TOWARDS SIMULATION OF BRAIN NETWORKS AT EXASCALE

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www.csn.fz-juelich.de
www.nest-initiative.org
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Human Brain Project
Partially supported by the European Human Brain Project (HBP)

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CORTEX

- higher brain functions
- surface of the mammalian brain (gray matter)
- strongly folded in 'higher' mammals
- efficient wiring between cortical areas through white matter
CORTICAL AREAS

- subdivision of cortex into areas according to
  - functional properties
  - histo-anatomical features (cytoarchitecture, e.g. Brodman areas)
- frequent coincidence of both definition
pyramidal cell in mouse visual cortex, Lee et al., 2006, PLOS Biology 4(2)
NEURON TYPES

(Binzegger et al., 2004, Journal of Neuroscience, 24 (39) 8441-8453)
CORTICAL CONNECTIVITY

- 100,000 neurons per cubic millimeter
- 10,000 synapses per neuron
- 3 km of axons per cubic millimeter
- densely packed
- in this volume all neurons touch

NEOCORTEX
a universal computational architecture

- nature employs the same local circuitry (microcircuit) across:
  - different species (mouse, ..., men)
  - different functional areas (visual, auditory, ..., motor)

(DeFelipe, 2011)
NEOCORTEX

a universal computational architecture

- similarities more striking than differences
- functional specificity arises from
  - specific connectivity between
    - subcortical and cortical areas
  - cortical areas

(DeFelipe, 2011)

(Budd & Kisvarday, 2012)
INTERACTIONS BETWEEN NEURONS

- 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.

- Each neuron receives input from 10,000 other neurons.
- Causing large fluctuations of membrane potential.
- Emission rate of 1 to 10 spikes per second.
DYNAMIC ELEMENTS ARE NOT THE PROBLEM

- size of neurons: 10-100 µm
- size of modern transistor: 10-100 nm
  - in 2d, 1 million transistors fit into 1 neuron
- number of neurons in cortex: about $10^{10}$
- number of transistors in modern microprocessor (Intel Broadwell-E5): about $10^{10}$
  - can we just scale this technology up?
- difficulties:
  - realization of natural density connectivity
  - heat dissipation

Lin et al. (2003), J. Neurophys., 90, 4

Imaging & Microscopy (http://www.imaging-git.com)
REALISTIC LOCAL CORTICAL NETWORKS

- 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$^3$
- total number of synapses = $(cN) \cdot N$
  - $\Rightarrow$ possible

MINIMAL LAYERED CORTICAL NETWORK MODEL

- 1 mm³
- 300 million synapses, 80,000 neurons
- 2 populations of neurons per layer:
  - E: Excitatory
  - I: Inhibitory
- E and I identical neuronal dynamics
- laterally homogeneous connectivity
- layer- and type-specific $C_{ij}^{xy}$
SIMULATION TECHNOLOGY: THE NEST INITIATIVE

collaborative effort and community building

Major goals:
- systematically publish new simulation technology
- produce public releases under GPL

network simulator of the Human Brain Project

- origins in 1994, registered society (since 2012)
- teaching at international tutorials and advanced courses:
  - Okinawa Computational Neuroscience Course OCNC, OIST, Japan
  - Latin American School on Computational Neuroscience LASCON, Brazil
  - annual NEST Conference, Aas, Norway
  - Computational Neuroscience CNS by OCNS, Seattle
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
- integrates knowledge of more than 50 experimental papers

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

available at: www.opensourcebrain.org
CRITIQUE OF LOCAL NETWORK MODEL

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

- 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.

Human cortex:

- $10^{10}$ neurons
- $10^{14}$ synapses
MESO- AND MACRO-SCALE MEASURES

brain-scale networks basis for:
- further measures by forward modeling
- comparison with mean-field models

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

and macroscopic measures
- EEG, MEG
- fMRI resting state networks
JUQUEEN, JÜLICH

K computer, RIKEN AICS, Kobe
Meeting the memory challenges of brain-scale network simulation

Susanne Kunkel, Tobias C. Potjans, Jochen M. Eppler, Hans Ekkehard Plesser, Abigail Morrison, and Markus Diesmann

