

Traversing the Application Landscape of Neuromemristive Computing



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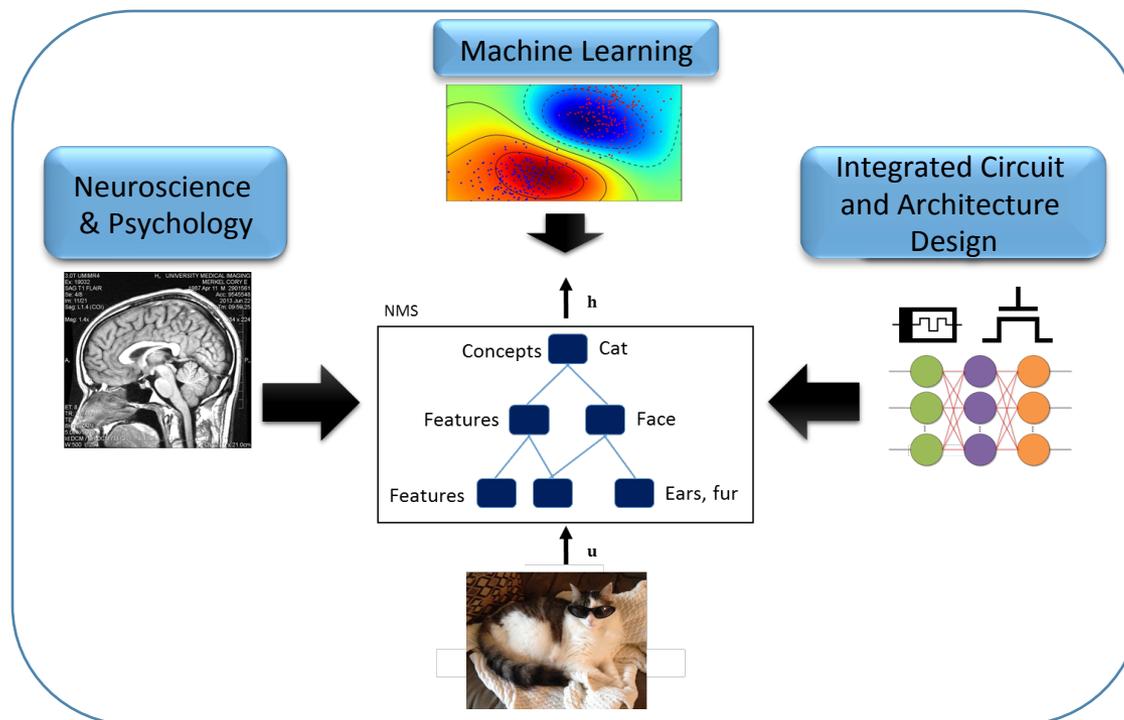
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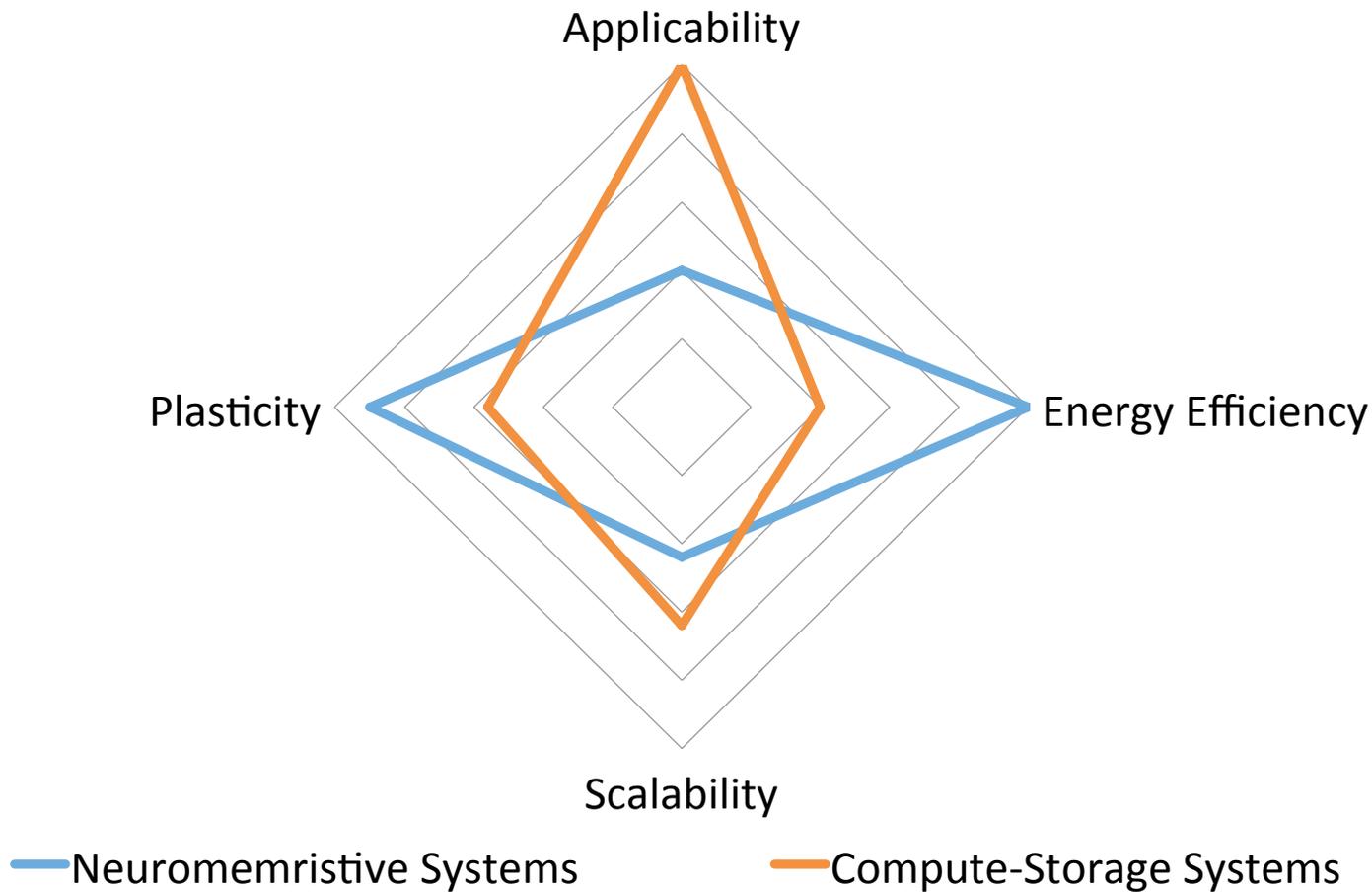
Neuromemristive Systems

Neuro-inspired CMOS/memristor hybrid systems for the next-generation of intelligent computing

- Application-driven, top-down design
- Abstractions of biological computation principles
- Roles of subcortical brain regions

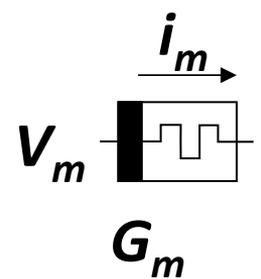


Neuromemristive Systems Overview

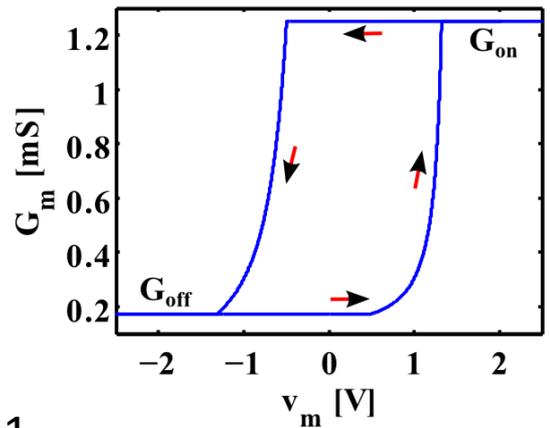


Memristors for Plasticity

- 2-terminal device with state-dependent Ohm's Law (Chua, 2011):



$$i_m = v_m G_m(\gamma, t)$$



- Redox RAM has best performance¹:

Metric	Flash	Memristors			Targets
		PCM	STT-RAM	RRAM	
Dynamic Range (\mathcal{U}/\mathcal{L})	-	1000	2	1000	> 4
Number of States	8-16	100	4	100	20-100
Retention	years	years	years	years	years
Energy (pJ/bit)	>100	2-25	0.1-2.5	0.1-3	0.01
Endurance (cycles)	10^4	10^9	10^{15}	10^{12}	10^9

¹Compiled from (ITRS, 2014; Yang *et al.*, 2013; Kuzum *et al.*, 2013; Ishigaki *et al.*, 2010)

Device Landscape

Memristive Devices

Chemical (Redox)



Physical

Phase Change

Ferroelectric (BaTiO₃)

Mechanical (Rotaxanes)



