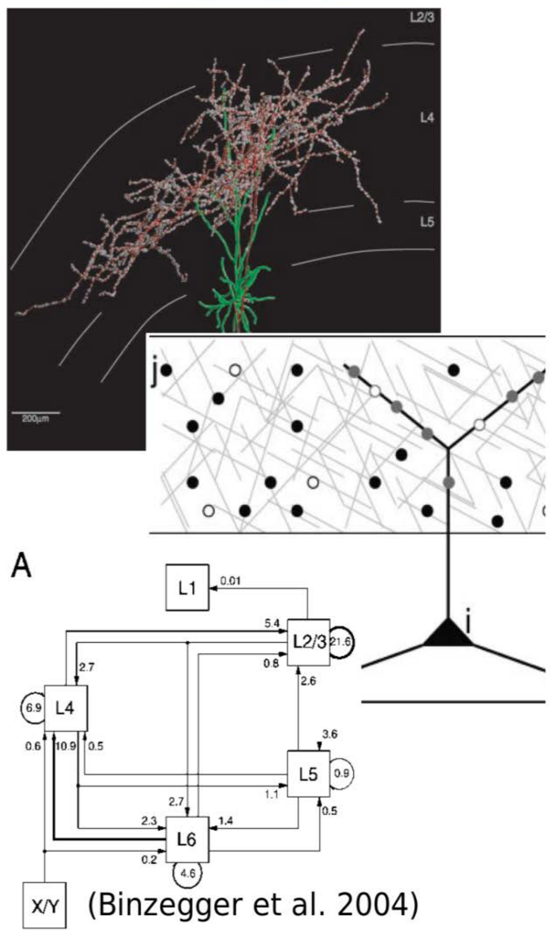
Minimal layered cortical network model

- 1 mm^3
- 1 billion synapses, 100,000 neurons
- 2 populations of neurons (E,I) per layer
- E and I identical neuronal dynamics
- laterally homogeneous connectivity
- layer- and type-specific C_{ij}^{xy}



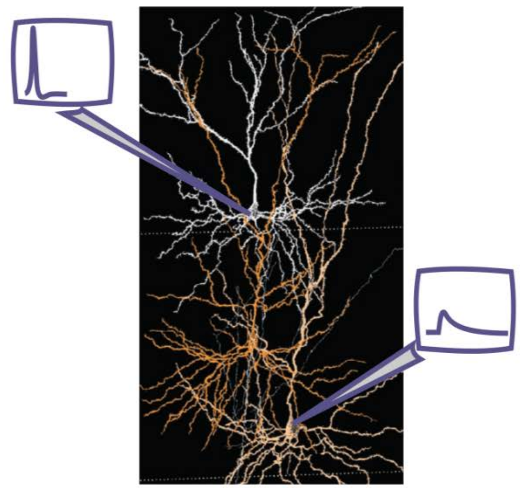
Anatomical data sets

in vivo anatomy



(Binzegger et al. 2004)

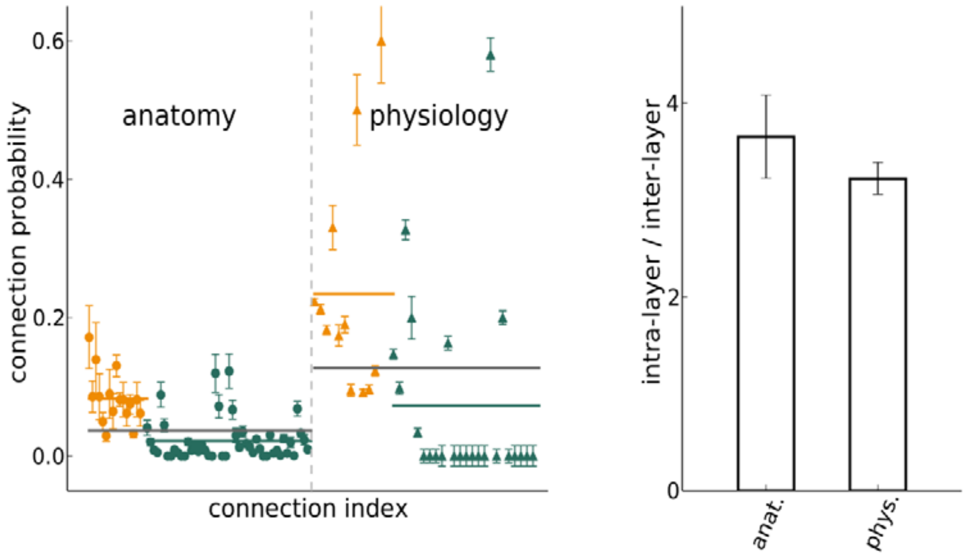
in vitro physiology

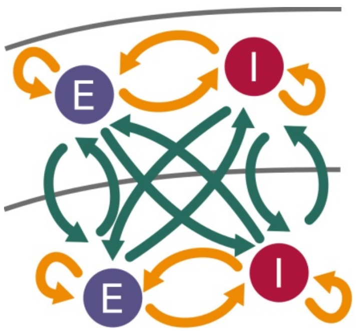


Type of connection[a]	Connectivity ratio
L5 pyramid to L5 pyramid	1:11 (15:163)
L2/3 pyramid to L2/3 pyramid	1:4 (65:247)
	1:10 (8:81)
L4 excitatory to L4 excitatory	**1:5.7 (4:23)**
L3 pyramid to L5 pyramid	1:1.8 (16:29)
[Postsynaptic apical dendrite]	
	1:1 (2:2)
L5 pyramid to L3 pyramid	1:29
L4 excitatory to L3 pyramid	1:3.6 (7:25)
(Presynaptic spiny stellates) (n = 4)	**1:10 (7:70)**
L5 pyramid to L5 interneuron	1:10.4 (7:73)
L5 interneuron to L5 pyramid	*1:8 (9:73)*

(Thomson et al. 2002)

