Introduction to Cognitive Neuromorphic Engineering

Emre Neftci

Institute for Neural Computation

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Historically, the term neuromorphic describes Very-Large-Scale Integration (VLSI) systems containing sub-threshold analog circuits that mimic neuro-biological architectures present in the nervous system.

(Mead, 1989)
The Hydroneuron

http://www.youtube.com/watch?v=yNt9sYhasnI
Neuromorphic Engineering

It is a discipline characterized by two main goals.

- To understand the computational properties of biological neural systems using analog circuits implemented in standard CMOS VLSI technology.
- To exploit the known properties of biological systems to design and implement efficient devices for engineering applications.

Neuromorphic engineering applies the computational principles discovered in biological organisms to those tasks that biological systems perform easily, but which have proved difficult to do using traditional engineering techniques.
Digital processor compared to the brain

At the system level, brains are orders of magnitude more efficient than digital processors. Why? The cost of an elementary operation (turning on transistor or activating synapse) is about the same. It’s not some magic about physics.

<table>
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<th>Fast global clock</th>
<th>Self-timed</th>
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<td>Distant memory</td>
<td>Local memory</td>
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<td>Deterministic, digital states (0,1)</td>
<td>Stochastic, analog states, digital comm.</td>
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<td>Devices frozen on fabrication</td>
<td>Constant adaptation and self-modification</td>
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The brain uses fundamentally different computational principles.

“We pay the factor of $10^4$ [in energy requirements] for taking all the beautiful physics that is built into those transistors, mashing it down into a 1 or a 0, and then painfully building it back up, with AND and OR gates to reinvent the multiply.” C. Mead 1990.
Power dissipation

BlueGene (IBM): 10 MW, 131072 processors in parallel, needs one floor of an entire building AND one floor for cooling devices.

Neurogrid (Stanford): 5 W, $10^6$ neurons, “rivaling BlueGene’s performance”.


Go: humans still outperform computers

- The game Go: 19 × 19 grid, $10^{360}$ possible states.
- Number of atoms in the universe $10^{82}$
Exploit the physics of silicon to reproduce the *bio*-physics of neural systems, using *subthreshold analog* circuits.

(Indiveri et al., 2011; Mead, 1989)
VLSI Integrate-and-Fire Neuron

Current Injection

(Indiveri, Chicca, & Douglas, 2006)
Synaptic dynamics
Excitatory Post-Synaptic Current (EPSC)

(Bartolozzi & Indiveri, 2007)
What about communication?

If we would use the same communication principle as in the brain we would have one wire per synapse ($10^{15}$ synapses in the brain).

But then we would get this...

![Image](image1.png)

Neurons are slow compared to digital circuits.

A better solution is to combine many connections into a single wire, and transmit *address-events*. 
Asynchronous Communication Protocol
Address Event Representation (AER)

(Deiss, Douglas, & Whatley, 1998)
Example of a Scalable Event-Based Reconfigurable Neuromorphic Systems (UCSD)

Hierarchical AER I&F Array Transceiver (HiAER IFAT)

- 0.13 μm CMOS, 25 mm²
- 65k dual-compartment conductance-based I&F neurons
- 65M synapses conductance-based dynamical synapses
- Reconfigurable, hierarchical AER interconnectivity

(T. Yu, S. Joshi, J. Park, S. Das, E. Neftci, C. Maier, G. Cauwenberghs)
We explained what neuromorphic engineering is, so what’s cognitive about it?

Nothing!

After 25 years, neuromorphic engineering has failed to deliver genuinely intelligent neuromorphic machines.

Why? Let’s understand first why digital computers are so successful.
Information processing systems

Computation

* e.g. sort numbers.

Algorithm

* e.g. quicksort.

Implementation

* e.g. computer language, CPU, logic gates.

There exists a very practical toolchain consisting of programming languages and compilers for configuring digital systems.
Neuromorphic Information processing systems

Computation
A “cognitive” task
e.g. Recognize gesture/speech, Play poker, 12AX

Algorithm
?

Implementation
Neuromorphic VLSI spiking neurons

Why is there no “Algorithm” for Neuromorphic Spiking Neurons?

- They are subject to fabrication variability and operating noise.
- Their parameters cannot be set with arbitrary precision (often just on or off!).
- Voltages used to set neuron parameters do not directly correspond to those of the mathematical description of the neuron.
- Only a small number of state variables can be observed.

Many existing models of computation based on spiking neural networks are incompatible with these limitations.
12AX: a simple cognitive task.

(Left) Stimuli are presented one at a time in a sequence. The participant responds by pressing the right key (R) to the target sequence; otherwise, a left key (L) is pressed. If the subject last saw a 1, then the target sequence is an A followed by an X. If a 2 was last seen, then the target is a B followed by a Y. (Right) A State Machine that can solve this task.

(O'Reilly & Frank, 2006)
Neural Engineering Framework


Multiplication:

Exploits mismatch of neurons: compatible with noisy and imprecise neurons (except for 1 point)

(Eliasmith & Anderson, 2004)
Solves 8 different cognitive tasks.
The most functional spiking neural network ever created, but requires a lot of neurons (2.5 million).
Custom cognitive task

(Neftci, Binas, Chicca, Indiveri, & Douglas, 2012)

On the State Machine level, this task is equivalent to the 12AX
The Soft Winner-Take-All (sWTA) Network

**sWTA network**

**Neuromorphic implementations of sWTA**

(Indiveri, Chicca, & Douglas, 2006)

(R. Douglas & Martin, 2007)

Proposal: the sWTA is an intermediate abstract layer that couples the behavioral model to the neuromorphic hardware

(Neftci, Binas, Chicca, Indiveri, & Douglas, 2012)
Visual Pattern Recognition Setup

(Neftci, Binas, Chicca, Indiveri, & Douglas, 2012)
95% of transitions were successful

In some ways, this is the most complex task ever achieved in a spiking neuromorphic system.

(Neftci, Binas, Chicca, Indiveri, & Douglas, 2012)
Summary

Neuromorphic systems mimic biological neurons on a physical substrate
- In the sub-threshold regime, CMOS transistors behave similarly to ion channels and dissipate less power.
- The neuron states are analog, but they communicate asynchronously using address-events.
- They operate in real-time, which makes them ideal for interfacing with the environment.

Cognitive Neuromorphic Engineering (CNE) is a multidisciplinary research field attempting to build the concepts and methods necessary for advancing neuromorphic systems towards a more cognitive quality of behavior.
- Quest for a “neural compiler”.
- Simple cognitive tasks such as the 12AX as testbenches.
UCSD: Gert Cauwenberghs, Srinjoy Das, Bruno Pedroni, Jongkil Park, Siddarth Joshi, Ken Kreutz-Delgado

INI, UZH: Jonathan Binas, Elisabetta Chicca, Ueli Rutishauser, Giacomo Indiveri, and Rodney Douglas

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Are we only limited by our understanding of the brain?


Indiveri, G., Linares-Barranco, B., Hamilton, T., van Schaik, A.,

