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14. ABSTRACT This workshop identifies state-of-the art advancements in neuro-technology and discusses future directions inspired by the human brain. Presentations given by a diversity of academic researchers and industrial leaders, each from different backgrounds, demonstrated new approaches based on their understanding of neuro-technology. These approaches include mathematical theories, neuro-signal measurement/analysis, software (deep learning) and hardware (commercially-available FPGA and neuro-emulation hardware) implementation, data representation/translation, architectural innovation, modeling, nanoscale devices and circuits.
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Report Title

Final Report: Frontiers in Neuromorphics Workshop

ABSTRACT

This workshop identifies state-of-the art advancements in neuro-technology and discusses future directions inspired by the human brain. Presentations given by a diversity of academic researchers and industrial leaders, each from different backgrounds, demonstrated new approaches based on their understanding of neuro-technology. These approaches include mathematical theories, neuro-signal measurement/analysis, software (deep learning) and hardware (commercially-available FPGA and neuro-emulation hardware) implementation, data representation/translation, architectural innovation, modeling, nanoscale devices and circuits.

Discussions following the presentations raised concerns from different viewpoints, and provided recommendations from theoretical advancement to commercializing production. From the theoretical view, further understandings of the fundamental brain features will provide the basis to overcome the limits in our current computation methods. For the implementation, the approach will need to be scalable, variation/noise tolerant and compatible with our current technologies in order to be demonstrated. On the commercialization side, user interfaces and the feasibility of design is important.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME PERCENT SUPPORTED
FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Foreword:

The Frontiers in Neuromorphics Workshop, sponsored by the Army Research Office (ARO), has been successfully held from April 14th to April 15th, 2016 at UCLA Engineering 4 Bldg, Shannon Room. This workshop aims to offer identification of the basic research directions inspired by brain methodologies to overcome limitations of current computational systems. The workshop also recommends promising pathways and resources for R&D of neuroscience.

Speakers from various backgrounds were invited from all over the US. They offered interesting talks from different aspects as well as a diversity of approaches from device level to system level implementations. Academia specialists from neuroscience, computer science, mathematics, data management, and neuromorphic engineering brought up promising solutions from mathematical theories to emerging silicon devices. Industrial representatives from large companies like Microsoft as well as start-ups like Nervana provided insight into large-scale systems and market needs. The workshop served as a very unique platform for facilitating the communication of new ideas and bringing together potentially new collaborations.

Statement of the problem studied:

The objective of this workshop is to address the next generation of information processing/computational architectures beyond Moore's Law limits, in light of the challenge announced by the White House Office of Science and Technology Policy: Nanotechnology-Inspired Grand Challenge for Future Computing. Our goal is to bring together scientific disciplines and application areas that appear to be converging towards new brain-inspired computational/information processing, to determine potential pathways, and to identify applications that would have immense benefits. The workshop provides identification of the basic research directions as learned from brain-inspired methodology for solutions that are beyond the capabilities of current computational systems and recommends the pathways and resources for research and development of neuromorphics.

Summary of the most important results:

The workshop composed of three sessions, each containing 4-5 presentations followed by discussion panels. During each discussion panel, presenters gathered to answer questions related to their talk or share general thoughts about their research fields.

A brief summary of the talks are as follows:

April.14 9:00-9:30, Dr. Andrew Hudson (UCLA)

Dr. Hudson's talk provided a detailed discussion on neurodynamics. In his presentation, he showed brain dynamics during different stages of anesthetic (from coma to seizure), and demonstrated control of the process through data analysis of principal components. He also suggested several spatial models for the recovery process.

April.14 9:30-10:00, Dr. Igor Ovchinnikov (UCLA)

Dr. Ovchinnikov presented a mathematical insight to creating the brain phase diagram, and new understanding of neurodynamics using supersymmetry theory and neuromorphic hardware emulation. Inspired from the new understanding, a new information processing/ optimization technique is demonstrated.

April.14 10:00-10:30, Dr. Eric Chung (Microsoft)

Dr. Chung demonstrated the use of FPGA for neuromorphic computing, implementing deep convolutional neural network for machine learning in their own searching engines. He showed that this approach provides hardware-level acceleration as well as system flexibility, and a significant advantage over conventional processors.

April.14 11:00-11:30, Dr. Wentai Liu (UCLA)

Dr. Liu studied dynamic behavior using data attained from high density probes. Through applying the Hibert-Huang Transform he was able to provide mathematical inverse reconstruction with the resolutions as high as fMRI.