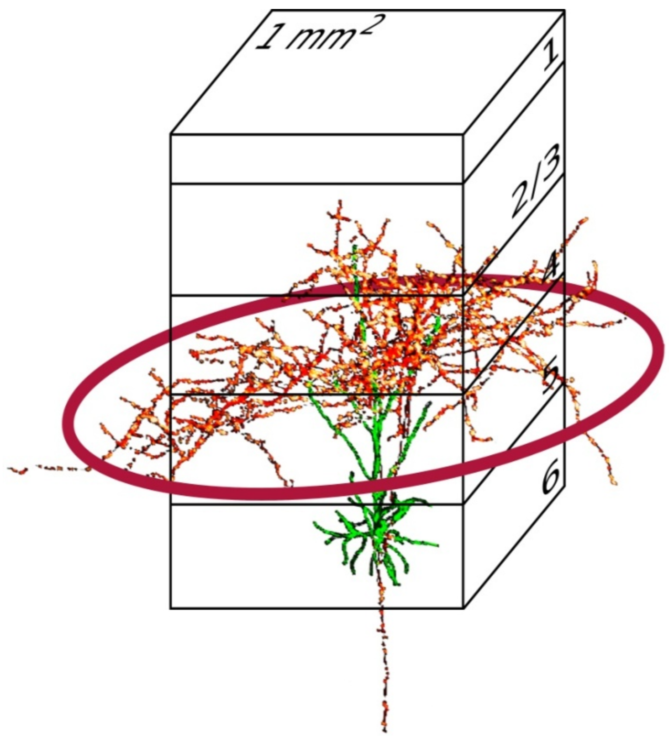
Consistency of connection probabilities

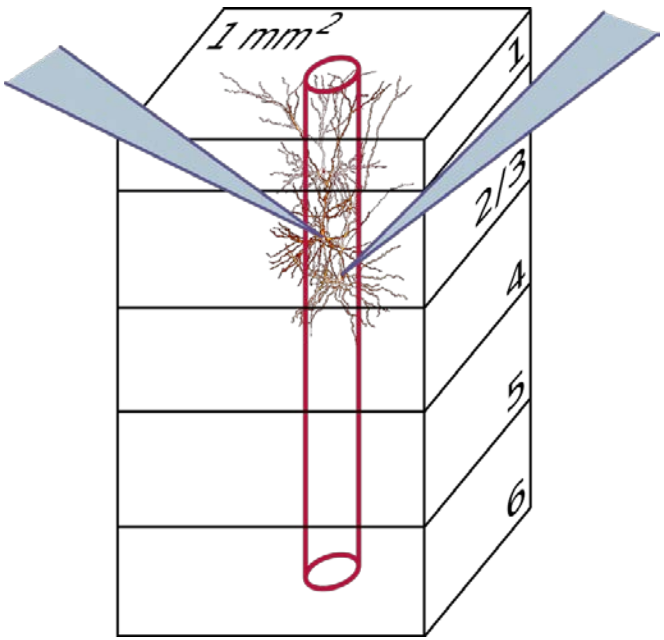




- yellow within layer, green across
- inconsistent averages
- consistent architectural relations