e.g. Pt/TiO_x/Pt

Anion Devices

Cation Devices

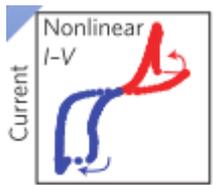
e.g. Ni/HfO_x/Cu

Bipolar Non-linear

Bipolar Linear

Nonpolar Bistable

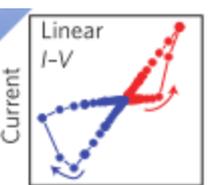
Nonpolar Threshold



Voltage



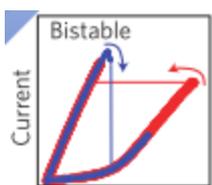
TiO_x, HfO_x, CuO_x



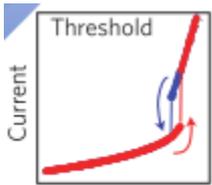
Voltage



Ag/GeS₂/W



Voltage

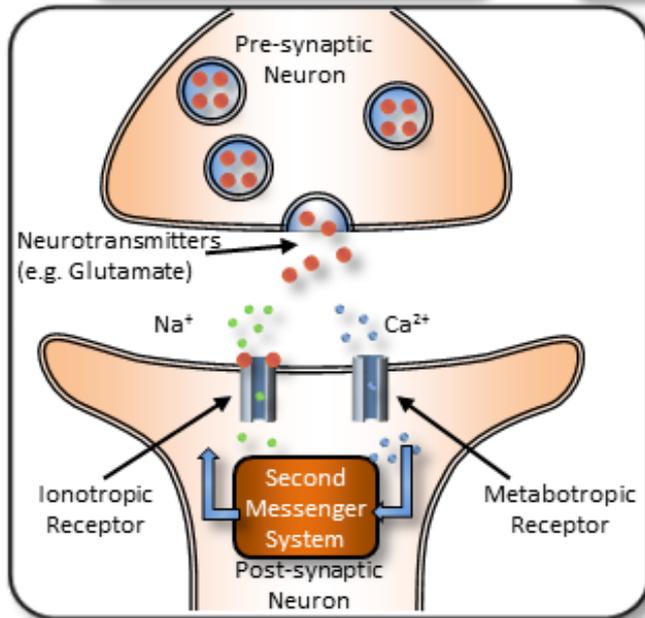


Voltage

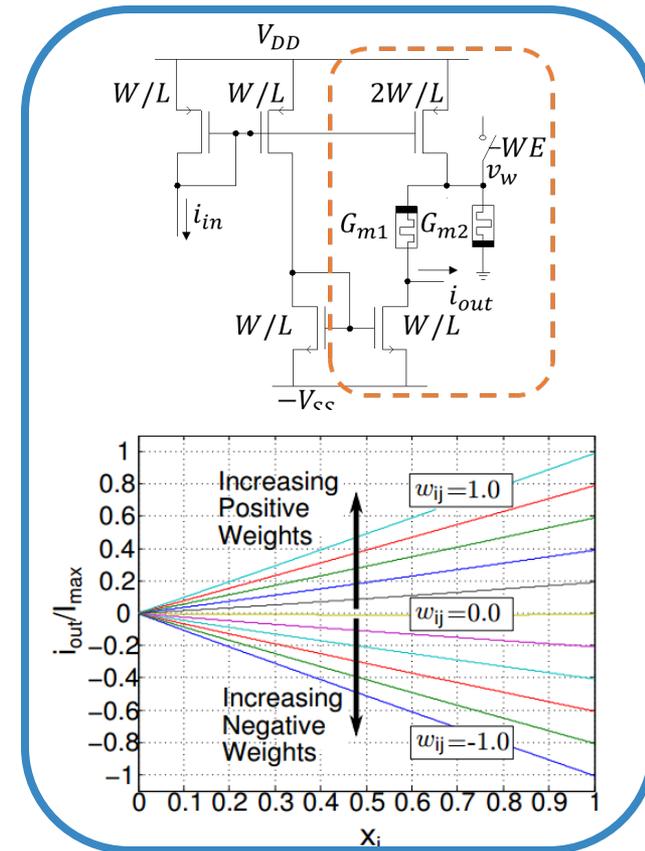
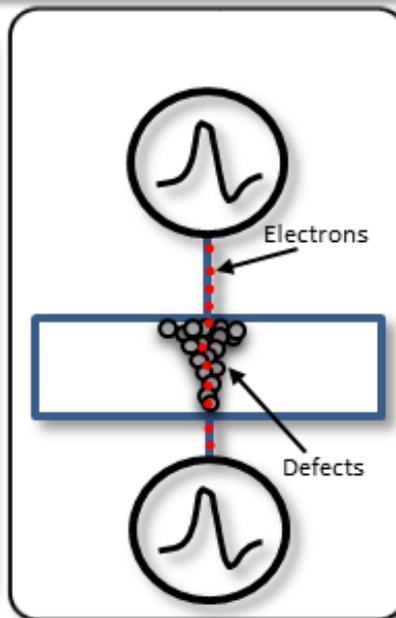
Memristors as Synapses

- Focus has been on synaptic weighting
- Small footprint and simple structure enables high density
- “Similarity” between biological synapse and memristive devices (Jo *et al.*, 2010)

Biological Synapse

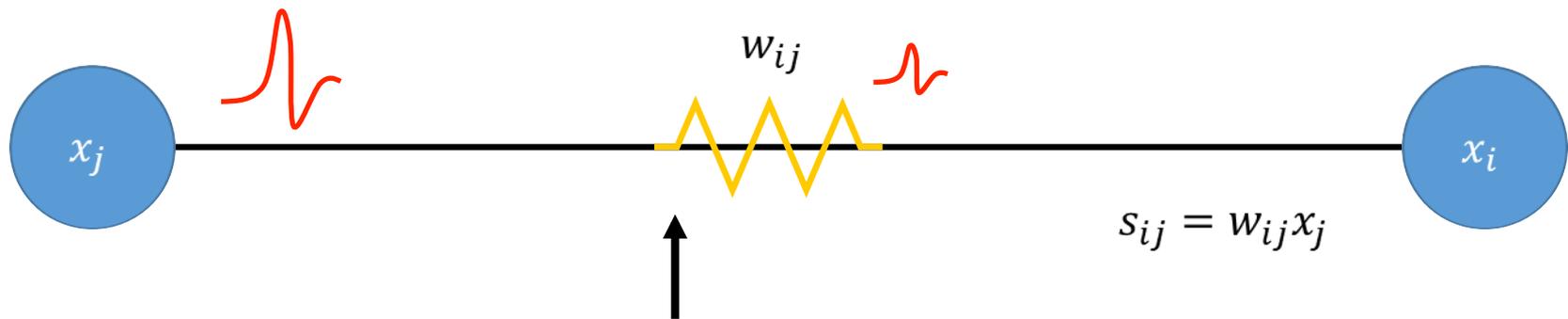


Memristor as a Synapse

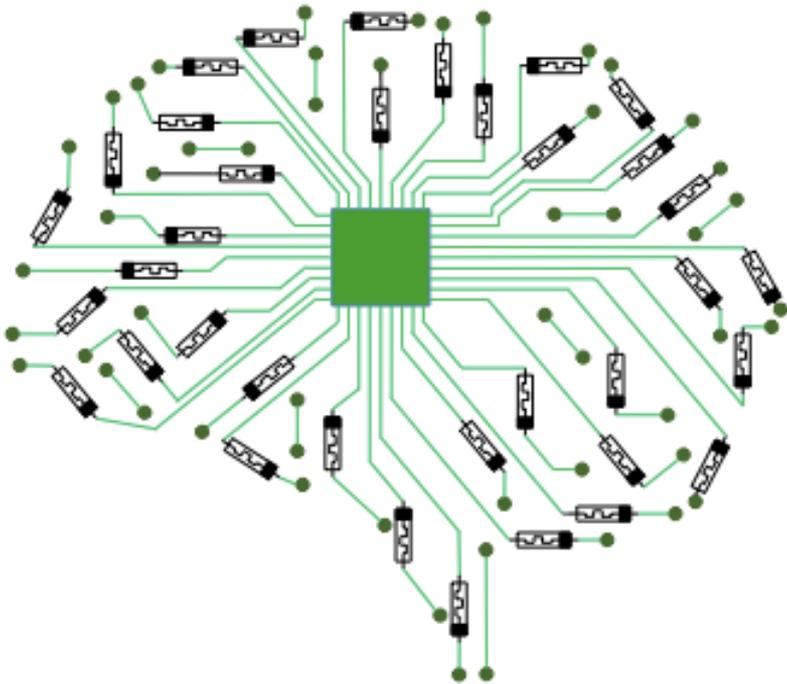


Synaptic Functions

- Provide physical interconnect
- Modulate signals
- Facilitate adaptation/learning



- Memristive devices provide all 3 in one medium



Application Landscape

Epileptic Seizure Detection

Epileptic Seizure Detection

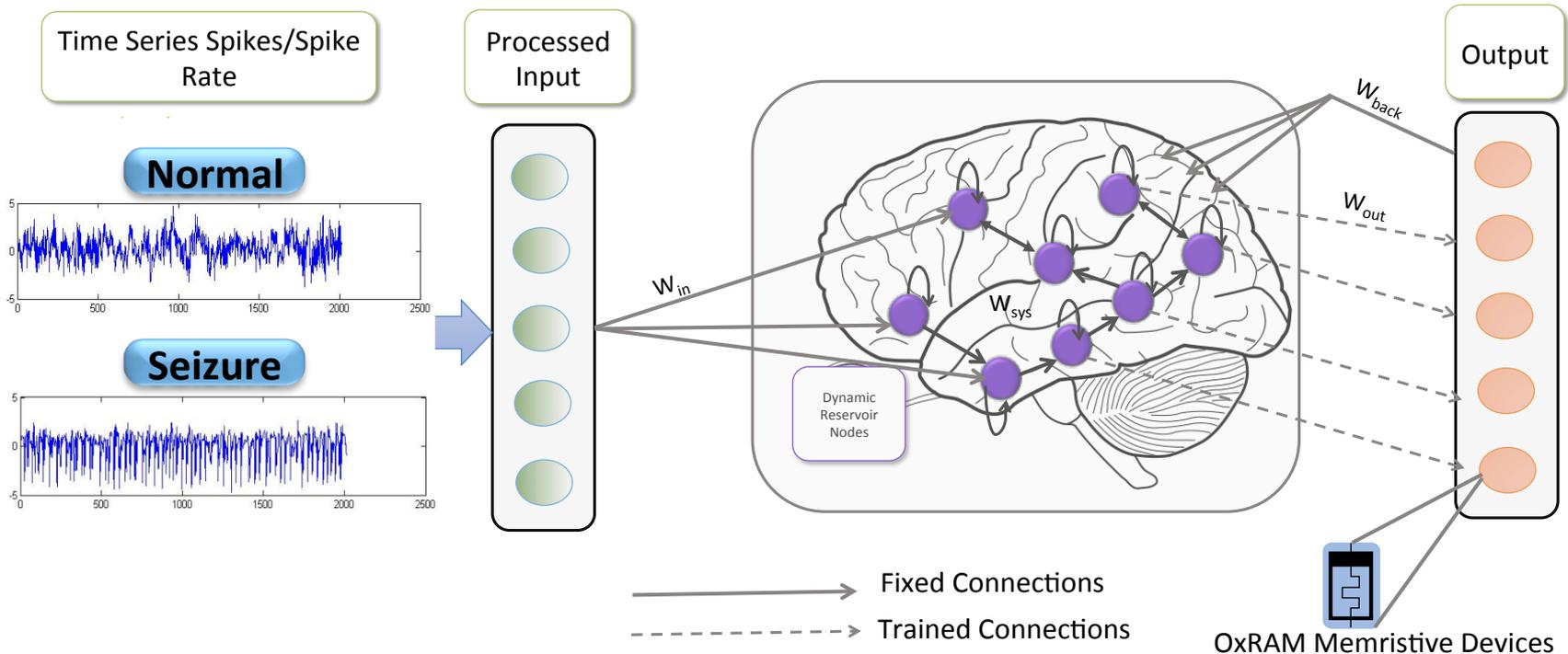
Epilepsy

- Epileptic seizure is a chronic disorder of the central nervous system
- One in 26 people will develop this disorder at sometime in their life (www.epilepsy.com)
- It can be often detected through analysis of electroencephalogram (EEG) signals