April.14 11:30-12:00, Dr. Hugh Blair (UCLA)

Dr. Blair provided an overview on closed-loop neuroprosthetics- device that maps observed patterns of brain activity onto generated patterns of brain stimulation. He demonstrated real-time computing implemented on FPGAs for rapid translation to wearable neuromorphic devices, and proposed that future devices may be able to speak to the brain using spikes - the language of the brain itself.

April.14 14:00-14:30, Dr. Jason Cong (UCLA)

Dr. Jason Cong has developed an adjustable FPGA-based model for neuromorphic computing as well as a platform for convenient programming of neural networks. Using these schemes, he has achieved orders of magnitude improvement in speed and energy per spiking event compared to state-of-the-art neuromorphic hardware in deep learning applications.

April.14 14:30-15:00, Dr. Shriram Ramanathan (Purdue)

Dr. Ramanathan's talk focuses on the physical properties of semiconductor-neuromorphic devices, focusing on correlated electron systems and emerging nonvolatile memory devices. He discussed several local state-change mechanisms that are promising candidates for neural-inspired systems.

April.14 15:00-15:30, Dr. Helen Li (Pittsburgh)

Dr. Li demonstrated the concept of brain-in-a-box using memristive devices. She proposed multiple approaches for the cross-bar array to show both temporal and spatial characteristics of the device. For proof of concept, she implemented a neuron cluster with neuromorphic co-processors and proposed improved learning methods.

April.14 15:00-15:30, Dr. Massimo Di Ventra (UCSD)

Dr. Di Ventra proved mathematically that NMP problems are solvable using polynomial resources. For proof-of concept, he built and simulated a self-organized dynamical system consisting of reversible logic and non-linear memory elements. Dr. Di Ventra also provided insight on the challenges of implementation this system in hardware.

April.14 15:30-16:00, Dr. Hysunsang Hwang (POSTECH)

Dr. Hwang discussed the device requirements for an artificial neural network and presented a CMOS-compatible analog ReRAM device for synapses. He provided information on the device characteristics with different DC/potentialiation/depression conditions and showed feasibility for pattern recognition and learning networks. One thing he noted is that devices in neuromorphic networks have the ability to tolerate device variability and is functional despite resistance variations.

April.15 8:30-9:00, Dr. Dimitri Strukov (UCSB)

Dr. Strukov discussed deep learning in convolutional neural network and hardware implementation of analog neural networks using CMOS/Memristors. He demonstrated experimental results in small scale firing-rate feedforward/recurrent neural networks using memristor technology, and showed redesign using commercially-available NOR flash circuits.

April.15 9:00-9:30, Dr. Amir Khosrowshahi (Nervana)

Dr. Khosrowshahi presented a cloud-based platform for machine intelligence. Their startup company developed optimized hardware and software for deep-learning/ neural-networks, and showed that through optimization we can readily achieve a significant improvement in energy /speed even with current available technology.

April.15 10:30-11:00, Dr. Kwabena Boahen (Stanford)

Dr. Boahen's team developed a neural network with true-time spiking activities named the neurogrid. Their objective was to emulate ion-channel activities inside a real neuron using sub-threshold analog computation. He showed the advantage of analog over digital computing in precision in neural networks.

April.15 11:00-11:30, Dr. Wei Liu (Michigan)

Dr. Liu demonstrated crossbar and embedded 1T1R implementation of ReRAM devices for in-memory computing and neuro-computing architectures. He trained the ReRAM arrays to reconstruct images and perform data clustering. He also presented STDP and rate dependent learning mechanisms, and that ReRAM devices with 2nd order state variables offer internal dynamics much like Ion dynamics inside neurons.

In addition to the presentations, discussion sessions held at the end of the session also provided valuable results. Through the discussion, attendees brought up their concerns, shared ideas and provided recommendations. Via these discussions, future pathways for development of neuromorphics become clear.

As a summary of the workshop and recommendation for future research, attendees agreed that more fundamental theoretical research on understanding the brain function is the basis to building new systems. Architectural innovation inspired by the brain, built upon currently-available technologies (deep learning, neural networks) and that beyond Von-Neumann (computing in memory) provides great improvement in energy as well as performance. Other promising research directions include, but are not limited to new nanoscale devices and technologies (memristors), novel circuitry (reversible logic gates), analog representation and computation, nonlinear elements, and built-in variability. Attendees also discussed industrialization of the related neuromorphic research. Their concerns focused on CMOS compatibility, scalability (i.e. functionalities per energy and scale or per complexity of problems), and variabilities. In addition, the workshop identified the importance of providing user-friendly platforms in EDA and new design methodologies.



