Billion-neuron memory models in slender blue genes

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ABSTRACT

The Brain Organization Simulation System (BOSS) at Stony Brook can model electrical activity in neuron networks with up to 131 billion synapse connections between neurons and 16,000 input synapses per neuron. BOSS can model one billion neurons if each has only 128 synapses. To have enough computer memory, large BOSS models run on 1,024 processor-nodes of NY-Blue, our local IBM Blue Gene/L supercomputer. Simulating each clock-second of electrical activity in 100 billion synapses and 8 million to 1 billion neurons takes 2 to 4 hours.

Slender computer memories limit the number of synapses in BOSS models. Each NY-Blue node has one gigabyte (billion bytes) of computer memory, half what most personal computers (PCs) provide. Details about 128 billion synapses, several million neurons, and billions of electrical signals passing between neurons fills nearly 1,024 gigabytes, one "terabyte", of memory.

The most recent version, V7, of BOSS uses more biologically relevant integrate-and-fire models of neurons than the simple voltage-sum-versus-threshold model BOSS used in V6 and earlier. Two differential equations track varying voltages within each neuron for each step, roughly 1 millisecond, of simulated time. Although the new V7 neuron model is computationally more complex, simulations of the same large networks execute 1.4 times faster under V7 than V6 if parameters produce the same average rates of firing per time step. The V7 networks pass only one signal per neuron firing versus two, pulse-on then pulse-off, for V6.

INTRODUCTION

The main BOSS project goal is to create a tool for neuroscientists to test large-scale neuron-based models of brain functions such as memory and learning. Traditional laboratory methods reveal details about electrical activity by one neuron or at most a few dozen. Precisely which neurons connect electrically is difficult to determine. BOSS may bridge the gap between individual neurons and structured networks of thousands.

Models of large networks of neurons can help test theories about brain mechanisms by predicting behavioral details observable by older methods. For example, individual human memories are theorized to be resonant patterns of electrical discharges among billions of neurons in many brain regions. Simulating many millions of neurons may show "memories in motion".

This year has seen repeated progress in discovering significant limitations to the sizes and complexities of neuron networks that can be simulated on 1,024 nodes of NY-Blue. Each new version of the BOSS code, from V2 to V7, made it possible to simulate or error-check models with ever larger numbers of neurons, synapses, or synapses converging on each neuron. One goal this year has been to determine how many times more super-computer memory and processing power are needed to simulate a neuronal network with as many neurons and synapses as the human brain.

[1]This research used resources at the New York Center for Computational Sciences at Stony Brook University/Brookhaven National Laboratory. The Center is supported by the U.S. Department of Energy under Contract DE-AC02-98CH10886 and by the State of New York.

METHODS

Computer Hardware System:
New York Blue[1] is an 18-rack IBM Blue Gene/L supercomputer with 18,432 computing nodes, each with 1 GigaByte (GB) of local memory, for a system total of 18 TeraBytes (TB) of dynamic memory. We have been using up to 1,024 processing nodes to simulate neuron networks that fill 1 TB of memory.

Computer Software Tools:
The BOSS discrete event simulation system is coded in the C++ language with calls to the standard Message Passing Interface (MPI) library to pass simulation events between adjacent nodes on NY-Blue.

Cell Model:
For BOSS versions up to V6, each neuron is modeled as a simple McCulloch-Pitts cell, a threshold element that sums arriving square-wave (2ms) input pulses sent by other neurons whenever one fires. For every (1ms) time step, if a neuron's input sum exceeds its fixed threshold, that neuron fires and sends firing pulses propagating along all its output connections (synapses) to other neurons. All BOSS versions allow periodic external stimuli to force subsets of neurons to fire regardless of their inputs or firing history.
Instead of modeling neurons as threshold elements, the latest BOSS version (V7) uses a flexible and more biologically relevant Integrate-and-Fire neuron model created by Izhikevich[2]. The new "Izhi" model has the following differential equations with four parameters (a, b, c, d) that can adjust models to match the firing patterns of many different types of brain neurons.

$$V' = 0.04V^2 + 5V + 140 - V + I_{ext}$$
$$u' = a(bV - u)$$
$$if\,(V \geq +30mV)\ \{V = c;\ u += d;\}$$