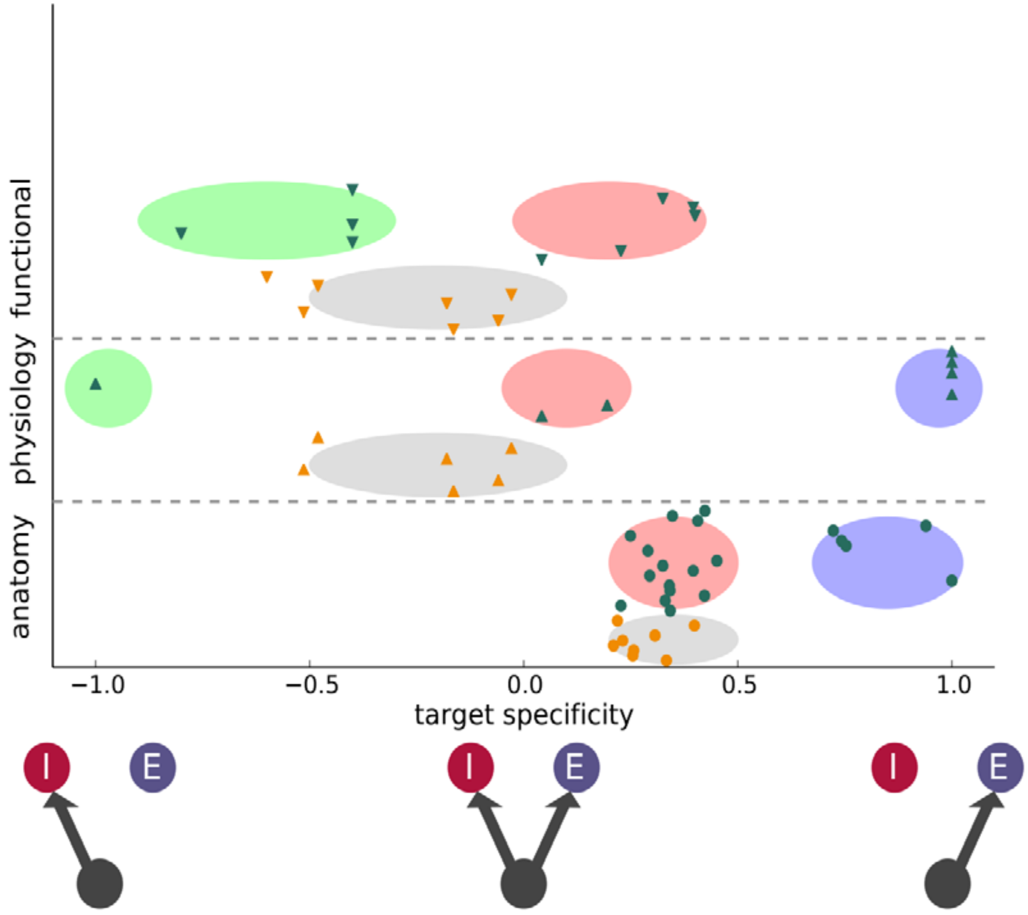
Lateral connectivity

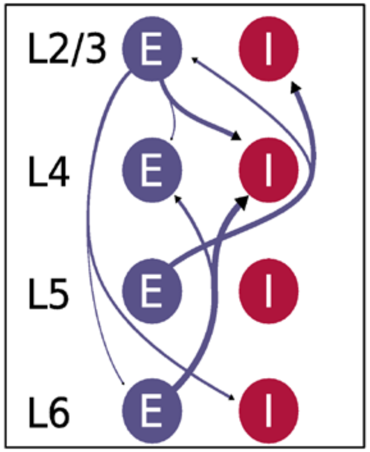




- correction for sampling radius using Gaussian model of distance dependents

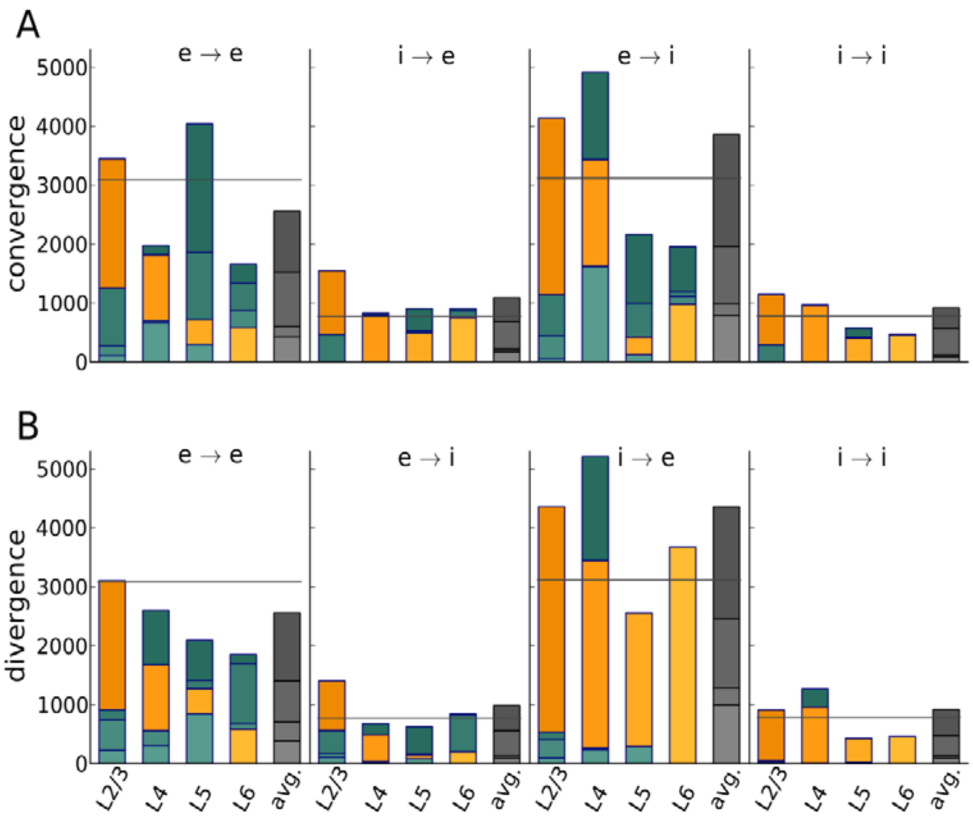
Target specificity

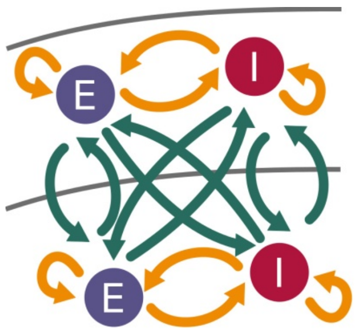




- correction for bias in anatomical method

Convergence and divergence

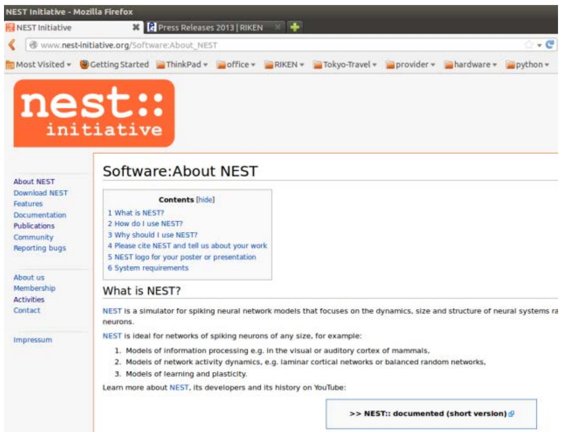




- dominated by within-layer connections
- e ⟶ e divergence reflects ”standard” loop
- e ⟶ i divergence reflects target-specific feedback

Simulation Technology: the NEST Initiative

collaborative effort and community building



Major goals:

systematically publish new simulation technology

produce public releases under GPL

- origins in 1994, collaboration of several labs (since 2001)
- registered society (since 2012)
- teaching in international advanced courses:
  - Okinawa Computational Neuroscience Course OCNC, Japan
  - Advanced Course in Computational Neuroscience ACCN, Europe
  - Latin American School on Computational Neuroscience LASCON, South America

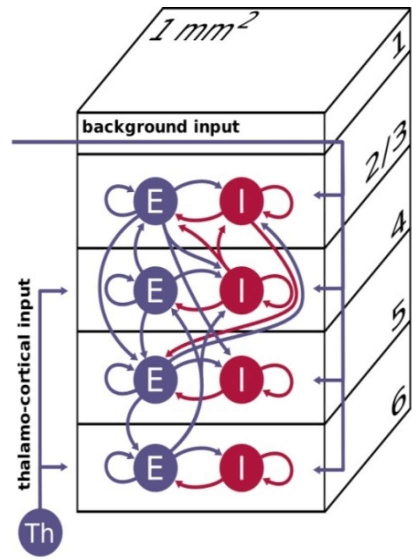
- core technology of Human Brain Project

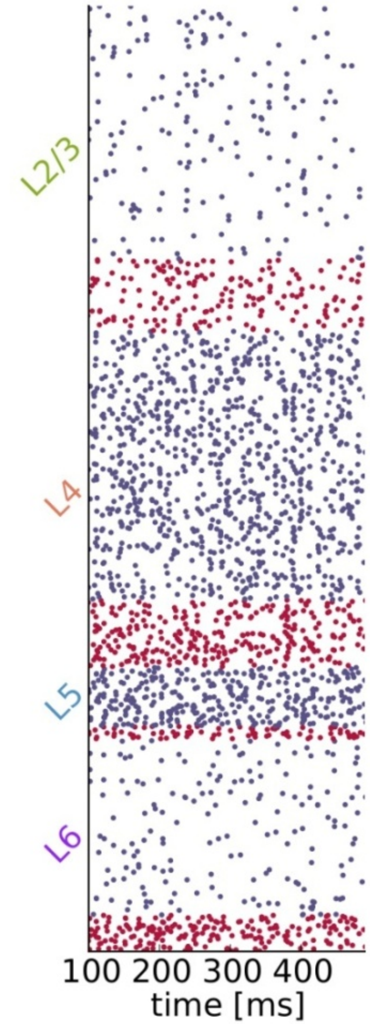
e.g.: Morrison, …, Diesmann (2005) *Neural Computation*
Zaytsev, Morrison (2013) *Frontiers in Neuroinformatics*

Local cortical microcircuit

taking into account layer and neuron-type specific connectivity is sufficient to reproduce experimentally observed:

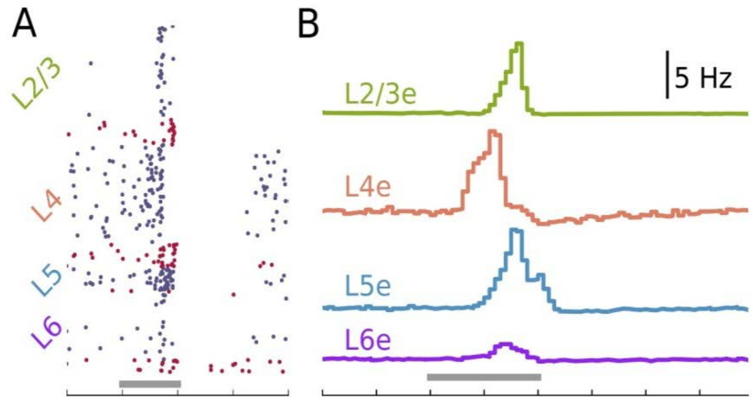
- asynchronous-irregular spiking of neurons
- higher spike rate of inhibitory neurons
- correct distribution of spike rates across layers

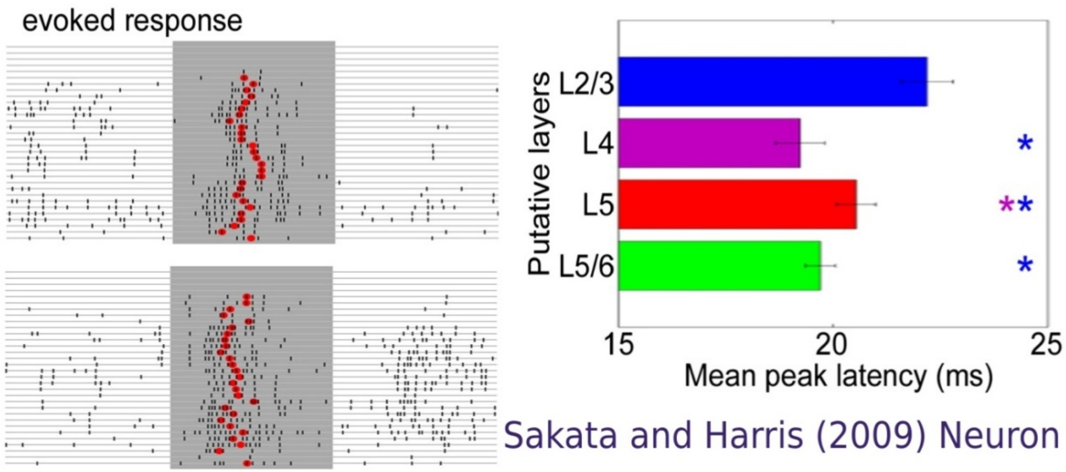




Potjans TC & Diesmann M (2014) The cell-type specific connectivity of the local cortical network explains prominent features of neuronal activity. *Cerebral Cortex* 24 (3): 785-806

