# Large-scale brain simulations: modeling a cat cerebellum

## J. ZITO, H. MEMELLI, R. J. OUKAOUR, I. C. SOLOMON, L. D. WITTIE

Stony Brook University, Stony Brook, NY 11794-4400

## INTRODUCTION

Our lab has built a unified complete system for creation, simulation, and visualization of large-scale models of brain structures. Parameters, specifying spatial distributions of neurons and synapses, control creation of models that are morphologically representative neuronal networks. Model sizes are limited primarily by the amount of computer memory available to hold runtime synapse data.

Our current models are based on the cerebellar literature for cats. Each cerebellar model consists of neurons of different types. On 4096 nodes of a Blue Gene super-computer with a total memory of 4096 GBs, we have run models of close to 1 billion neurons connected by 180 billion synapses, more than a third the size of the cat cerebellum. We are using our models to test theories about the functioning of brain circuitry. We are constantly improving our system to include important features such as synaptic learning.

## METHODS

**Computer Hardware**

-NY-Blue[1]: an IBM BlueGene supercomputer at Brookhaven National Lab, we use up to 4,096 processor nodes for models that fill 4TB of memory.

- The system can also run on standard PCs for smaller model sizes.

**Software**

Our simulation system and its initialization phase are coded in C++ with calls to the standard Message Passing Interface (MPI) library.

The Visualizer is also coded in C++ and uses the FLTK ("Fast Light Toolkit"), a cross-platform GUI toolkit written in C++ that supports OpenGL

**Cell Morphology Model:**

Axonal and dendritic fields, where all synapses are located, are approximated as 3D rectilinear boxes, based on measurements from literature.

**Cell Firing Model:**

The Izhikevich (integrate-and-fire type) model. Different firing frequencies and firing behaviors are achieved by using different values of the parameters.

$$V' = 0.04V^2 + 5V + 140 - u + I_{ext}$$
$$u' = a(bV - u)$$

**Connectivity:**

A detailed input parameter file statistically describes the neuronal and synaptic configuration of the tissue. Our "Staggered Walk" practical algorithm that performs a walk through axonal and dendritic volumes to place synapses [1].

**Learning:**

We have implemented simple synaptic learning based on classic STDP rules, with synaptic weights changing depending on pre and post-synaptic firing.

**First tissue model:**

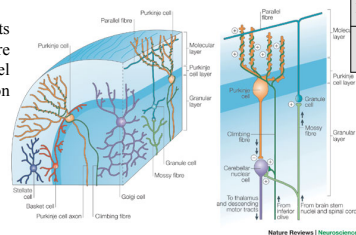The cerebellum with its regular layered structure was ideal for us to model using our simulation system.



**Figure 1. Drawing of cerebellum layers and major cell types**
From Apps & Garwicz 2005-

## MODELING THE CAT CEREBELLUM

*Matching neuroanatomy statistics from literature:*

We gather detailed statistics from cerebellar literature to parametrize our model, to match as closely as possible the measurements of the cat cerebellum in terms of cell counts of different types, sizes of neuritic fields and synaptic connectivity. The cerebellar model consists of neurons of twelve types including: Purkinje, granule, Golgi, basket, stellate, mossy and climbing fibers.



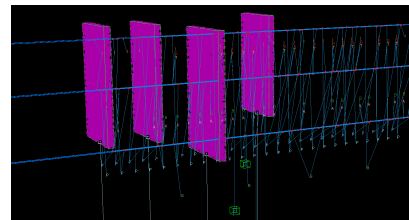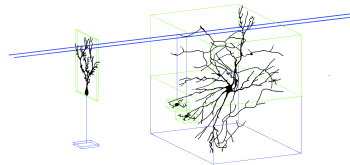**Figure 2. Four cerebellar neurons and their synaptic regions**