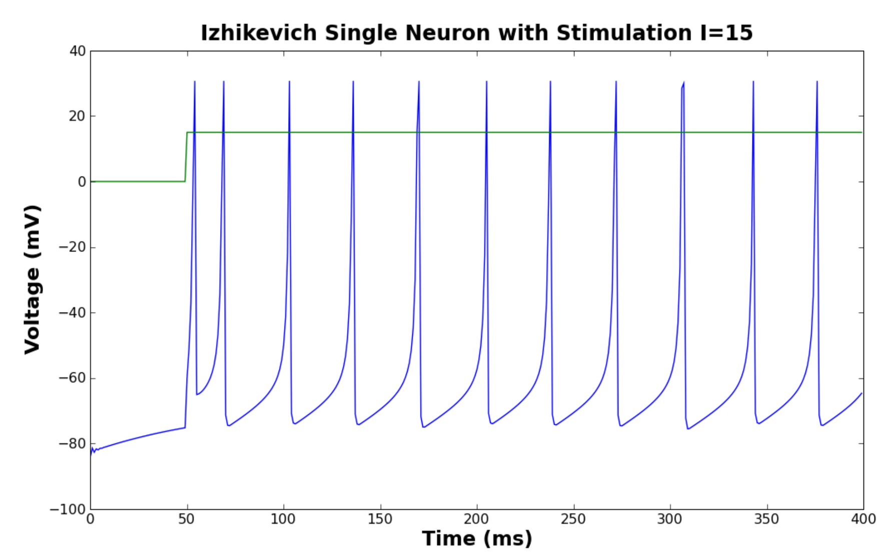

Figure 1. Voltage and firing spikes of a single neuron in our V7 networks, using Izhikevich[2] parameters for "regular spiking" cortical neurons. Starting at cycle 50 (ms), it receives an input of I_{ext}=15 each cycle.

Neuron Network Topology:
The neurons in our nets consist of equal numbers of E-cells, which strongly excite a few very local neurons, and of I-cells, which weakly inhibit many surrounding neurons. An E-cell and I-cell pair lie at each (x,y) lattice point of a square planar "field". To avoid edge discontinuities, end-around links connect opposite field "edges" for both dimensions. A few parameters control the underlying event simulation engine, the number of neurons in each model, the firing characteristics of all neurons, the strengths and durations of their axonal firing pulses, and the spatial distributions of axonal links that carry firing pulses between neurons.

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096	098	100	102	104	106	108	110	112	114	116	118	120	122	124	126
128	130	132	134	136	138	140	142	144	146	148	150	152	154	156	158
160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190
192	194	196	198	200	202	E I	206	208	210	212	214	216	218	220	222
224	226	228	230	232	234	236	238	240	242	244	246	248	250	252	254
256	258	260	262	264	266	268	270	272	274	276	278	280	282	284	286
288	290	292	294	296	298	300	302	304	306	308	310	312	314	316	318
320	322	324	326	328	330	332	334	336	338	340	342	344	346	348	350
352	354	356	358	360	362	364	366	368	370	372	374	376	378	380	382
384	386	388	390	392	394	396	398	400	402	404	406	408	410	412	414
416	418	420	422	424	426	428	430	432	434	436	438	440	442	444	446
448	450	452	454	456	458	460	462	464	466	468	470	472	474	E I	478
480	482	484	486	488	490	492	494	496	498	500	502	504	506	508	510

Figure 2. All threshold cells receiving (blue) +15 E-pulses from excitatory E-cell 204 and (red) -1 I-pulses from inhibitory I-cell 205 in a 16x16 field containing 256 E-cells and 256 I-cells.

[2]E. M. Izhikevich, "Simple model of spiking neurons," *IEEE Trans Neural Netw,* vol. 14, pp. 1569-72, 2003.

RESULTS

BOSS is progressing rapidly.
-By September 2009, by pre-summing signal pulses waiting to arrive at the same neuron and time, BOSS V3 needed only 256 GB of memory for 119 million neurons or 15 billion synapses. V4 had new BOSS options, but the same model size limits as V3.
- By May 2010, V5 on 1,024 nodes could simulate 1 billion neurons with 104 billion synapses, but no more than 118 billion synapses (from 231 milllion neurons); if models had more than 512 synapses per neuron, V5 used too much memory for firing signals sent between NY-Blue nodes.
-By July 2010, BOSS V6 had modeled up to 131 billion synapses on 1,024 nodes; one model had 125 billion synapses, 12.5 million neurons, and 10,000 synapses per neuron.
-As of today, BOSS V7 can simulate the same large models as V6 but using the more biologically relevant Izhikevich neuron model.