Supercomputers ready for use as discovery machines for neuroscience

Moritz Helias, Susanne Kunkel, Gen Masumoto, Jun Igarashi, Jochen Martin Eppler, Shin Ishii, Tomoki Fukai, Abigail Morrison, and Markus Diesmann

Spiking network simulation code for petascale computers

Susanne Kunkel, Maximilian Schmidt, Jochen M. Eppler, Hans E. Plesser, Gen Masumoto, Jun Igarashi, Shin Ishii, Tomoki Fukai, Abigail Morrison, Markus Diesmann, and Moritz Helias

Provides the evidence that neuroscience can exploit petascale systems

Makes supercomputers accessible for neuroscience

Mathematical model of memory consumption
NEST- MAXIMUM NETWORK SIZE

- using 663,552 cores of K
- using 229,376 cores of JUQUEEN
- worst case: random network
- exc-exc STDP

- 1.86x10^9 neurons, 6000 synapses/neuron
- 1.08x10^9 neurons, 6000 synapses/neuron

- Aug 2nd 2013, press release Juelich, RIKEN, and OIST
- Oct 10th 2014, Kunkel et al. (2014) Front Neuroinform 8:78
MULTI-AREA MODEL OF MACAQUE VISUAL CORTEX

- rich anatomical data sets available (e.g., CoCoMac)
- close to human
- 32 areas structured in layers comprising $8 \times 10^8$ neurons
- downscaled model with $4.1 \times 10^6$ neurons and $2.4 \times 10^{10}$ synapses

architectural types from Hilgetag et al. (2015) with data by Helen Barbas

From Dombrowski et al. (2001), Cereb Cortex
CONSTRUCTION of cortico-cortical connectivity

CoCoMac

FLN from Markov et al. 2014

Ercsey-Ravasz et al. (2013), Neuron
STRUCTURAL CONNECTIVITY REVEALS FUNCTIONALLY RELEVANT COMMUNITY STRUCTURE

clustering by map equation method (Rosvall et al. 2010)
MULTI-AREA MODEL: DYNAMICAL RESULTS

- stable resting state with heterogeneous laminar rate patterns and irregular firing
- cortico-cortical interactions trigger increased spike bursts in higher visual areas

V1 data of Chu et al. (2014)

comparison between experimental and simulated data
MULTI-AREA MODEL: DYNAMICAL RESULTS

- activity propagates in feedback direction
- inter-area interactions mimic experimental resting-state fMRI

PUBLICATION OF MODEL STRUCTURE

- manuscript just describing model construction
- available since Nov 16th 2017 as advance online
- will make model code available as open source as for microcircuit model
THE PROBLEM OF POST-PETASCALE

- 1 second biological time:
- 6 to 42 min on K computer
- 8 to 41 min on JUQUEEN
- wiring: 3 to 15 min

more than one synapse

3g kernel
- infrastructure
- sparse table

4g kernel (2014)

- memory consumption not suitable for exascale
- not fast enough for studies of plasticity
OPTIMIZED STORAGE OF SYNAPSES IN 4G

4g kernel

(A) local threads

(i) synapses

(ii) used synapse types

(B) Memory usage (GB)

- since 2005 synapses on postsynaptic node
- ideally distributed network construction
- used by many codes
- sparse table replaces vector of sources
- optimized for sparseness of synapse types
- communication by MPIAllgather

(B) Memory usage (GB)

- at exascale, beyond 1 billion neurons
- sparse table dominates memory
A TWO-TIER CONNECTION INFRASTRUCTURE

- directed communication: MPIAlltoall
- requires information on presynaptic node
- breaks principle successful since 2005
- parallel construction implies subsequent communication of network structure
SIMULATION TECHNOLOGY FOR EXASCALE ARCHITECTURES

- maximum filling scenario
- ideal scaling of memory at exascale
- local memory independent of network size
- receive buffer independent of network size
Extremely Scalable Spiking Neuronal Network Simulation Code: From Laptops to Exascale Computers

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shows how to make memory consumption of compute nodes independent of network size
Seemingly a dead end

While current simulation technology enabled researchers to begin studying brain neuronal networks, it also represented a dead end on the way to exascale. Supercomputers are composed of about a hundred thousand small computers nodes, each equipped with a number of processors doing the actual calculations. “Before a neuronal network simulation can take place, neurons and their connections need to be created virtually, which means that they need to be instantiated in memory of the nodes. During the simulation a neuron does not know on which nodes it has target neurons, therefore, its short electric pulses need to be sent nodes. Each node then checks which of these electric pulses are relevant to virtual neurons that exist on this node”, says Susanne Kunkel of KTH Royal Institute in Stockholm.