**Figure 3. Purkinje and Granule cells visualized**

## MODEL SIZES AND RUNTIMES

| Hardware | PC | 128 BG nodes | 512 BG nodes | 4096 BG nodes | Cat |
|---|---|---|---|---|---|
| Model Size in mm | 13 mm² | 51.2 mm² | 204.8 mm² | 1638.4 mm² | 4200 mm² |
|  | 2.9 x 4.5 | (8 x 6.4) | (8 x 25.6) | (32 x 51.2) |  |
| Total Neurons | 7.8 million | 31 million | 124 million | 1 billion | ~2.4 billion |
| Total Synapses | 1.4 billion | 5.6 billion | 22.4 billion | 180 billion | ? 300 billion |
| INIT Time | 5 min | 12.6 min |  | 3 min | - |
| Sim Time |  | 8.5 hrs |  | 51 min | 1 second |

**Table 2. Model Sizes and simulation runtimes**

## VISUALIZATIONS
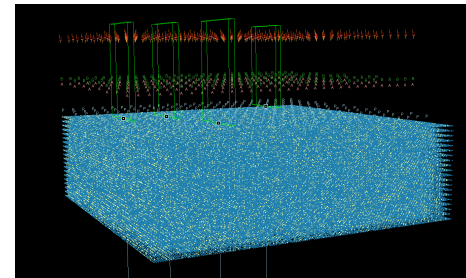


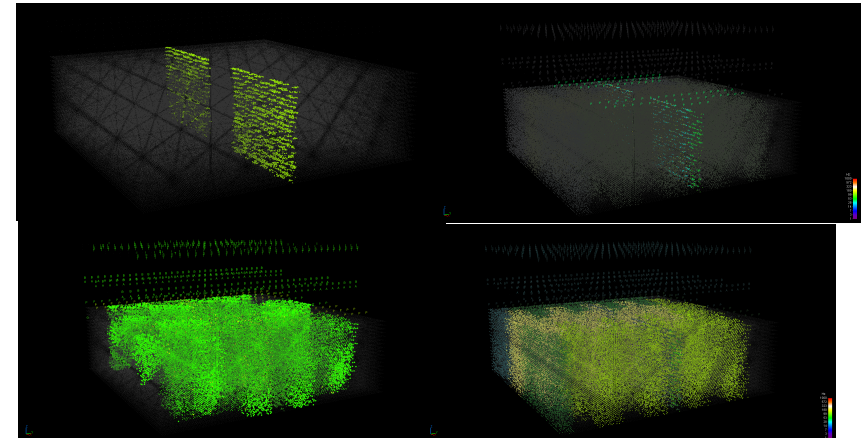| Cell Type | Ratio (per Purkinje) | Cell Counts |
|---|---|---|
| Purkinje | 1 | 205,000 |
| Granule | 1769 ± 51 | 367 million |
| Golgi | 0.33 | 25,000 |
| Basket | 6 | 230,000 |
| Stellate | 16 - 17.5 | 344,000 |
| Climbing Fibers | 1 | 205,000 |
| Mossy Fibers | 4 | 3.8 million |
| Glomeruli (rosettes) | 68 | 76 million |
| **TOTAL** | - | **990 million** |

**Table 1. Cat cerebellum**



**Figure 4. Firing activity**

## CONCLUSIONS

1. Approximating neuronal shapes and morphologies into neuritic 3D-volumes is appropriate for building large-scale neuronal network simulation models.
2. Initializing huge models and locating billions of synapses is computationally costly; we have implemented an efficient "Staggered Walk" algorithm to solve the problem.
3. We can model a third of the cat cerebellum in our simulation system on 4,096 Blue Gene/L nodes.
4. ?

## FUTURE DIRECTIONS

1. Further improve the structural model to better match literature for the cat cerebellum.
2. Optimize our simulator for faster run-times and better parallel communication.
3. Use our large-scale simulation system to analyze various cerebellum function theories.
4. Implement gap-junctions and analyze their effect in overall cerebellar activity.
5. Improve and analyze the learning mechanisms in our models.

## REFERENCES

1. J. Zito, H. Memelli, K. G. Horn, I. C. Solomon, and L. D. Wittie, "Application of a "Staggered Walk" Algorithm for Generating Large-Scale Morphological Neuronal Networks," Computational Intelligence and Neuroscience, 2012,