Use Cases

- Served as an early alert system to preclude any unwanted exertion
- Controlled delivery of drugs to reduce side effects
- Continual monitoring for proactive interventions for antiepileptic drug failures

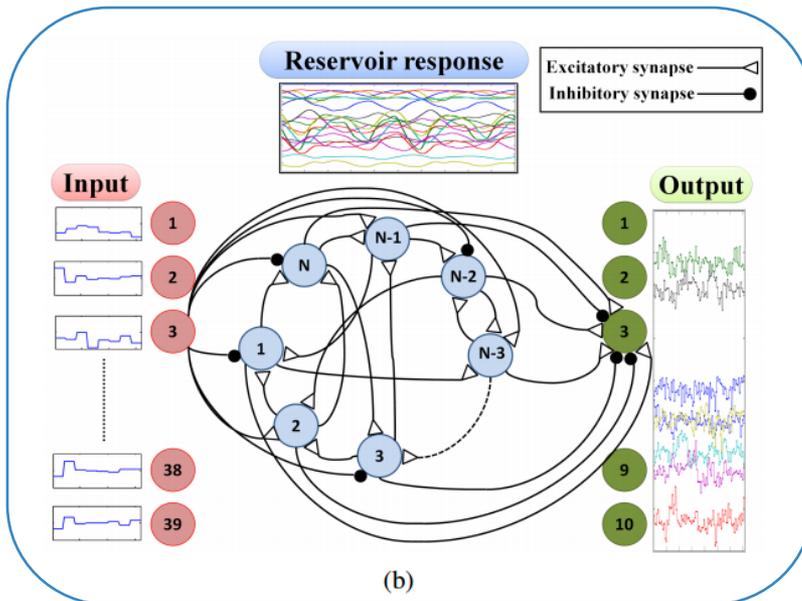
Ab-Initio Architectural Framework



- Partially-trained ANN with a recurrent network topology (Jaeger, 2001)
 - Recurrent (Reservoir) layer of nodes interconnected with random weights
 - Read out layer with trained weights

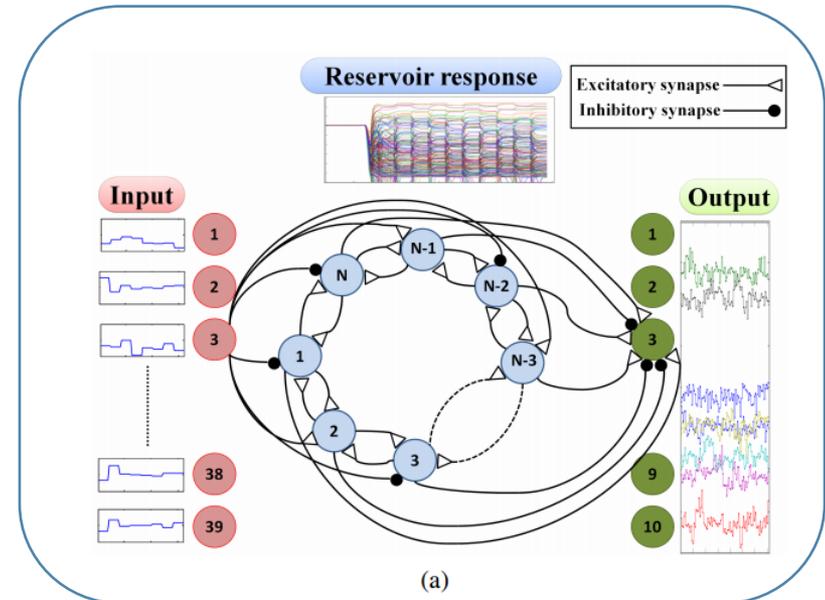
Closer Look

Random topology



- Nodes are randomly connected
- Varied degree of connectivity
- Needs more dense architecture to be implemented

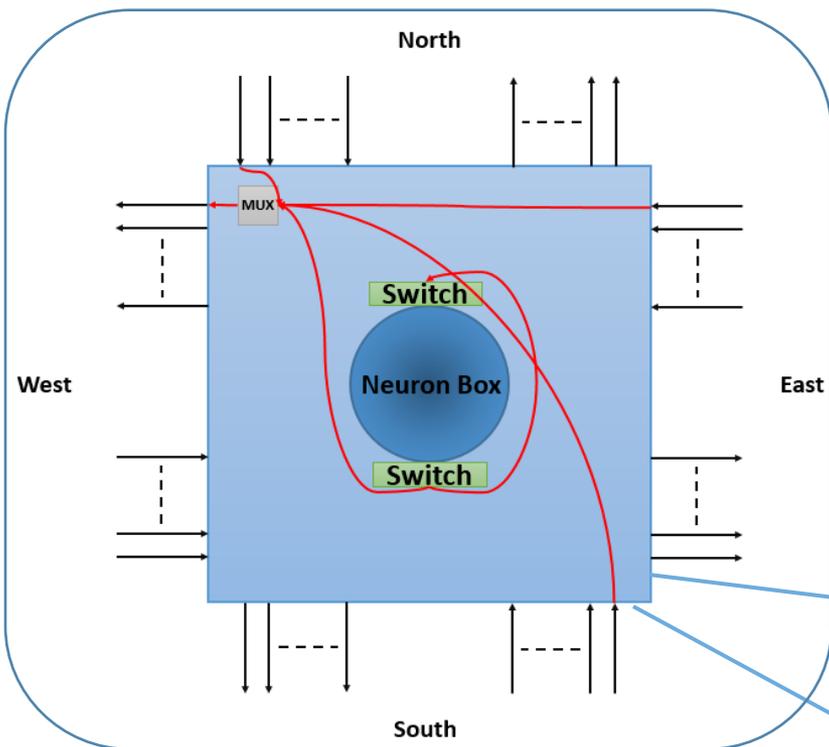
Ring topology



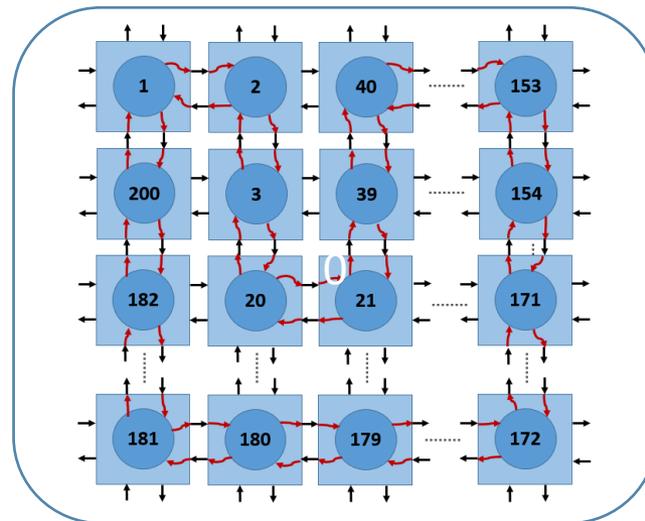
- Each node is connected to only two neighbors
- Low degree of connectivity
- Easily implemented in hardware

Reconfigurable Neuronal Arrays

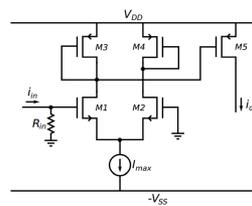
Neuron Box



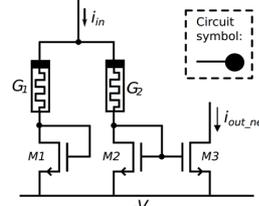
Ring topology



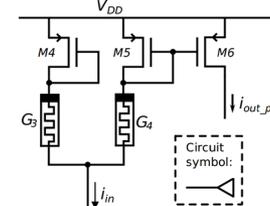
- Contains a neuron and all of its associated synapses
- MUXs are used to route signals to pre-specified paths