The current algorithm for network creation is efficient because all nodes construnction takes particular part of the network at the same time. However sending all electric pulses and creating all nodes is not suitable for simulations on exascale systems. “Checking the role of each electric pulse efficiently requires one bit of information per processor if neuron in the whole network. For a network of 1 billion neurons a large part of memory in each node is consumed by just this single bit of information per neuron”, adds Markus Diesmann.

This is the main problem when simulating even larger networks: the amount of computer memory required per processor for the extra bits per neuron increases the size of the neuronal network. At the scale of the human brain, this would require the memory available to each processor to be one hundred times larger than in supercomputers. This, however, is unlikely to be the case in the next generation supercomputers. The number of processors per compute node will increase by memory per processor and the number of compute nodes will rather stay the same.

Breakthrough by new algorithm

The breakthrough reported in a recent publication is a new way of constructing neuronal network in the supercomputer. Due to the algorithms, the memory requirement on each node no longer increases with network size. At the beginning of the simulation the new technology allows the nodes to exchange information about who need send neuronal activity data to whom. Once this knowledge is available, the exchange of neuronal activity data between nodes can be organized in such a way that a node only increments the information it receives. An additional bit for each neuron in the network is not necessary.

A beneficial side effect

While testing their new ideas, the scientists made an additional key insight, rep Susanne Kunkel. “When analyzing the new algorithms we realized that our new technology would not only enable simulations on exascale systems but it would...”
WEAK SCALING AT PETASCALE

- JUQUEEN (blue) and K (red)
- K computer consistently better
5G FASTER THAN 4G AT PETASCALE

- 5g designed for exascale, but substantially faster already at petascale
- reduced serialization by receive buffer size (JUQUEEN: 16 cores, 4 threads)
- “sort” avoids spike duplication if multiple targets on compute node
- enables representation of further biophysical phenomena like axonal delays
- repeated pattern: research on high-end systems helps smaller systems
5G FASTER THAN 4G AT PETASCALE

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<th></th>
<th>Build time</th>
<th>Presim time</th>
<th>Sim time</th>
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<tbody>
<tr>
<td><strong>8 threads</strong></td>
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<tr>
<td>4g</td>
<td>2.4</td>
<td>0.3</td>
<td>28.4</td>
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<tr>
<td>5g</td>
<td>1.9</td>
<td>4.6</td>
<td>12.7</td>
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<thead>
<tr>
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<th>Build time</th>
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<tr>
<td><strong>64 threads</strong></td>
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<tr>
<td>4g</td>
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<tr>
<td>5g</td>
<td>0.5</td>
<td>4.3</td>
<td>5.2</td>
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(times in minutes, 1 second of biological time)

- 28,672 MPI processes, 18,000 neurons/process, 11,250 synapses/neuron
NEXT STEPS

- now communication overhead is much reduced
- local spike delivery including plasticity computation dominates
- presently doing profiling to address this next
SUMMARY

- models as building block of further studies ([www.opensourcebrain.org](http://www.opensourcebrain.org))
- need for brain-scale models
- full-scale model of macaque visual cortex
- correspondence to brain activity on multiple levels
- 5g NEST code ready for exploration of exascale systems
- very good memory constancy in weak scaling
- 55% speed-up compared to 4g on large petascale systems
- improved threading reduces run time from 30 min to 5 min

next steps:
- make 5g available in public NEST release
- improve now dominating local spike delivery
- prepare for massively parallel threading on compute nodes
REFERENCES

Neuroscience
Potjans TC, Diesmann M Cerebral Cortex (2014) 24(3):785-806
Schmidt M., Bakker R., Hilgetag CC., Diesmann M., van Albada SJ. (2017) Multi-Brain Struct Func (advance online) DOI:10.1007/s00429-017-1554-4

Simulation technology