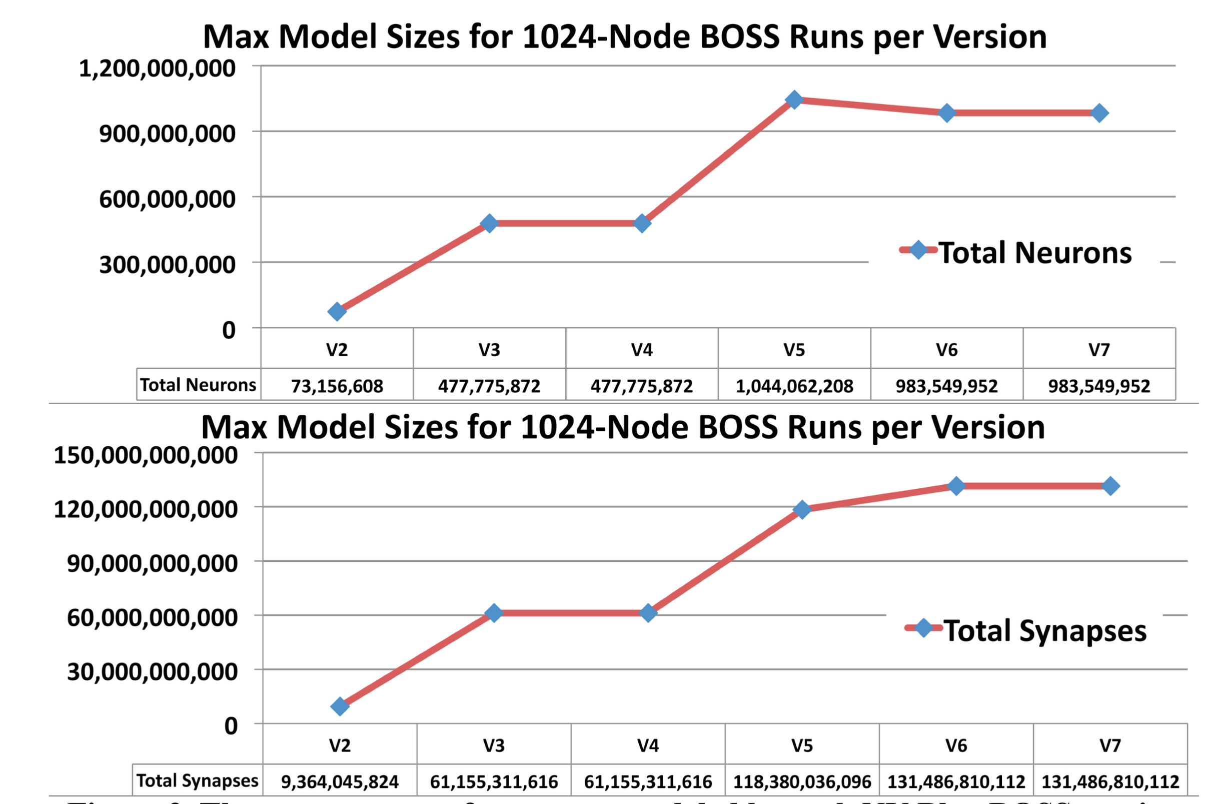

Figure 3. The most neurons & synapses modeled by each NY-Blue BOSS version.