Response to transient inputs

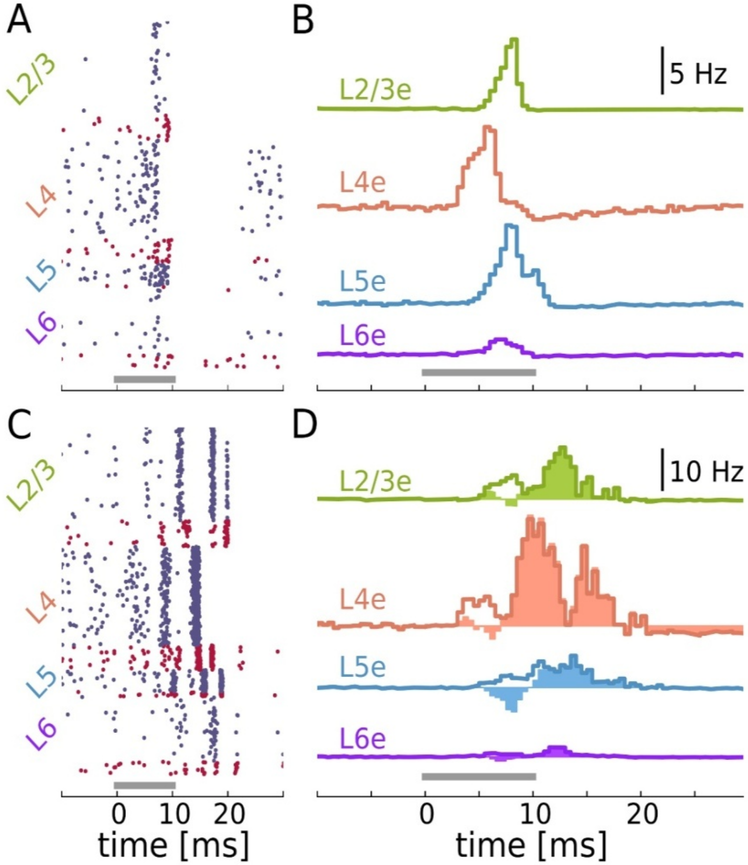




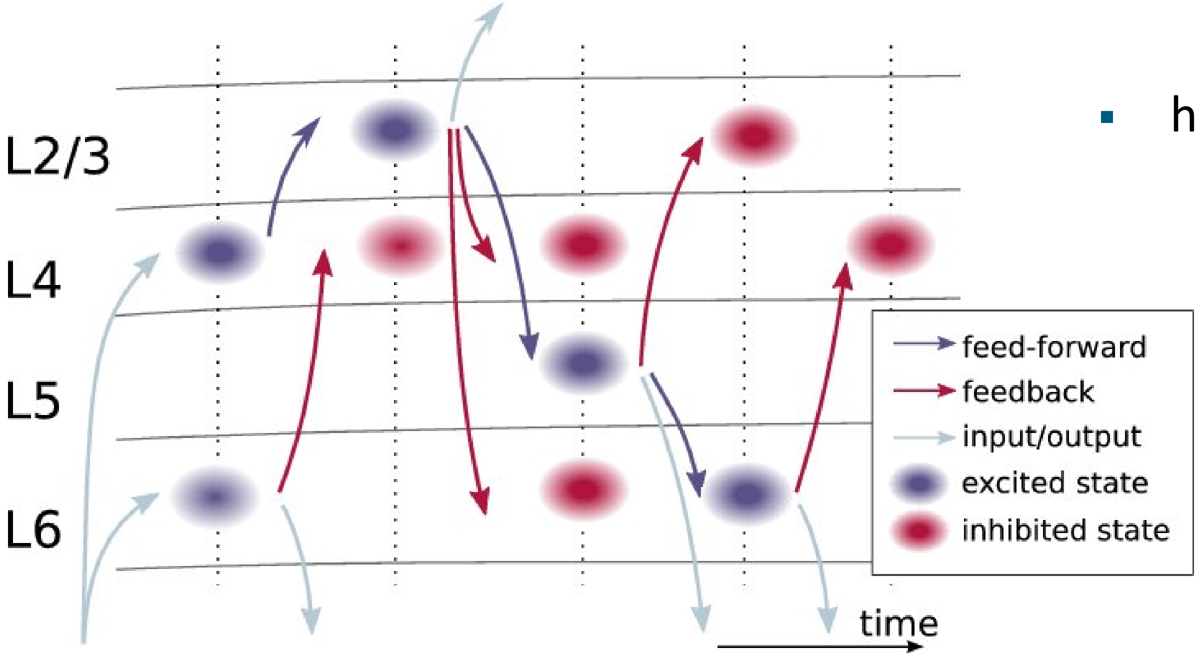
Sakata and Harris (2009) Neuron

Response to transient inputs

- T = -0.4
- T = +0.4



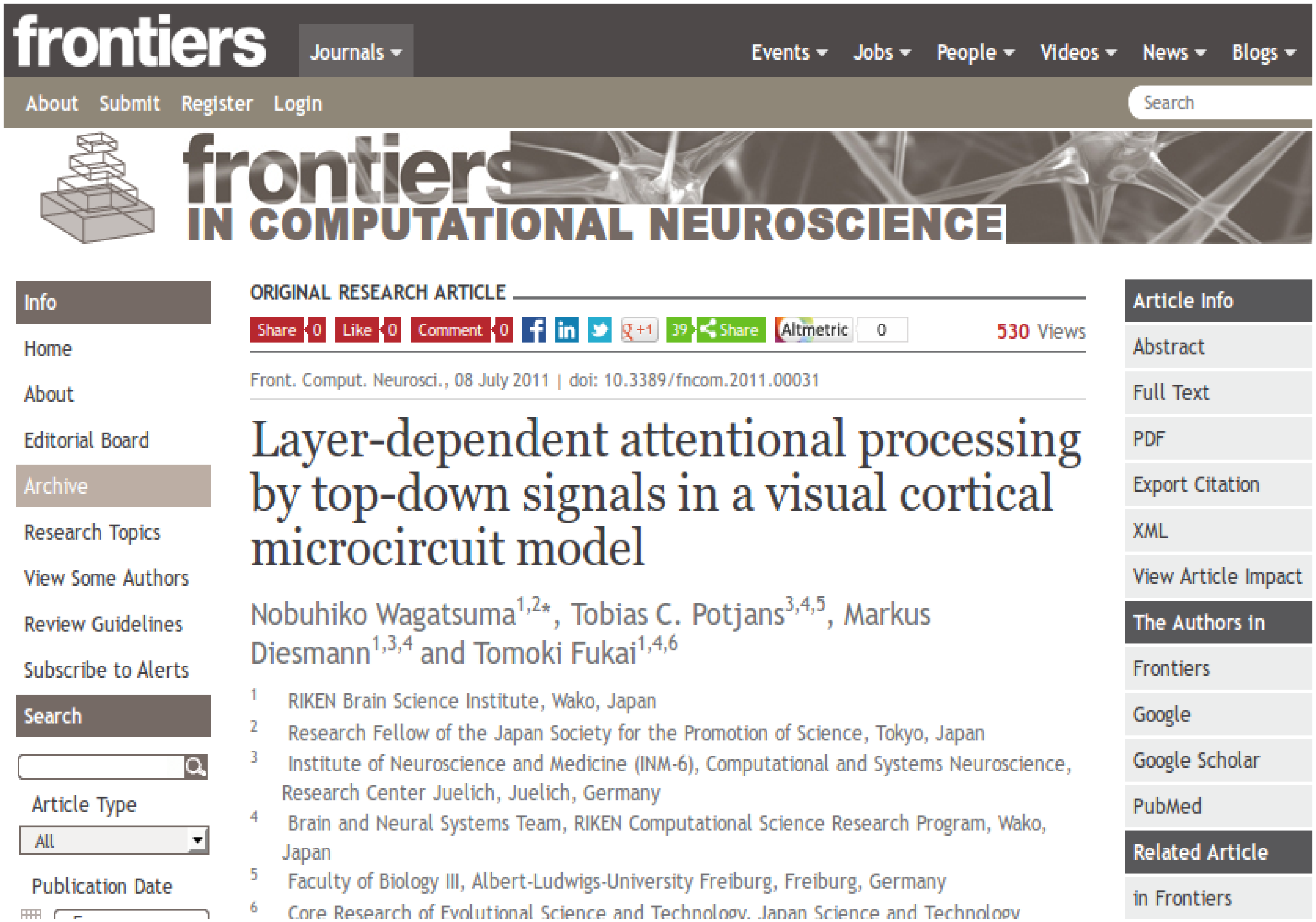
Hypothesis on cortical flow of activity



- handshaking between layers

Potjans TC & Diesmann M (2014) The cell-type specific connectivity of the local cortical network explains prominent features of neuronal activity. *Cerebral Cortex* 24 (3): 785-806

Building block for functional studies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Front. Comput. Neurosci., 08 July 2011 | doi: 10.3389/fncom.2011.00031

Layer-dependent attentional processing by top-down signals in a visual cortical microcircuit model

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3 Institute of Neuroscience and Medicine (INM-6), Computational and Systems Neuroscience, Research Center Juelich, Juelich, Germany

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5 Faculty of Biology III, Albert-Ludwigs-University Freiburg, Freiburg, Germany

6 Core Research of Evolutional Science and Technology, Japan Science and Technology