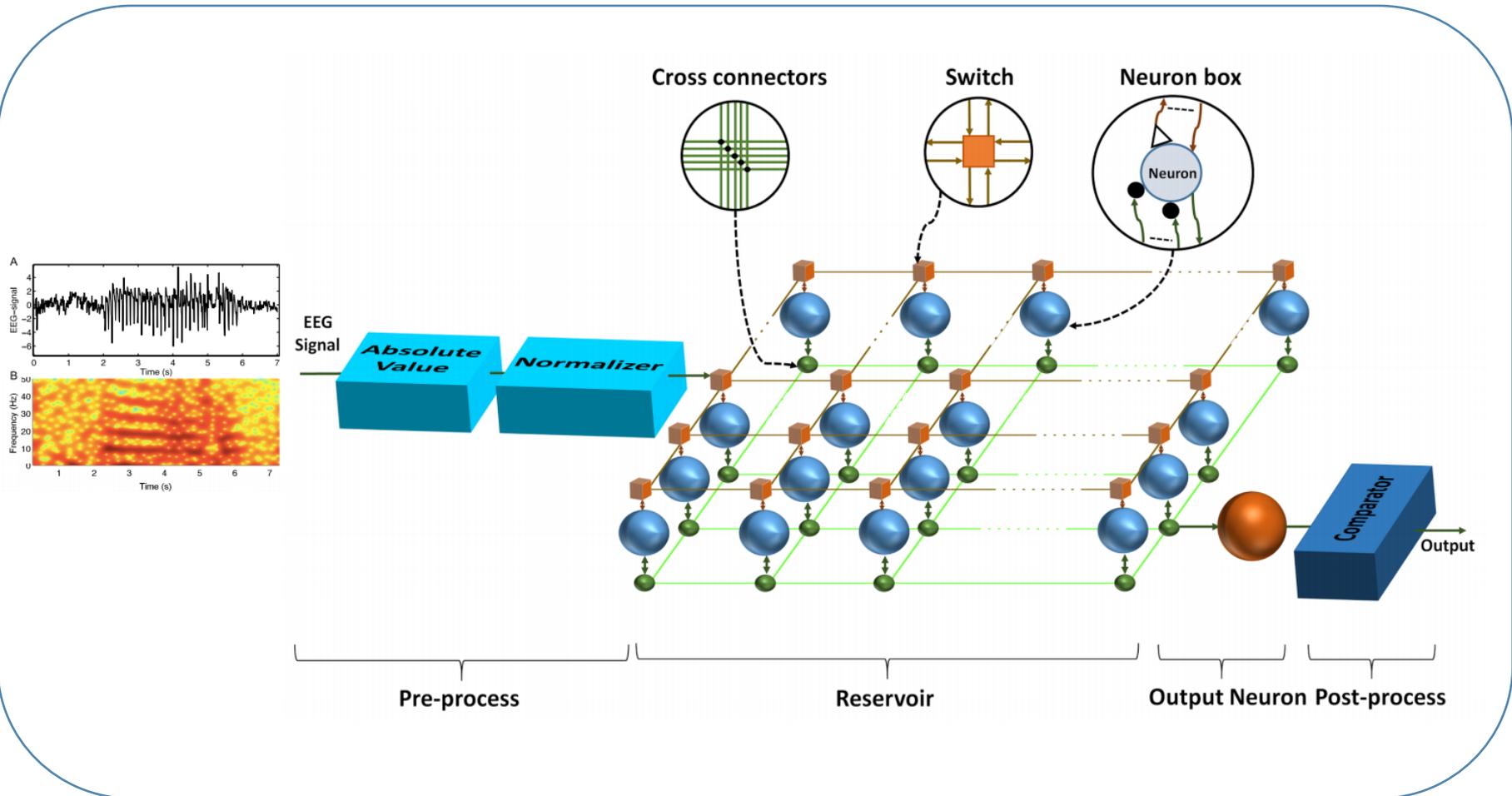
Neuron



Synapses

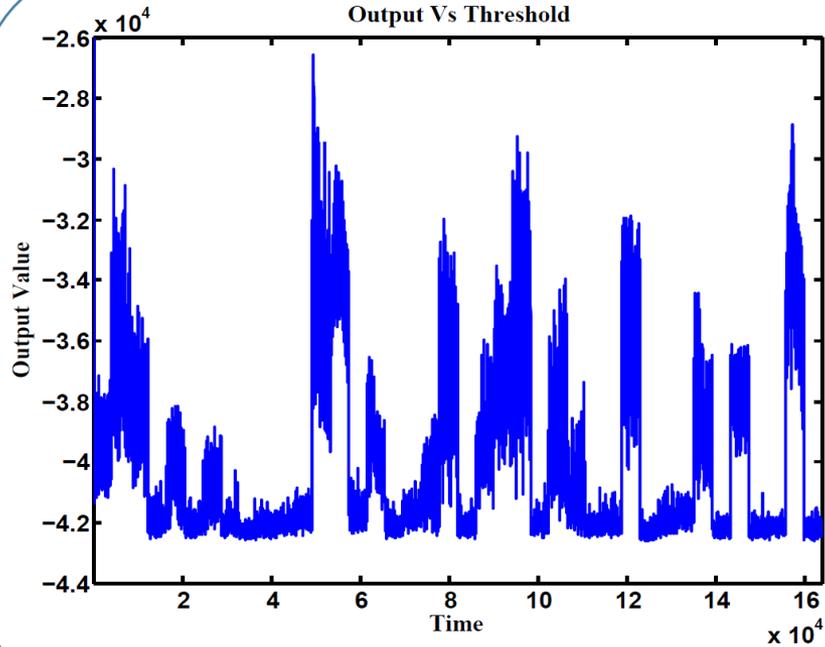


Epileptic Seizure Detection System

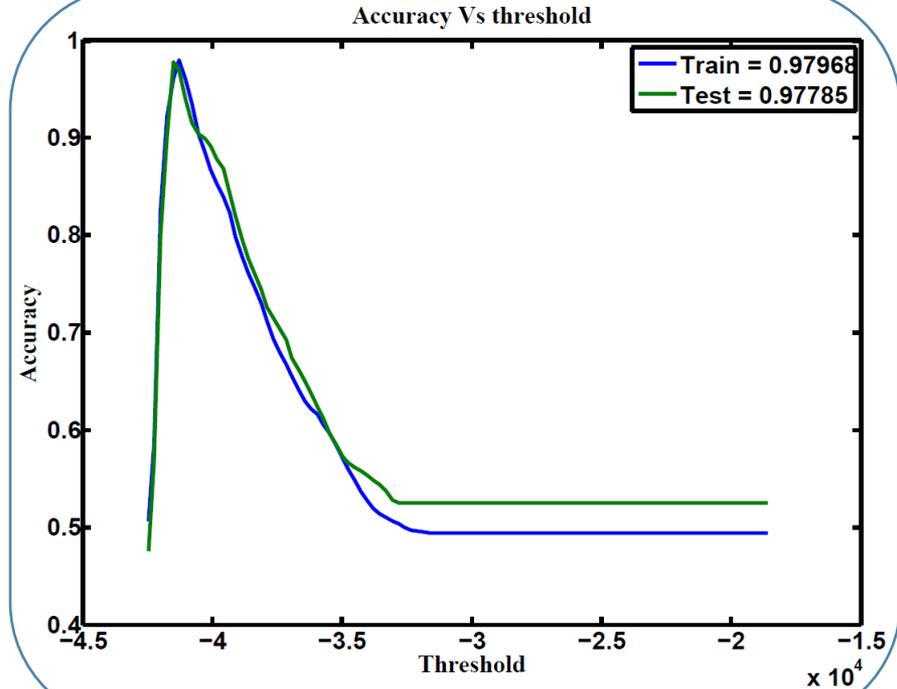


Seizure Detection Accuracy

Output



Accuracy



Speech Emotion Recognition

Speech Emotion Recognition

Use case

- Recognize the emotional status of a human, based on speech, such as anger, fear, happiness etc.
- Useful in human-computer interaction
- Using speech for emotion recognition is simpler and requires less computational resources compared with other inputs such as facial expressions.

Neutral

Anger

Dataset

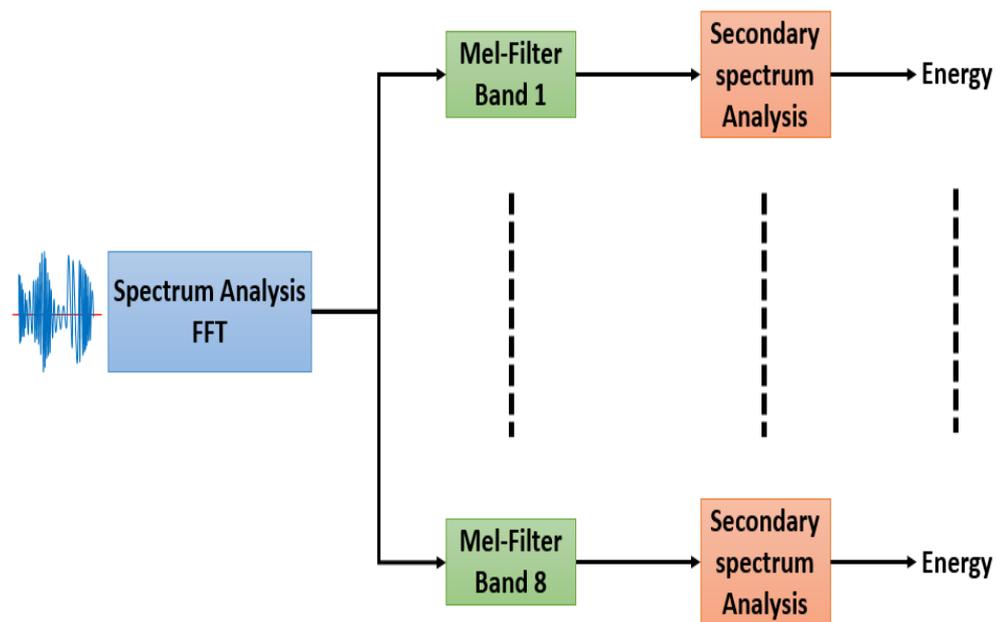
- The Berlin database of Emotional Speech
 - Ten actors(five male and five female)
 - Ten different daily German sentences
 - Seven emotional status
- 800 Wave files
- Neutral vs. Anger
 - 78 Neutral
 - 78 Anger

Feature Extractor

Mel-Filter

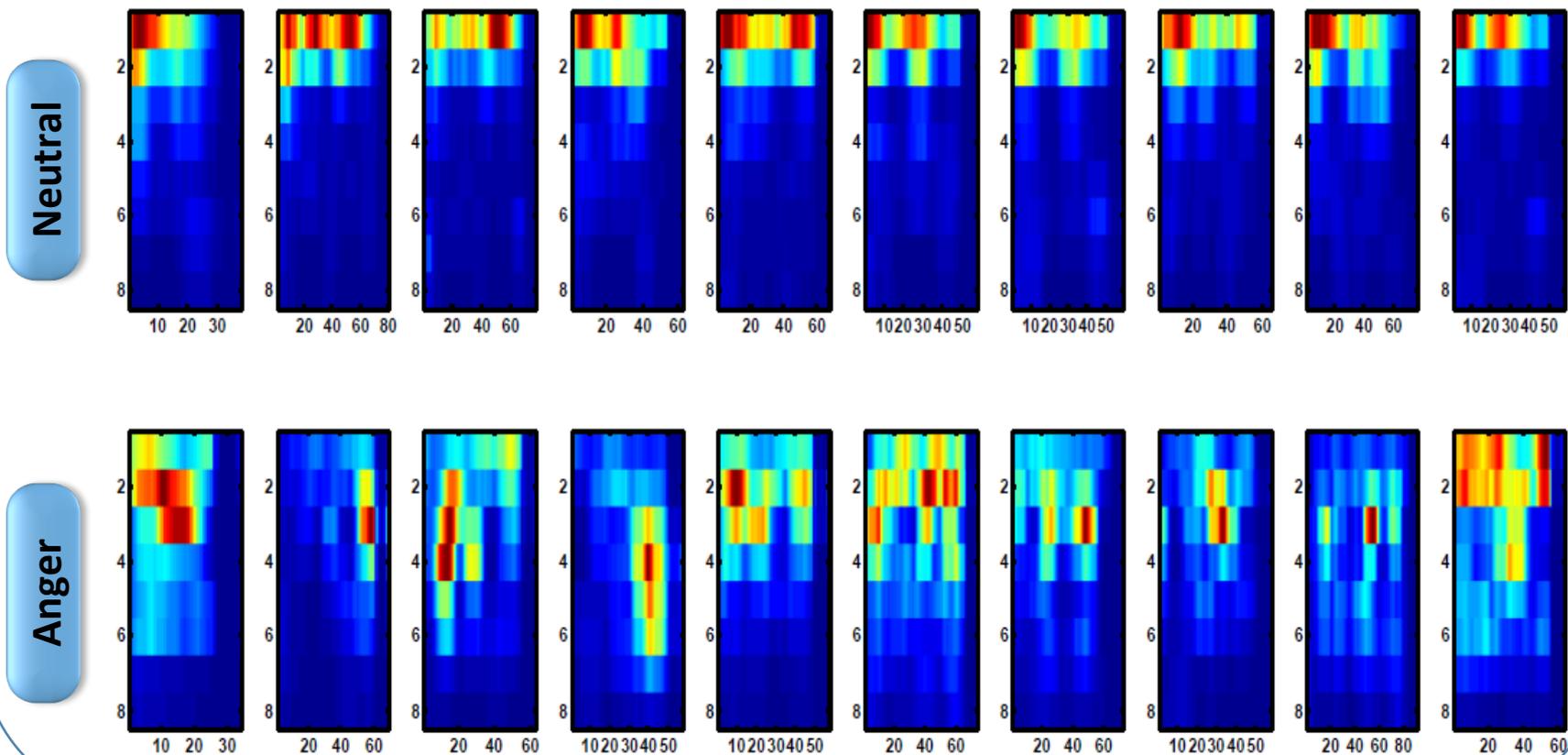
- Extract desired components of emotional information.
- 8 Mel-Filter bands were used to measure energy at different Mel-Frequencies