Frontiers in Neuromorphics Workshop PROGRAM

APRIL 14 – Thursday
8:15 AM – 5:30 PM
Engr 4 Bldg, Shannon Room 54-134

TIME	PRESENTER
8:15AM-8:45AM	Light Breakfast – Tesla Room 53-125 E4
8:45AM-9:00AM	Introduction by Dr. Joe Qiu - ARO
9:00AM-9:30AM	Dr. Andrew Hudson – UCLA Title: Spontaneous neuronal dynamics during recovery of consciousness from isoflurane anesthesia
9:30AM-10:00AM	Dr. Igor Ovchinnikov – UCLA Title: Neurodynamics, Supersymmetry Breaking and Optimization
10:00AM-10:30AM	Dr. Eric Chung – Microsoft Title: Accelerating Artificial Intelligence at Cloud Scale
10:30AM-11:00AM	BREAK
11:00AM-11:30AM	Dr. Wentai Liu – UCLA Title: Memristors: from devices to neuromorphic computing applications
11:30AM-12:00PM	Dr. Hugh Blair – UCLA Title: Neuromorphic computing for neuroprosthetic devices: Talking to the brain in its own language

12:00PM-12:30PM	BREAKOUT SESSION
12:30PM-2:00PM	LUNCH – Engr 4 2 nd Floor Patio
2:00PM-2:30PM	Dr. Jason Cong - UCLA
2:30PM-3:00M	Dr. Shriram Ramanathan – Purdue University Title: Emergent Intelligence
3:00PM-3:30PM	Dr. Helen Li – Pittsburgh University Title: Embrace the BRAIN Century: Challenges in Nanotechnology Enabled Neuromorphic Computing Design
3:30PM-4:00PM	BREAK
4:00PM-4:30PM	Dr. Massimo Di Ventra – UCSD Title: Memcomputing: A Brain-Inspired Memory-Enabled Computing Paradigm
4:30PM-5:00PM	Dr. Hyunsang Hwang – Postech Title: ReRAM-based Analog Synapse and IMT Neuron Device for Neuromorphic System
5:00PM-5:30PM	BREAKOUT SESSION
6:30PM-8:00PM	DINNER by Invitation ONLY – Faculty Center

APRIL 15 – Friday
 8:00 AM – 2:30 PM
 Engr 4 Bldg, Shannon Room 53-134

TIME	PRESENTER
8:00AM-8:30AM	Light Breakfast – Tesla Room 53-125 E4
8:30AM-9:00AM	Dr. Dmitri Strukov – UCSB Title: Neuromorphic Computing with Emerging Memory Technologies
9:00AM-9:30AM	Dr. Amir Khosrowshahi – Nervana Systems Title: Rethinking Computation: A Processor Architecture for Artificial Intelligence
10:00AM-10:30AM	BREAK
10:30AM-11:00AM	Dr. Kwabena Boahen – Stanford University Title: Neuromorphic Chips: Combining Analog Computation with Digital Communication
11:00AM-11:30AM	Dr. Wei Lu – University of Michigan Title: Memristors: from Devices to Neuromorphic Computing Applications
11:30AM-12:00PM	BREAKOUT SESSION
12:00PM-2:00PM	LUNCH –Tesla Room 53-125 E4
2:00PM-2:30PM	ADJOURN

Budgetary Report:

Invited Speakers Reimbursements	The speakers were reimbursed for their airfare and transportation cost to/from UCLA.	\$5,921.48
Meals served for day and a half	The meals were served for a full and a half days to 30 attendees which conforms to the per diem rate under UCLA policy. (2 breakfast, 2 lunches, 4 refreshments and 1 dinner served)	\$4401.52
Lodging at UCLA Guesthouse	The total cost for lodging for the invited speakers	\$1815.00
Labor Cost	The services provided for meeting logistics, preparation, setup and cost management.	\$\$5,715.73
Miscellaneous Cost	The fees incurred for the use of facility rentals and services, hosting webpage, parking permits, poster prints, etc.	\$2,146.27
TOTAL COST	Frontiers on Neuromorphics Workshop	\$20,000.00