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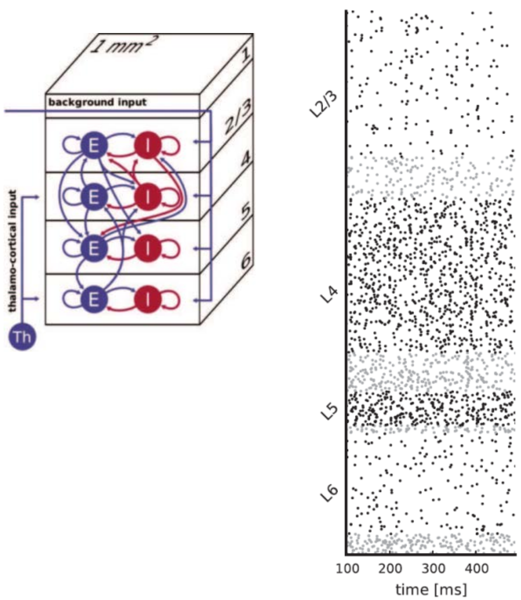
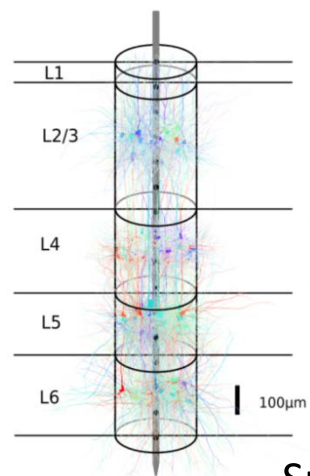
Building block for mesoscopic studies

- David Dahmen, Jannis Schücker, Tom Tetzlaff
- in EU BrainScaleS with Gaute Einevoll (UMB, Norway)



+

´Morphology



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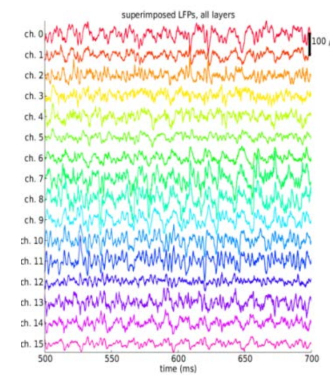
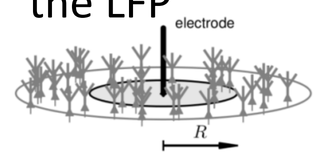
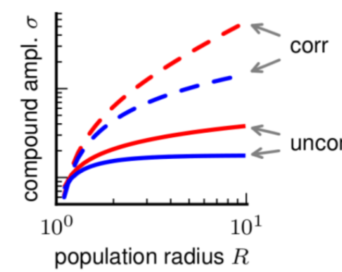
Laminar LFP profile



Spatial reach of the LFP





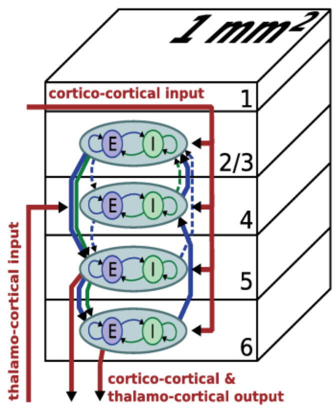
Linden H, Tetzlaff T, Potjans TC, Pettersen KH, Grün S, Diesmann M, Einevoll GT (2011) Modeling the spatial reach of the LFP. *Neuron* 72(5):859-872

Critique of local network models

Local Cortical Network Connections:

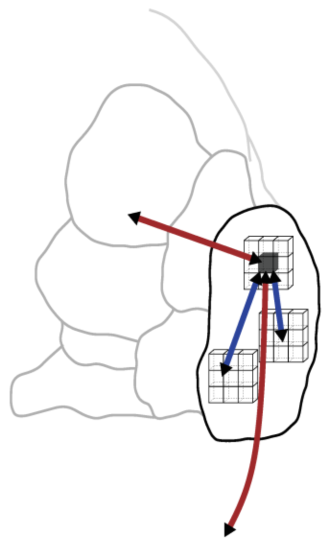
✓ local connections
✓ realistic synaptic modeling
✗ a major part of synapses missing

⇛ input dependent local network dynamics



Cortical Area Network Connections:

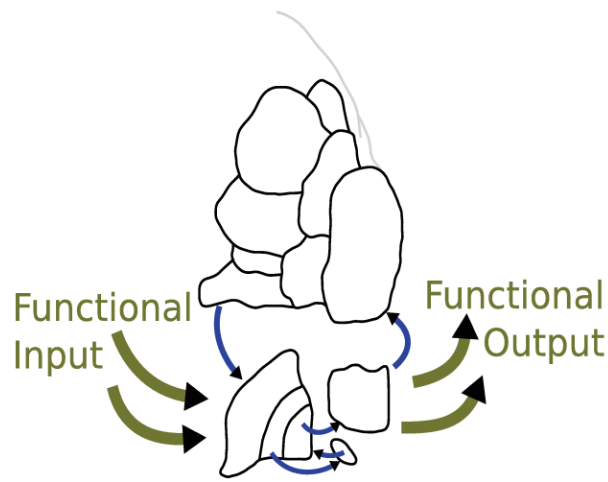
✓ intrinsic connections
✗ many synapses missing



Brain-scale Connections:

✓ all connections

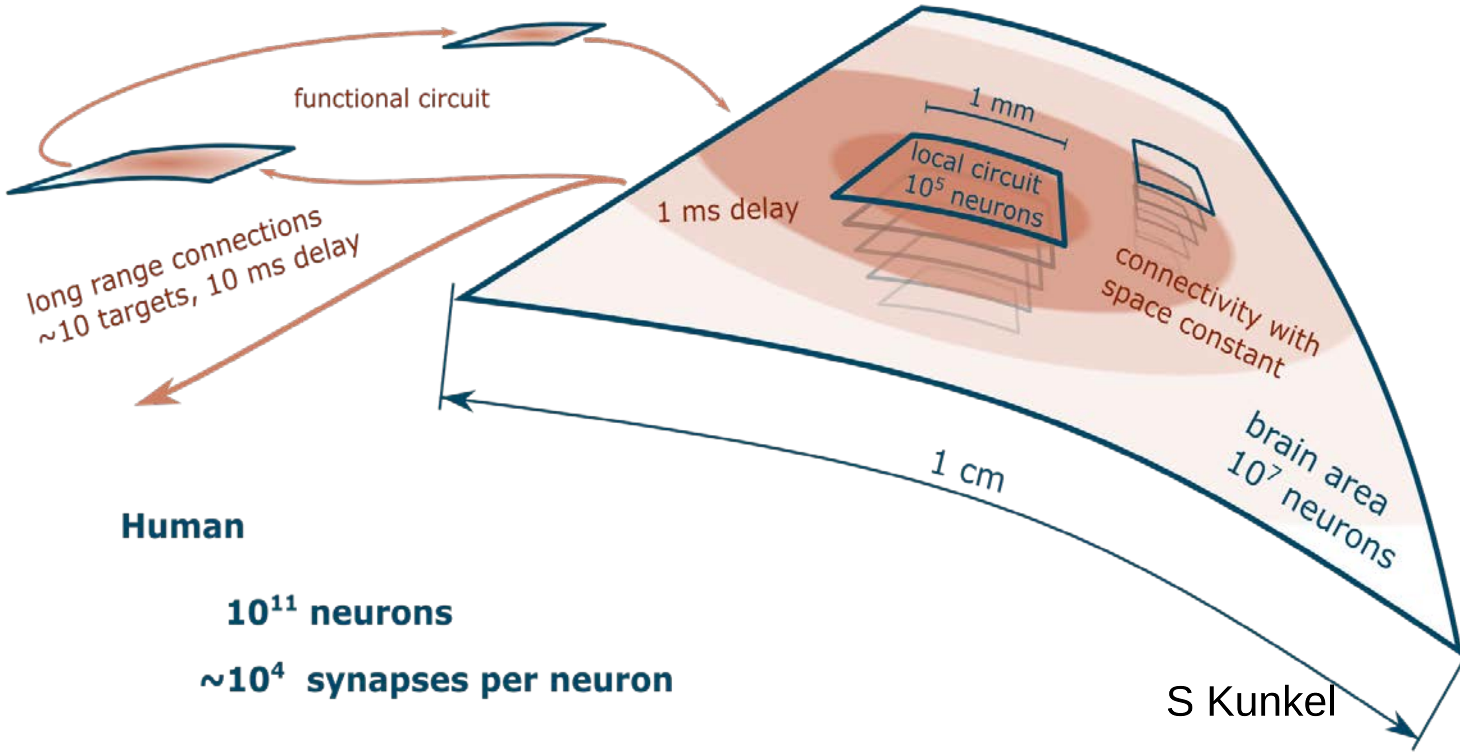
⇛ bottom-up and top-down approach meet on this level



Brain and Neural Systems Team, RIKEN Computational Science Research Program
Pilot study: jinb33 (2008) Jugene *Brain-scale simulations* FZ Juelich

Brain-scale connectivity

a network of networks with at least three levels of organization:



S Kunkel

- neurons in local microcircuit models are missing 50% of synapses
- e.g., power spectrum shows discrepancies, slow oscillations missing
- solution by taking brain-scale anatomy into account

Meso- and macro-scale measures

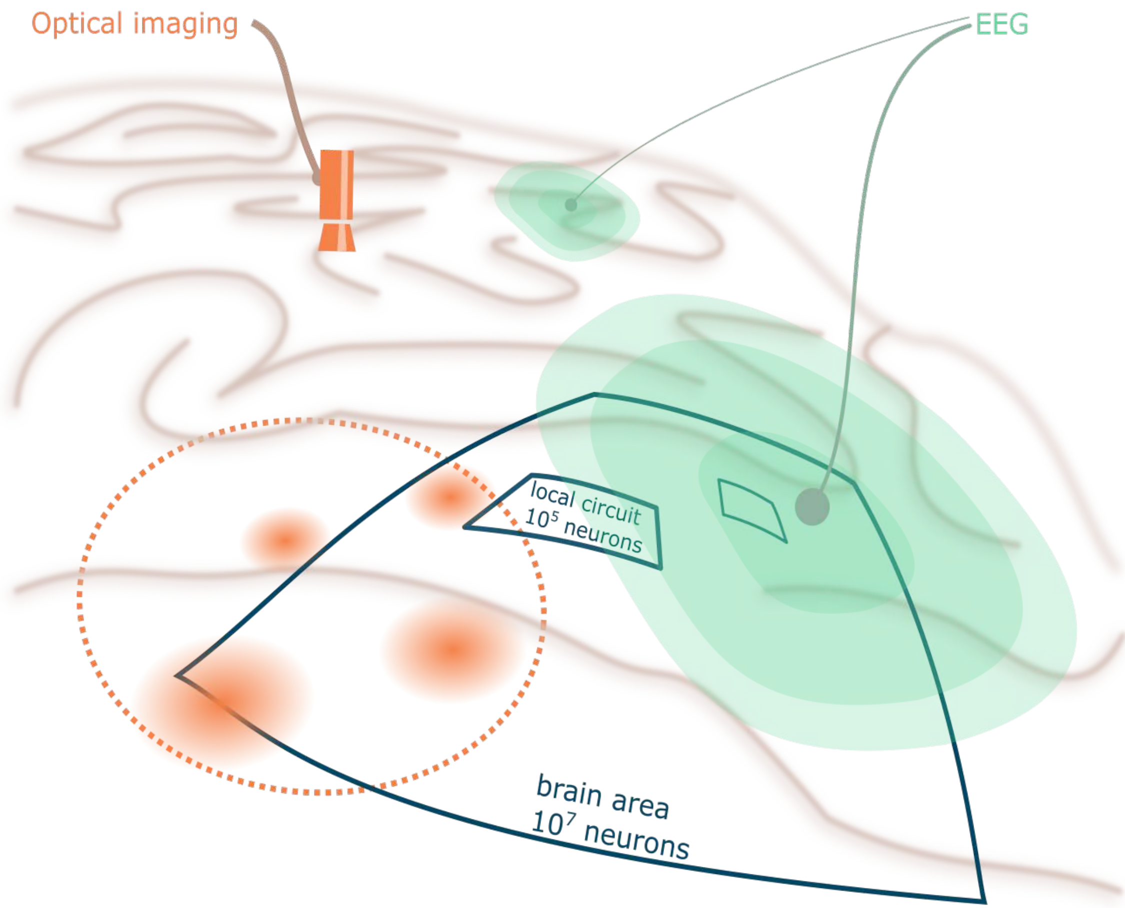
brain-scale networks
provide the substrate for