Algorithm



Feature Extractor

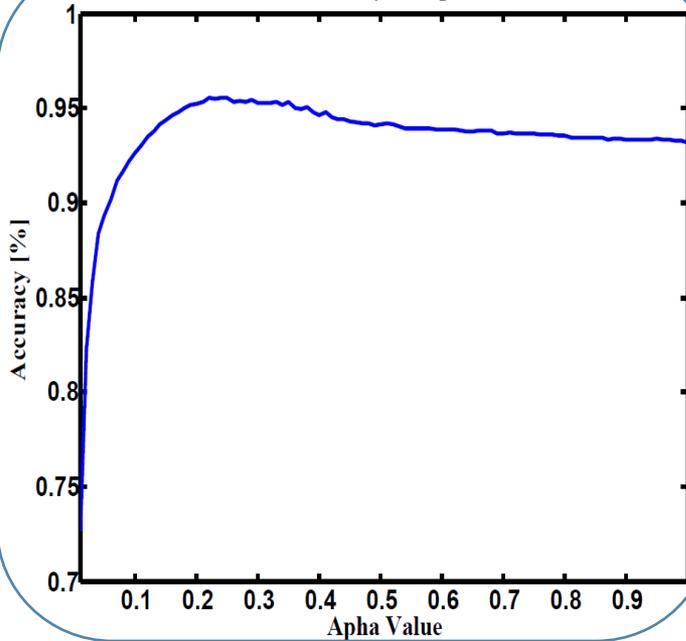
Features (Neutral and Angry)