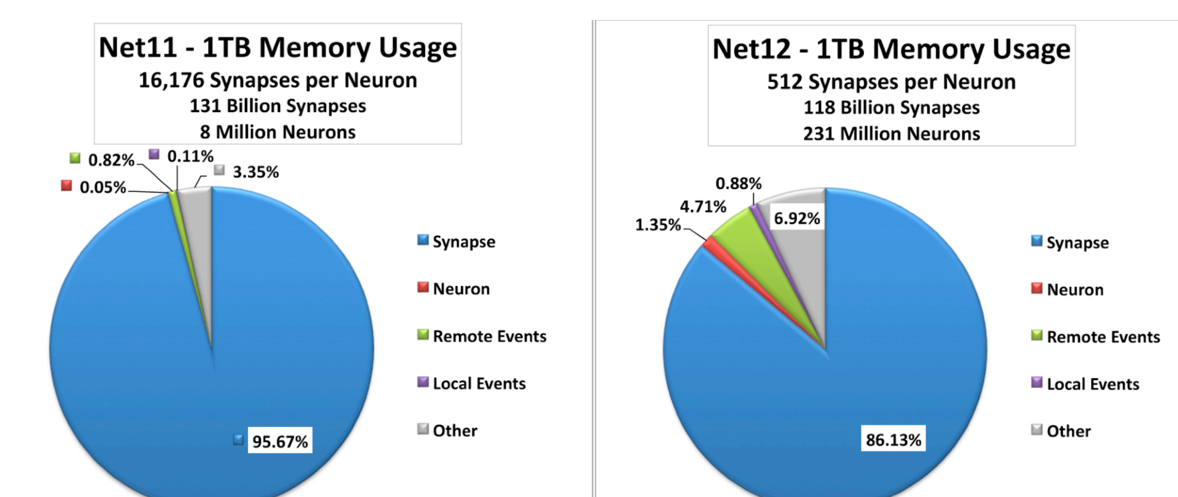

Figure 4. Synapse details fill NY-Blue memory for BOSS (V7) models of huge networks.

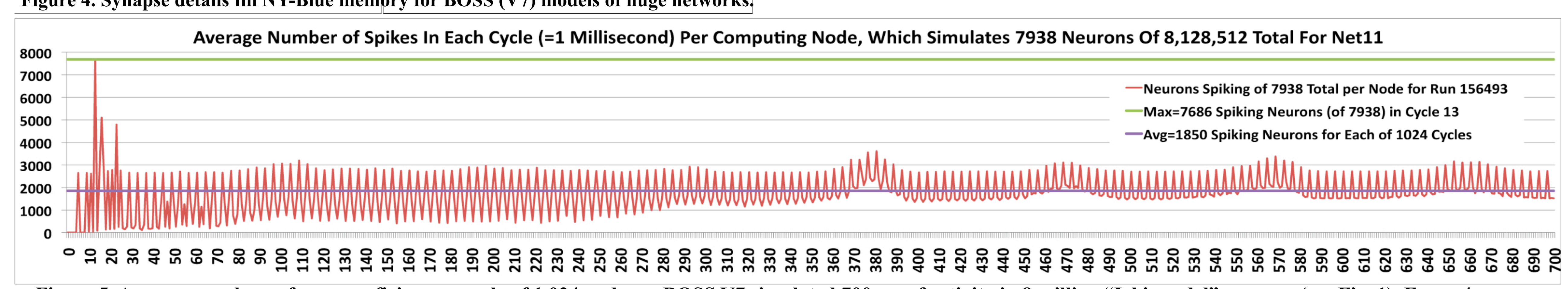

Figure 5. Average numbers of neurons firing per node of 1,024 nodes as BOSS V7 simulated 700 ms of activity in 8 million "Izhi-model" neurons (see Fig. 1). Every 4 ms external stimuli forced 6% of the neurons to fire (at 250 Hz). After 20 ms of initial erratic bursts, network firing stabilized at 250 Hz with a spontaneous 11 Hz undertone.

CONCLUSIONS

1. Memory for storing synapses will limit the size of neuronal networks simulated on Blue Gene supercomputers with only 1 GB of memory per node.
2. Careful parallelization mechanisms and efficient data structures are needed when running brain-scale simulations. For instance, just pre-summing the potentials for neurons that have remote connections allowed to run bigger models with many more synapses per neuron.
3. Runtime is not the limiting factor. One second of biological time, even with very high firing frequencies, can be simulated in only a few hours of computer time (in the order of minutes with more realistic, lower firing frequencies).
4. Replacing our simple cell model with "Izhikevich neurons", did not slow simulation. In fact, "Izhi-models" ran 1.4 times faster.
5. BOSS would need about 8,000 terabytes of memory to model all 100 billion neurons and trillion synapses of a human brain. Jaguar, the largest supercomputer in the USA, has 300 terabytes. Machines with enough memory and power to simulate networks of the size of the human brain should arrive before 2017.

	BOSS on NYBlue	Jaguar estimates	Human brain
Synapses	1.3×10^{11}	$\sim 3.9 \times 10^{13}$	$\sim 10^{15}$
Comp Memory (TB)	1	300	~7700

FUTURE DIRECTIONS

1. We will start using our simulation engine to analyze computational neuroscience questions in large-scale neuronal network models.
2. We may replace the Izhikevich equations with other, even more complex Hodgkin-Huxley-like equations and test the computational boundaries for large-scale models.
3. We plan to introduce synaptic learning changes, to build memory models and look for signs of "memories in motion".
4. We also have a single-processor C++ version of a more general BOSS initializer (INIT) that already can create cerebellar cortex tissue models. We are working on extending INIT to run in parallel on NY-Blue.