mesoscopic measures

- local field potential (LFP)
- voltage sensitive dyes (VSD)

and macroscopic measures

- EEG, MEG
- fMRI resting state networks

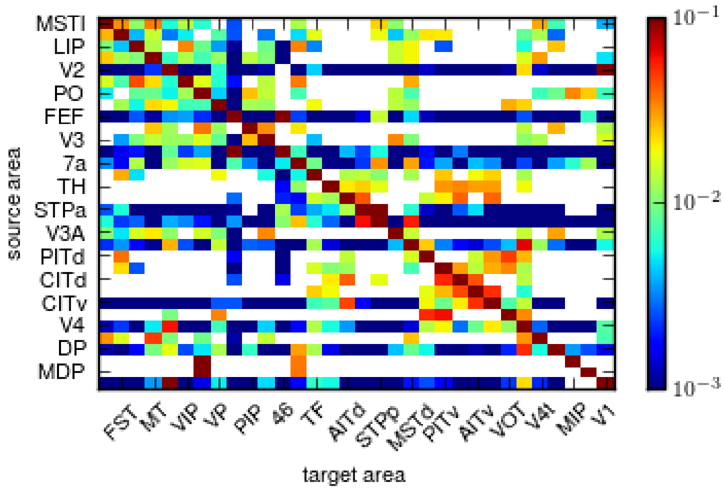


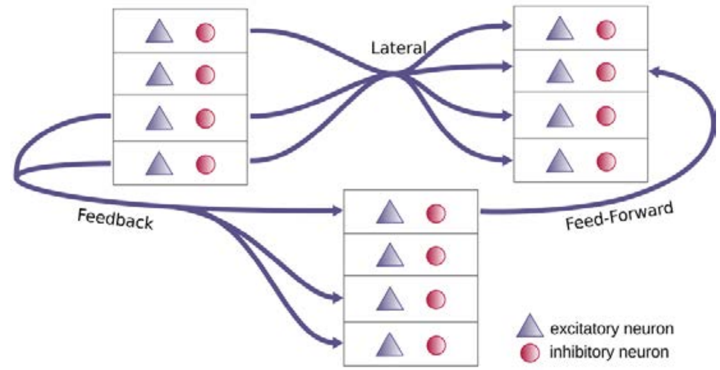
S Kunkel

connecting biophysical modeling to the field of neuroimaging

Norges miljø- og biovitenskapelige universitet

Multi-area model of macaque visual cortex



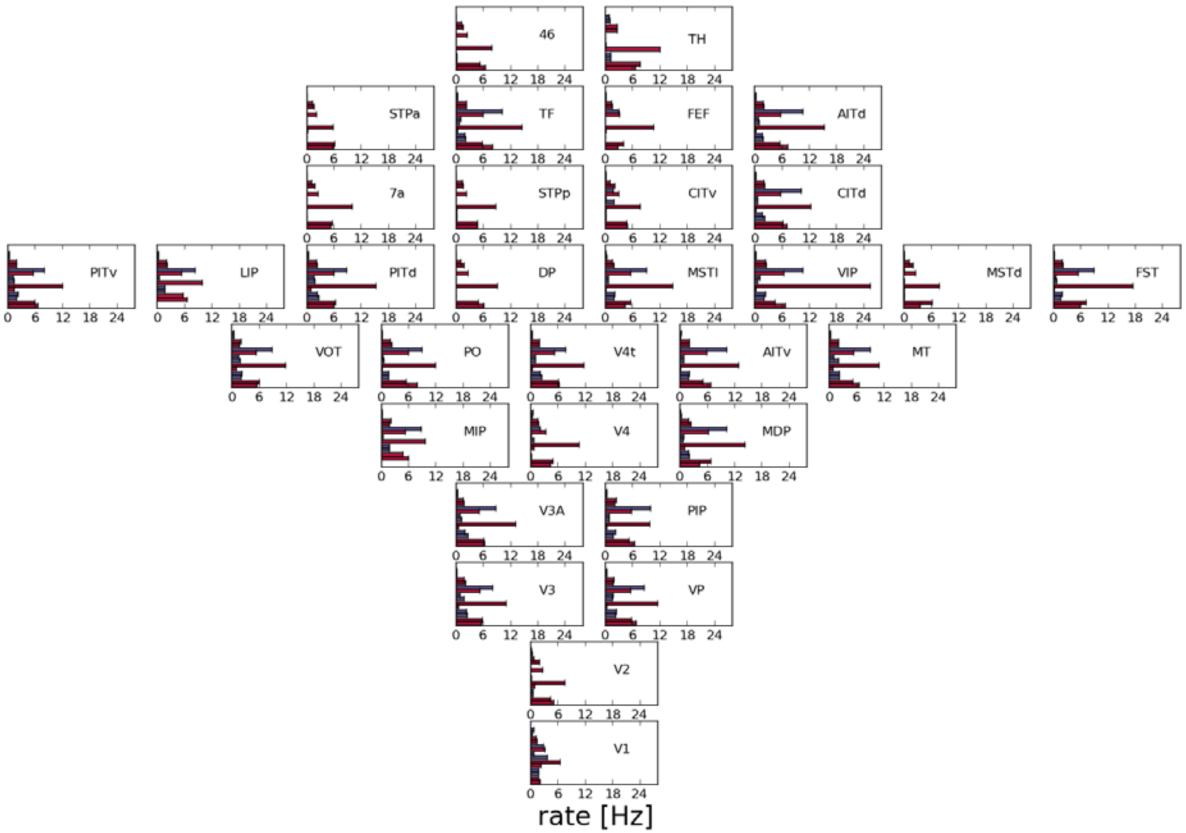


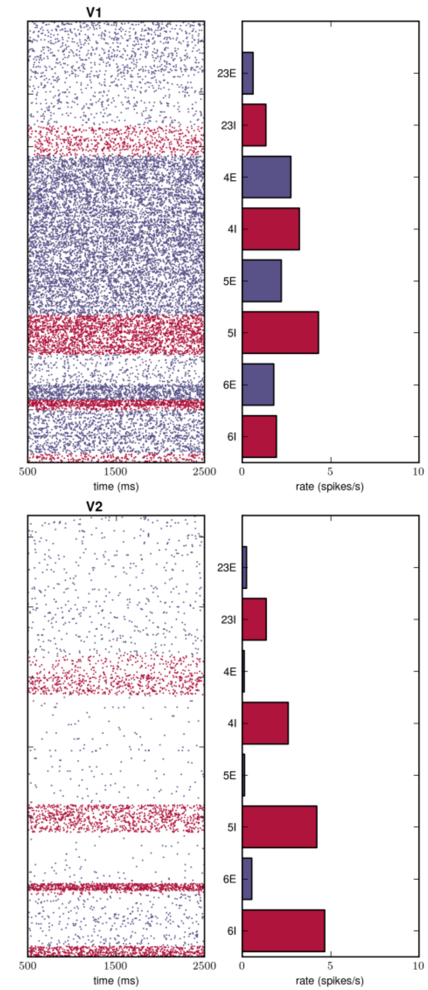
- macroscopic connectivity data for macaque visual cortex most complete
- prototype for human brain
- model 1: cubic millimeter multi-layered microcircuits connected by inter-area network
- model 2: realistic relative size of cortical areas
- model 3: full-scale

- matrix shows in-degree onto target areas in relative proportions
- data from CoCoMac database (Rembrandt Bakker curator) enriched by quantitative data from Kennedy lab (Markov et al., 2012)
- model enables iterative data integration