Framework Optimization

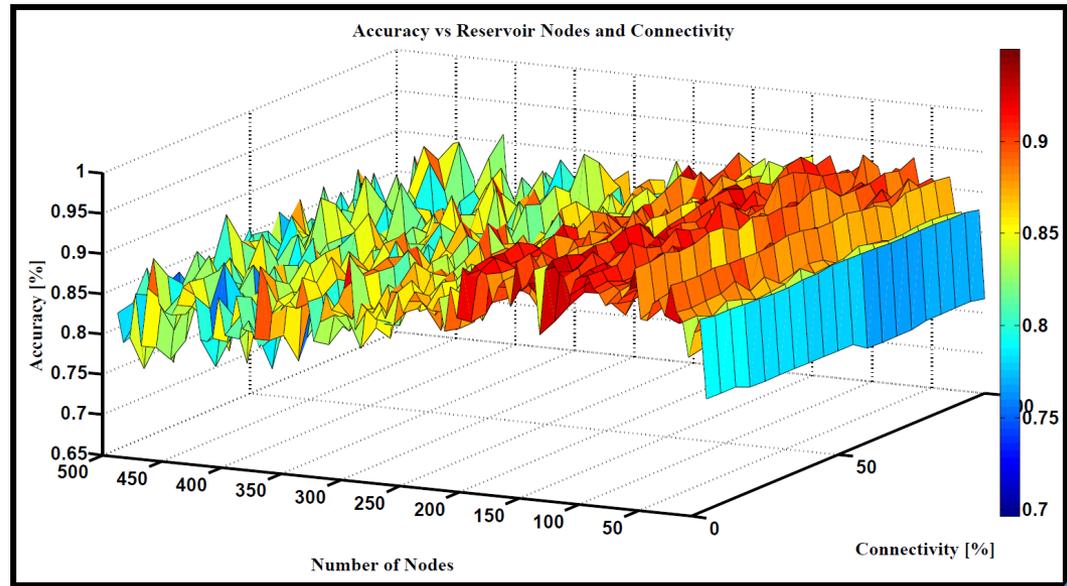
Learning Rate

Accuracy vs Alpha



Reservoir Nodes & Connectivity

Accuracy vs Reservoir Nodes and Connectivity

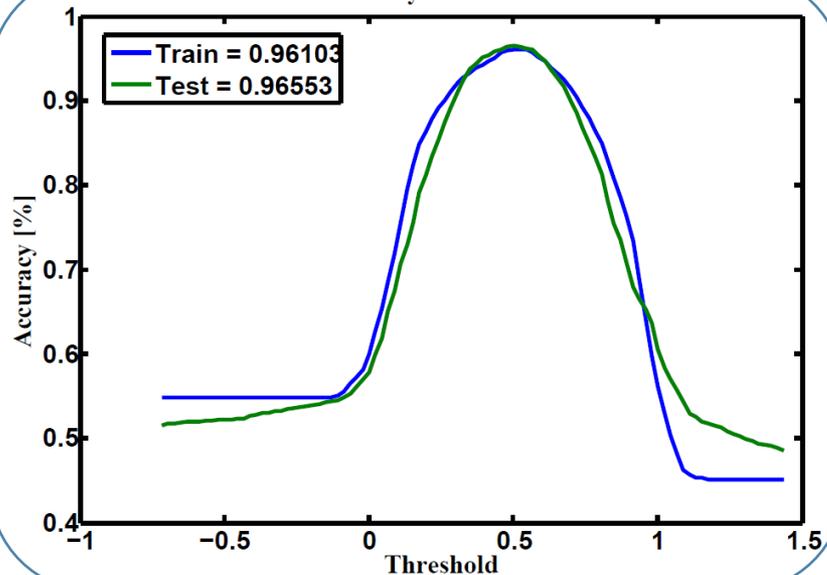


CISDA 2015

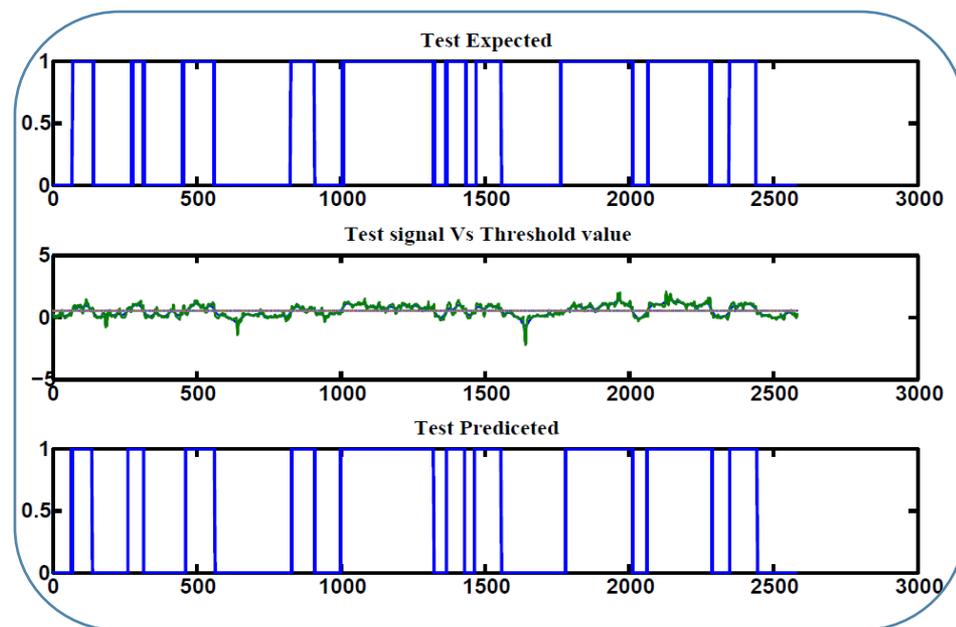
Speech Emotion Recognition

Accuracy

Accuracy Vs threshold



Analysis

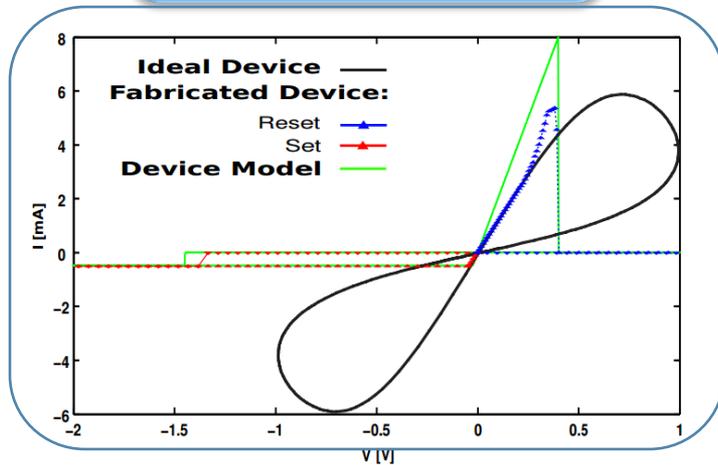


CISDA 2015

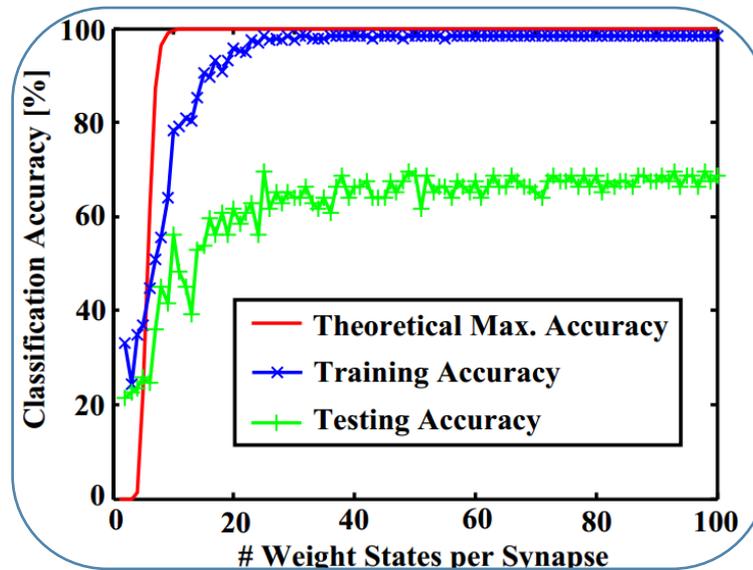
Speech Recognition

Speech Recognition

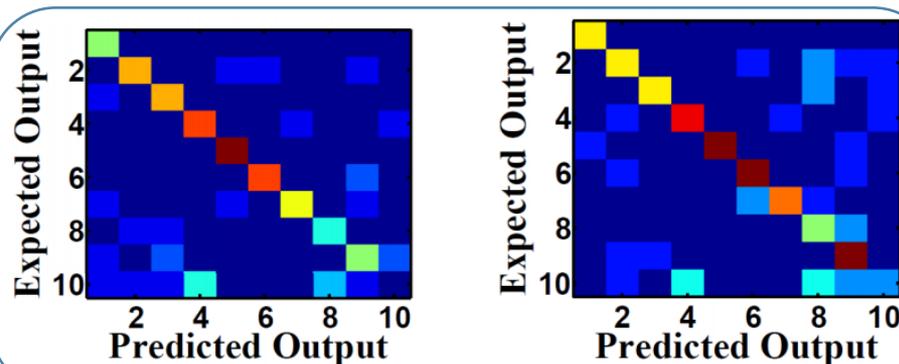
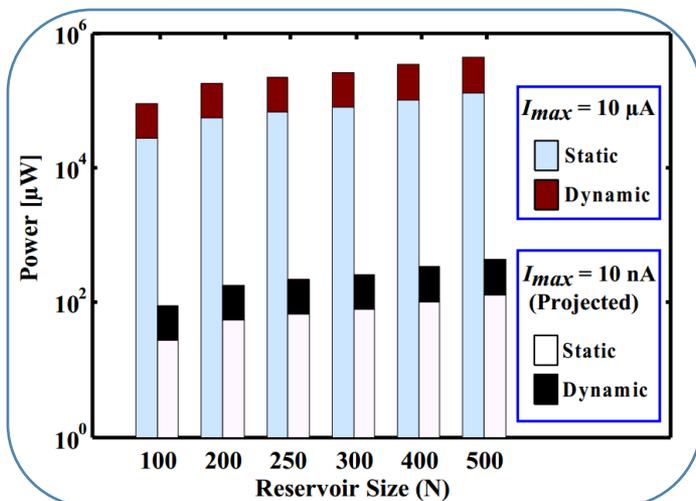
Bi-stable Memristor



Network Accuracy

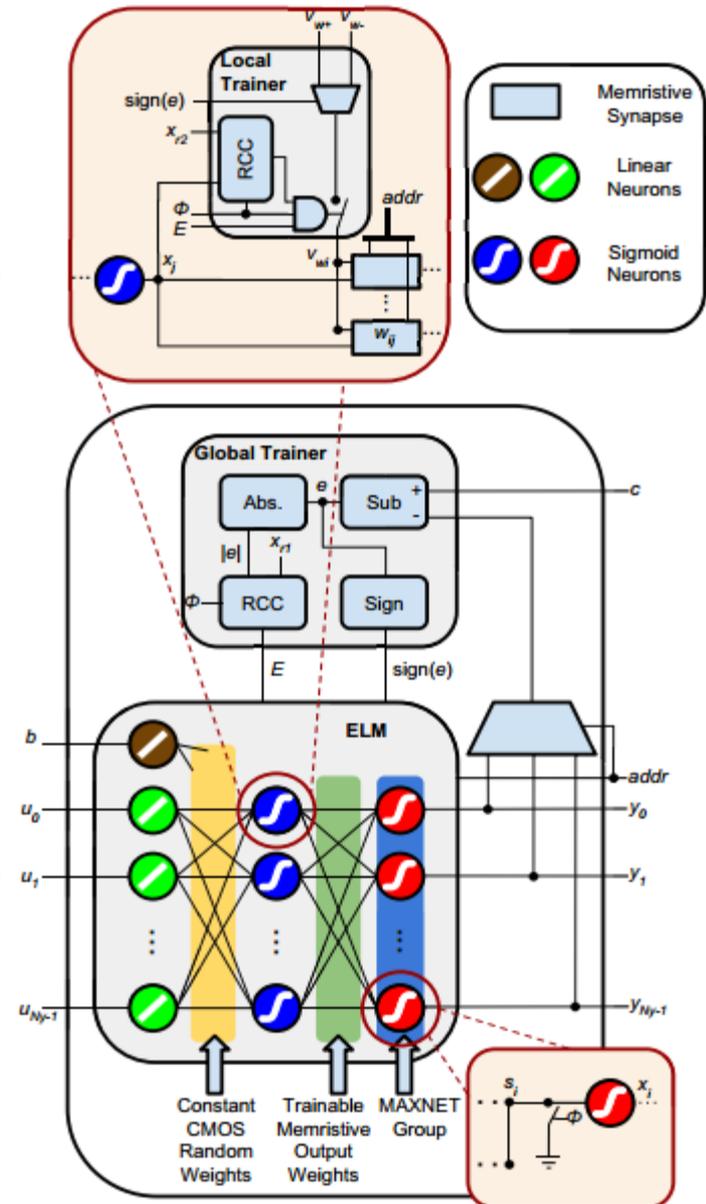
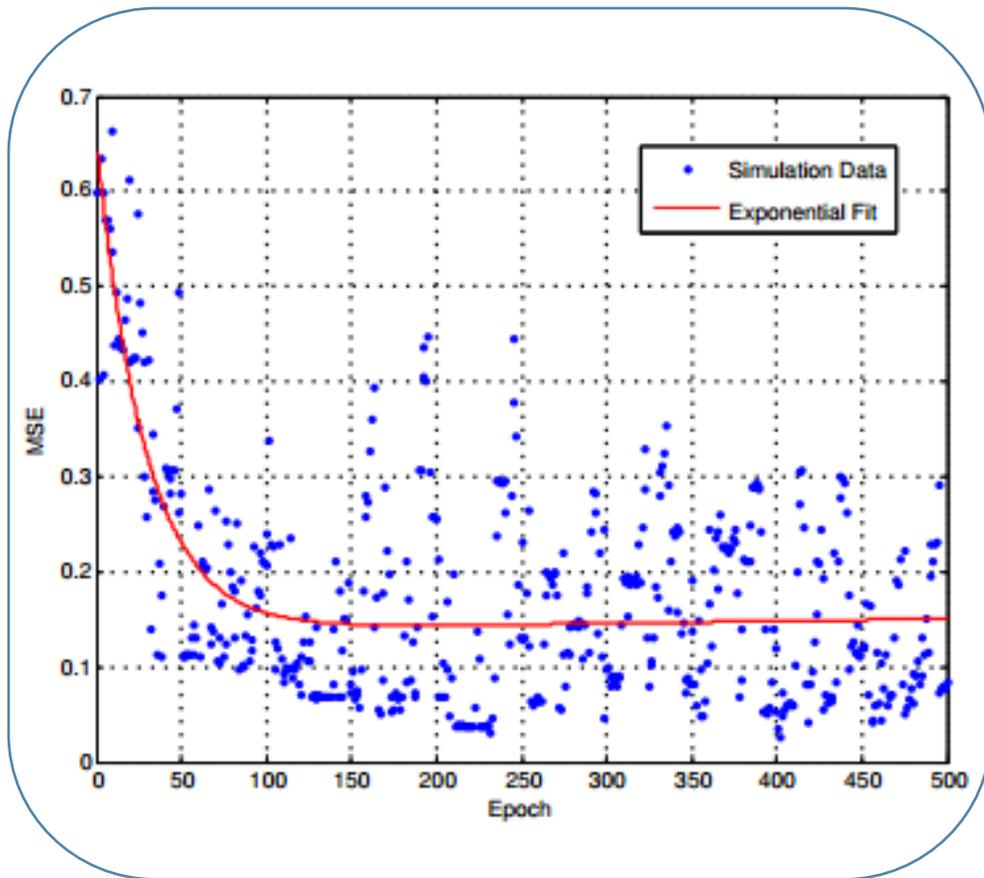


Power Consumption



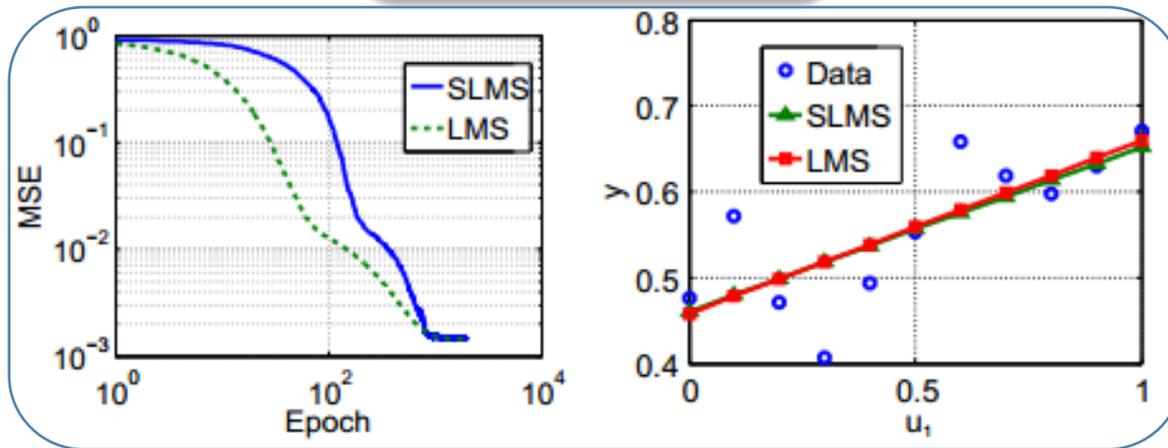
Vision

Visual Feature Extraction

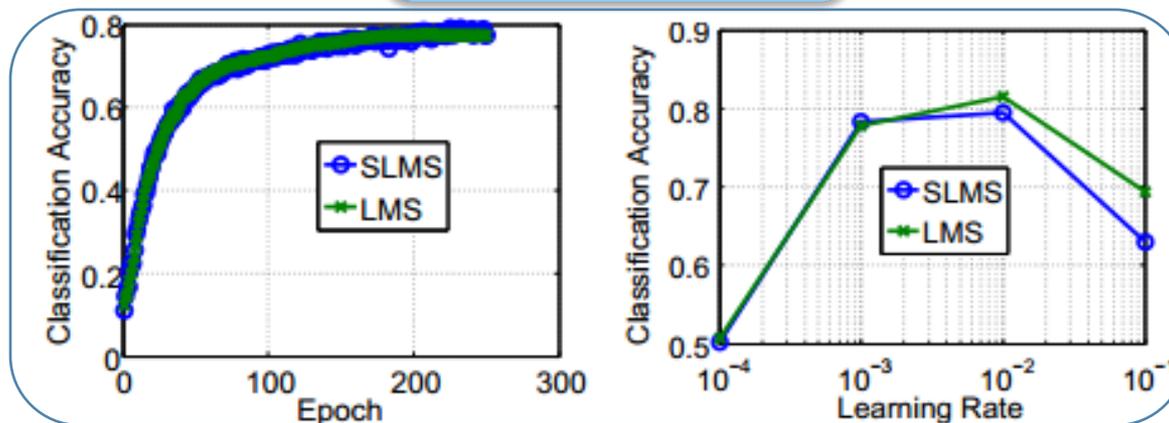


Linear and Logistic Regression

Linear Regression



MNIST Classification



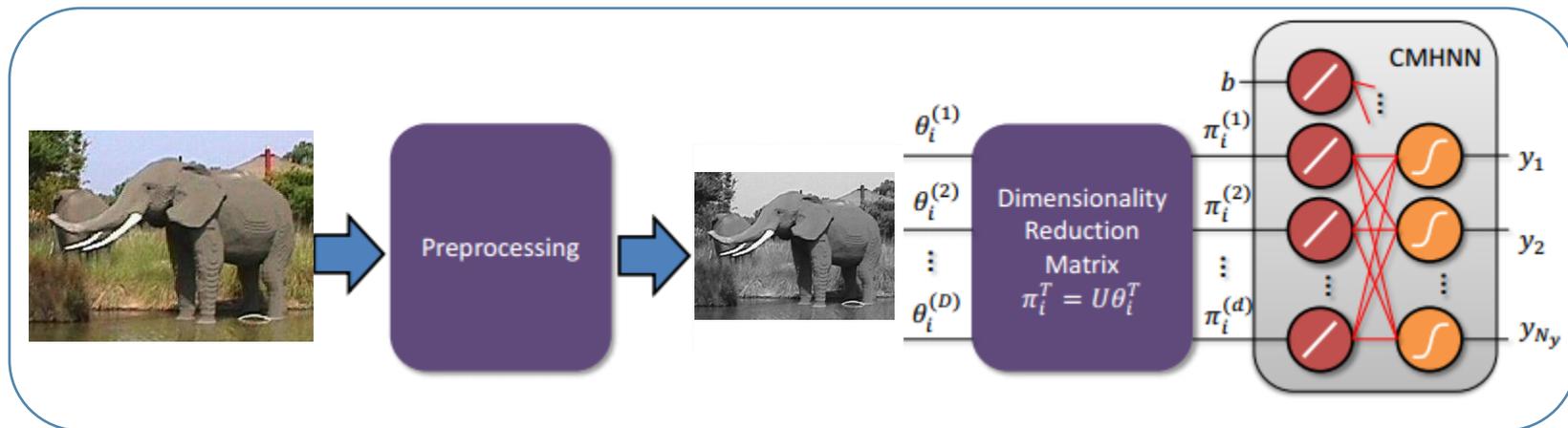
SOCC 2014

Stochastic training algorithms reduce the implementation cost (> 3X area reduction) of regression problems on neuromemristive substrate

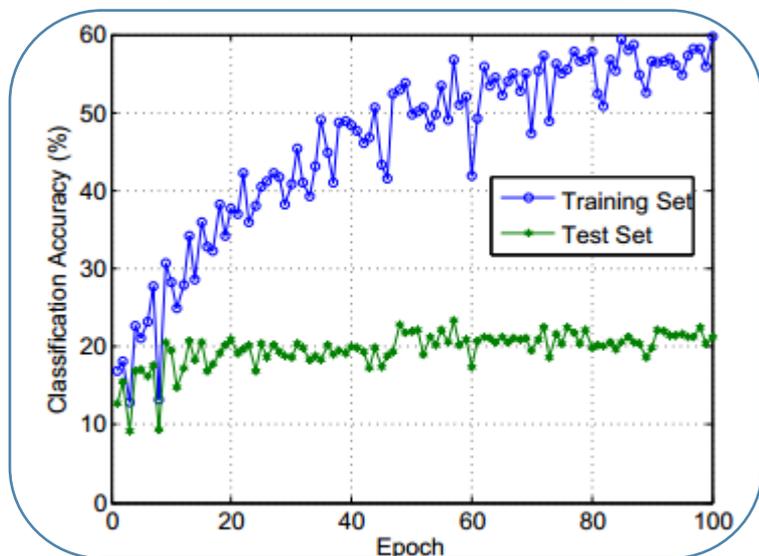
Caltech101 Dataset after Preprocessing



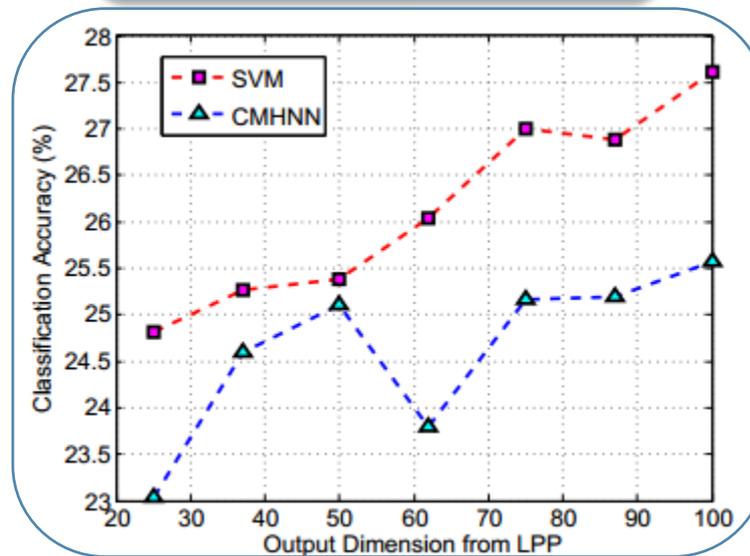
Real-time Target Classification



Classification Accuracy

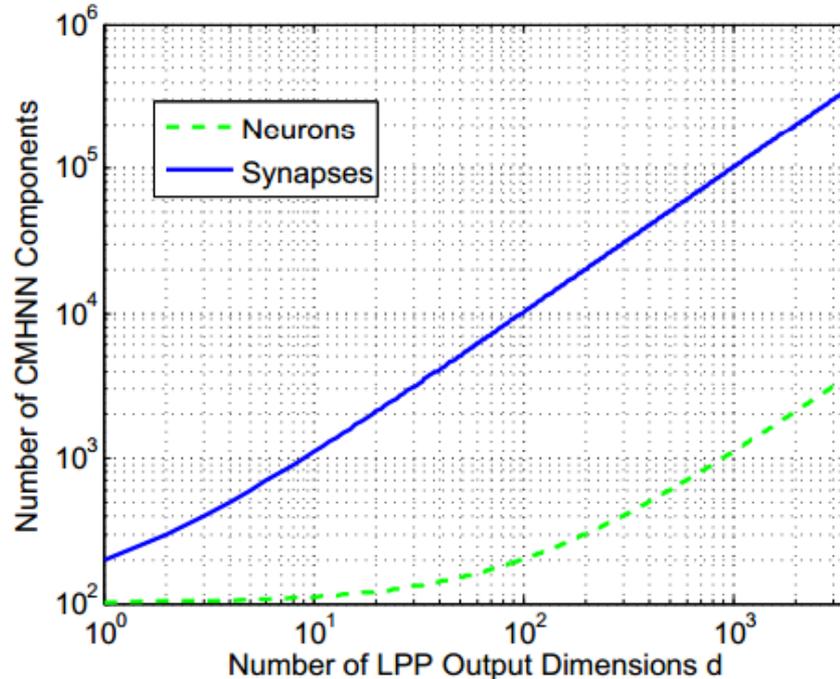


Dimensionality Reduction



Area Cost

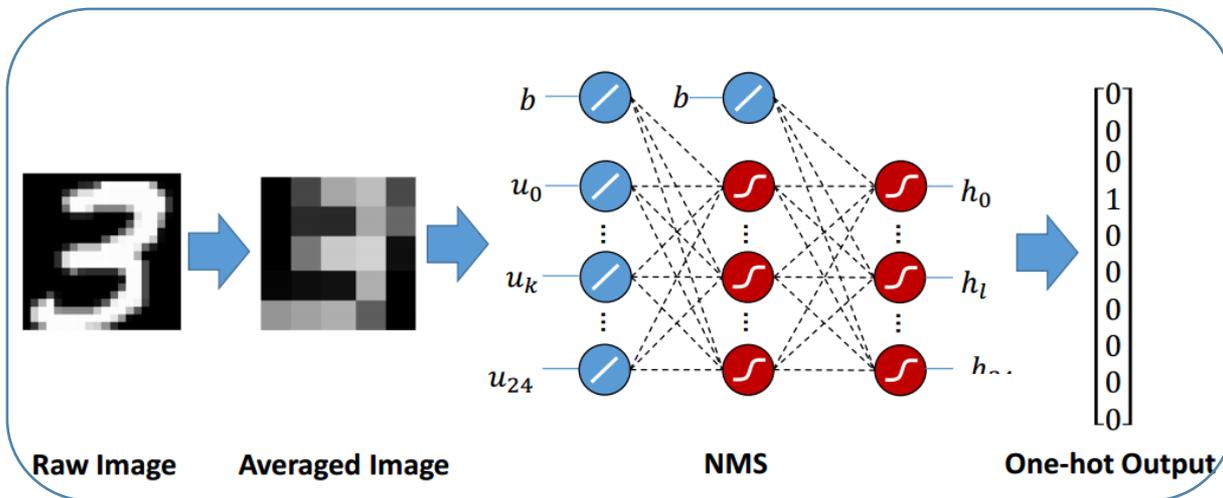
- Area cost increases with more dimensions