Multi-area model of macaque visual cortex

- Max Schmidt, Sacha van Albada, Rembrandt Bakker



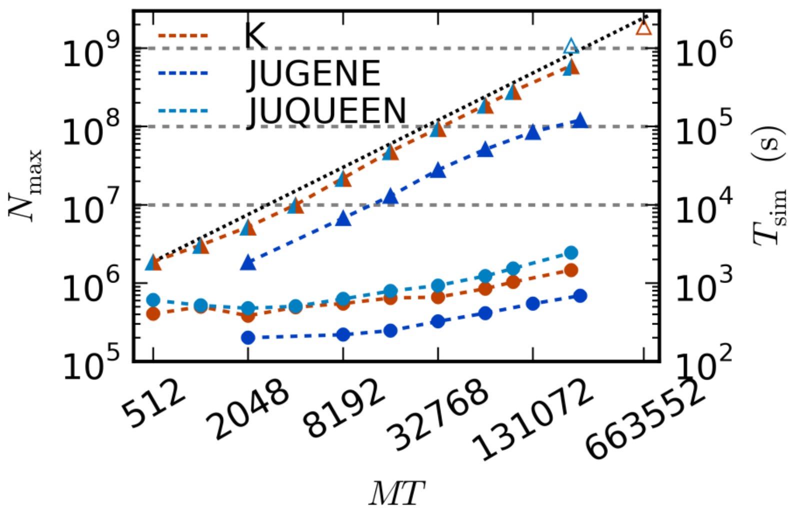


Population-specific firing rates with areas arranged according to Felleman and Van Essen hierarchy

Record simulation 2013

- largest simulation to date
- scales to largest computers (petascale)
- worst case scenario: random network
- well picked up by media
- manuscript in preparation
- MoU with RIKEN AICS in Kobe

4g simulation kernel



future plans (HBP ramp-up phase):
- release 4g simulation kernel for production

future plans (HBP operational phase):
- exploit massive parallelism of processors
- develop communication architecture for exascale systems
- develop and promote interactive supercomputing

Human Brain Project

Mitglied der Helmholtz-Gemeinschaft

A new connection routine

Obstacles so far:

- No published connection routine in NEST or PyNN which randomly connects the neurons of two populations given the total number of connections.
- No flexibility in choosing the distribution of the synapse parameter which allowed for connecting a large network in an adequate time span.

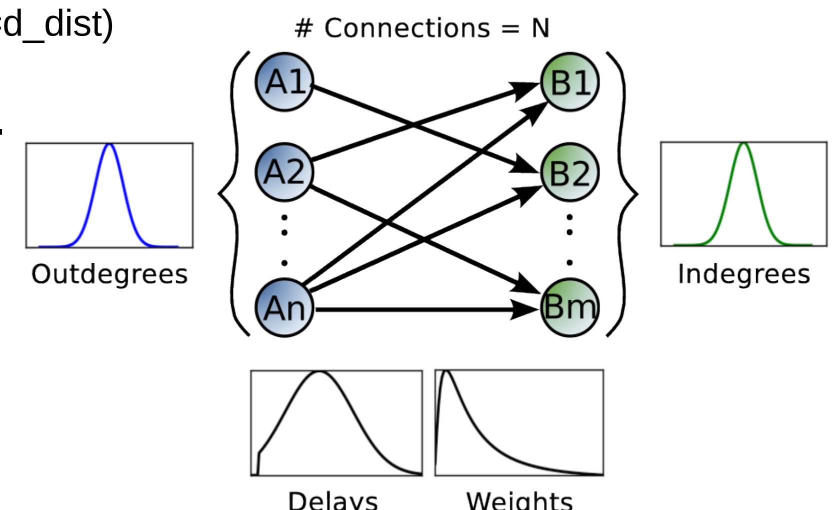
nest.Connect() and its relation to PyNN:

- Connection-rule can be chosen from a dictionary of pre-defined connectivity patterns.
  - Most patterns are parallelized using MPI and OpenMP.
- Synapse parameter can be randomized via numerous pre-defined random distributions.
  - Evaluation of random distribution is passed on to the C++-level.
- Usage of common terminology of synapse parameters and distributions in PyNN and NEST.
- Implementation of FixedTotalNumberConnector in PyNN.

Connecting the microcircuit

Connecting two excitatory populations with PyNN:

- Initialize the connector with the number of synapses going from pop1 to pop2.
  - » conn = sim.FixedTotalNumberConnector(n_syn)
- Set the parameters for the weight and delay distribution.
  - » d_dist = sim.random.RandomDistribution('normal_clipped', [d_m, d_sd, 0.1, np.inf])
  - » w_dist = sim.random.RandomDistribution('normal_clipped', [w_m, w_sd, 0., np.inf])
- Initialyze the synapse with the weight and delay distributions.
  - » syn = sim.StaticSynapse(weight=w_dist, delay=d_dist)
- Create the projection from pop1 to pop2.
  - » proj = sim.Projection(pop1,pop2,conn,syn)

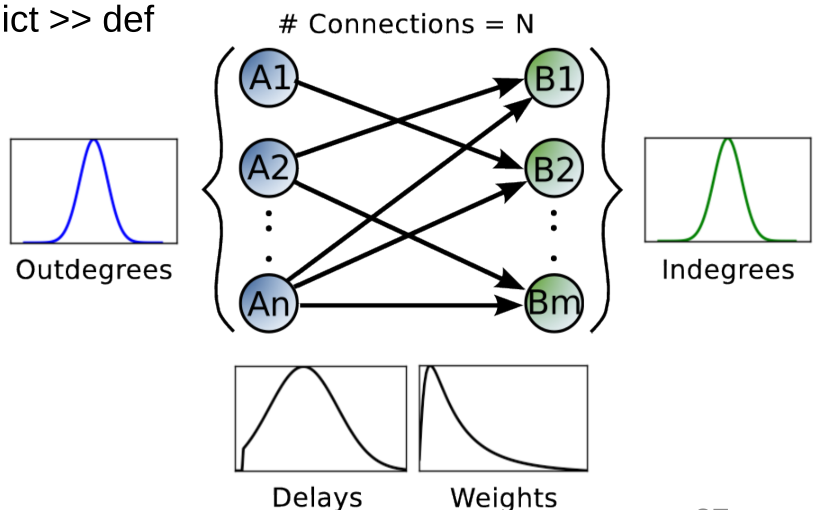


Connecting the Microcircuit

Connecting two excitatory populations with SLI:

- Specify the connectivity pattern and the total number of connections.
  - » /conn_dict << /rule /fixed_total_number /N n_syn>> def
- Initialize the weight and delay distributions.
  - » /weight_dict << /distribution /lognormal_clipped /mu w_m /sigma w_sd /min 0.0 >> def
  - » /delay_dict << /distribution /normal_clipped /mu d_m /sigma d_sd /min 0.1 >> def
- Insert the weight and delay distributions into the synapse dictionary.
  - » syn_dict << /weight weight_dict /delay delay_dict >> def
- Connect pop1 with pop2.

» sources targets conn_dict syn_dict NewConnect



Summary

- model of local cortical network explains cell type specific spike rates
- importance of target specificity
- proposal of handshake mechanism between layers
- already in use as a building block in further studies
- need for brain-scale models
- difficulty of instantiating the model with general purpose simulator
- distributed parameters as a high-level concept
- implemented in next coordinated release of NEST and PyNN
- including open source SLI and PyNN versions of model