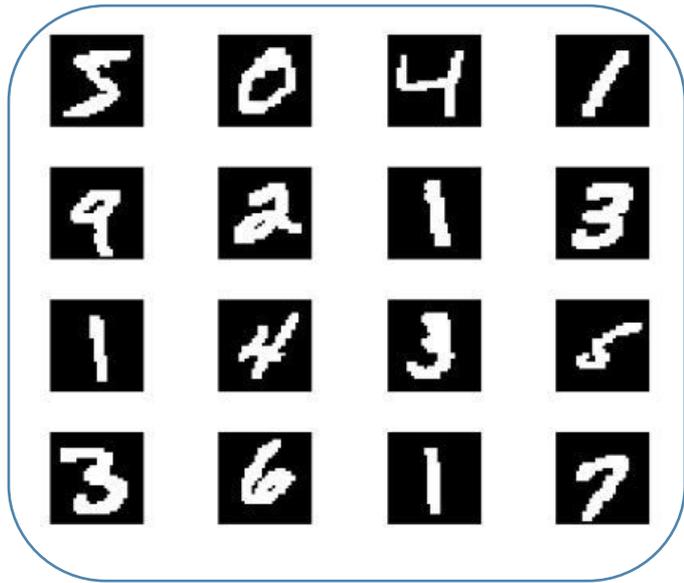
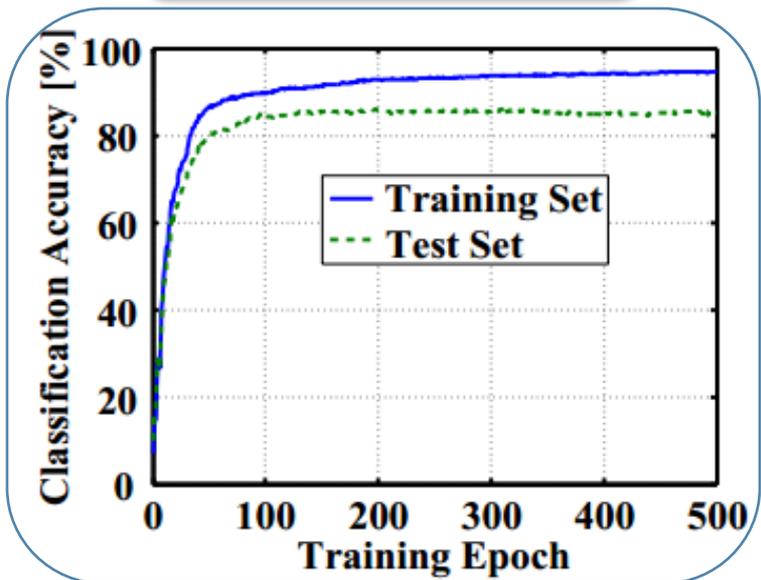
SOCC 2014

- By reducing from $60 \times 60 = 3600$ dimensions to 100 dimensions, we get a **97% reduction** in the size

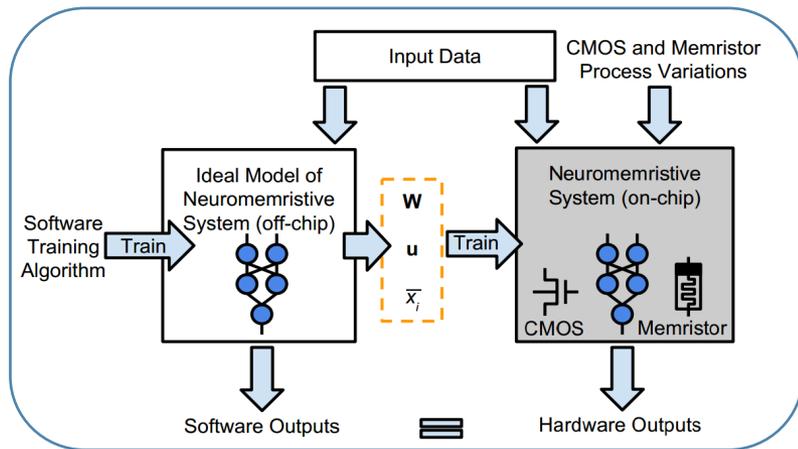
Classification with On-Chip Training



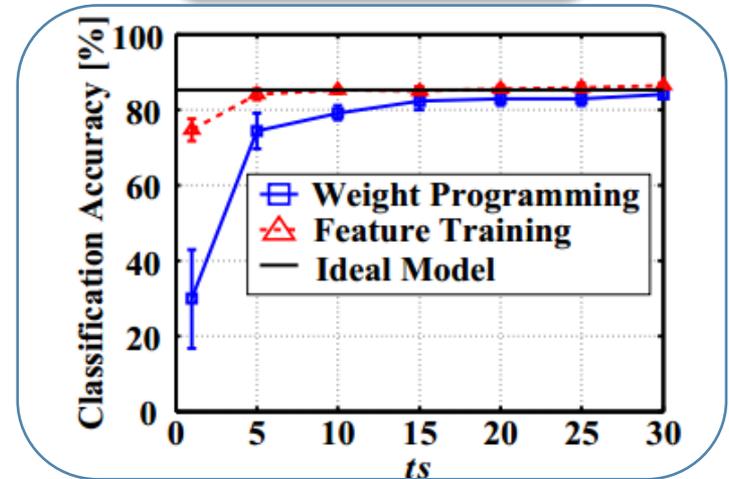
Classification Accuracy



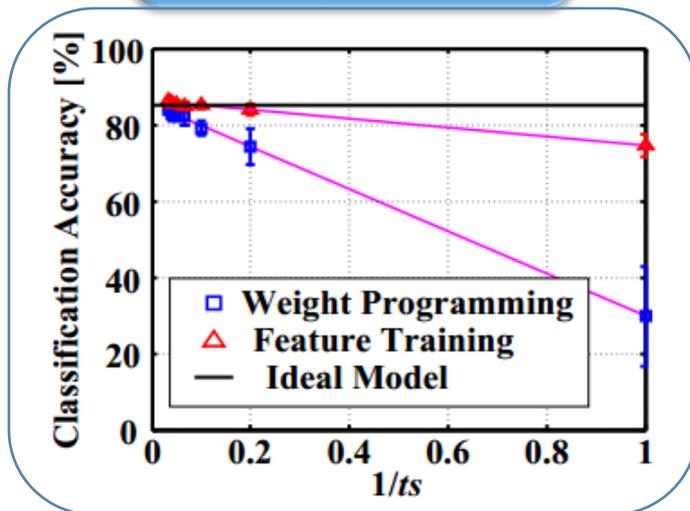
Classification with On-chip Variations



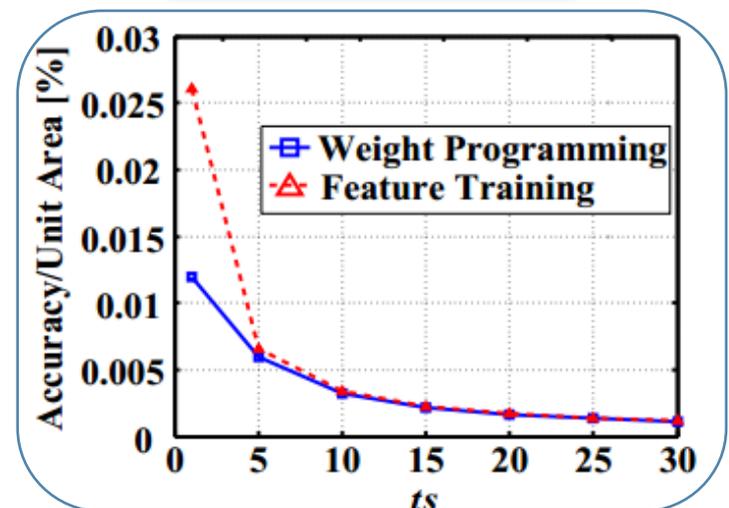
Accuracy vs. Area



Accuracy vs. Area⁻¹



Accuracy/Unit area



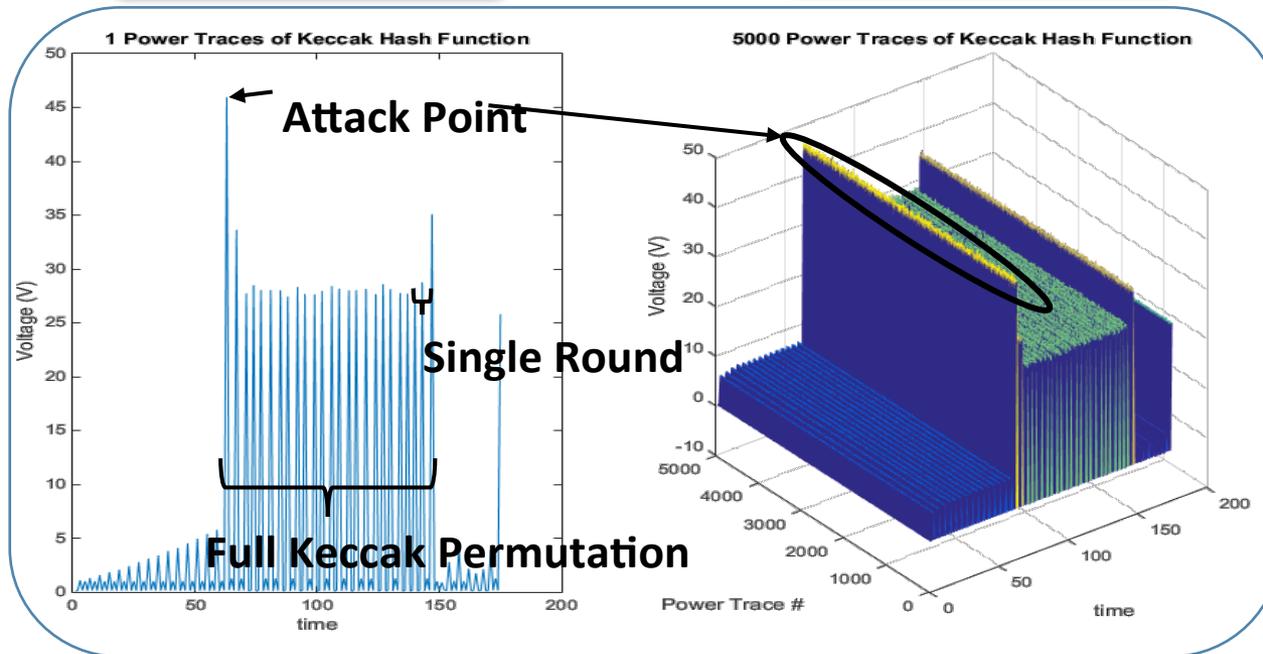
Secure Neuromemristive Primitives

Countermeasures for Power Attacks

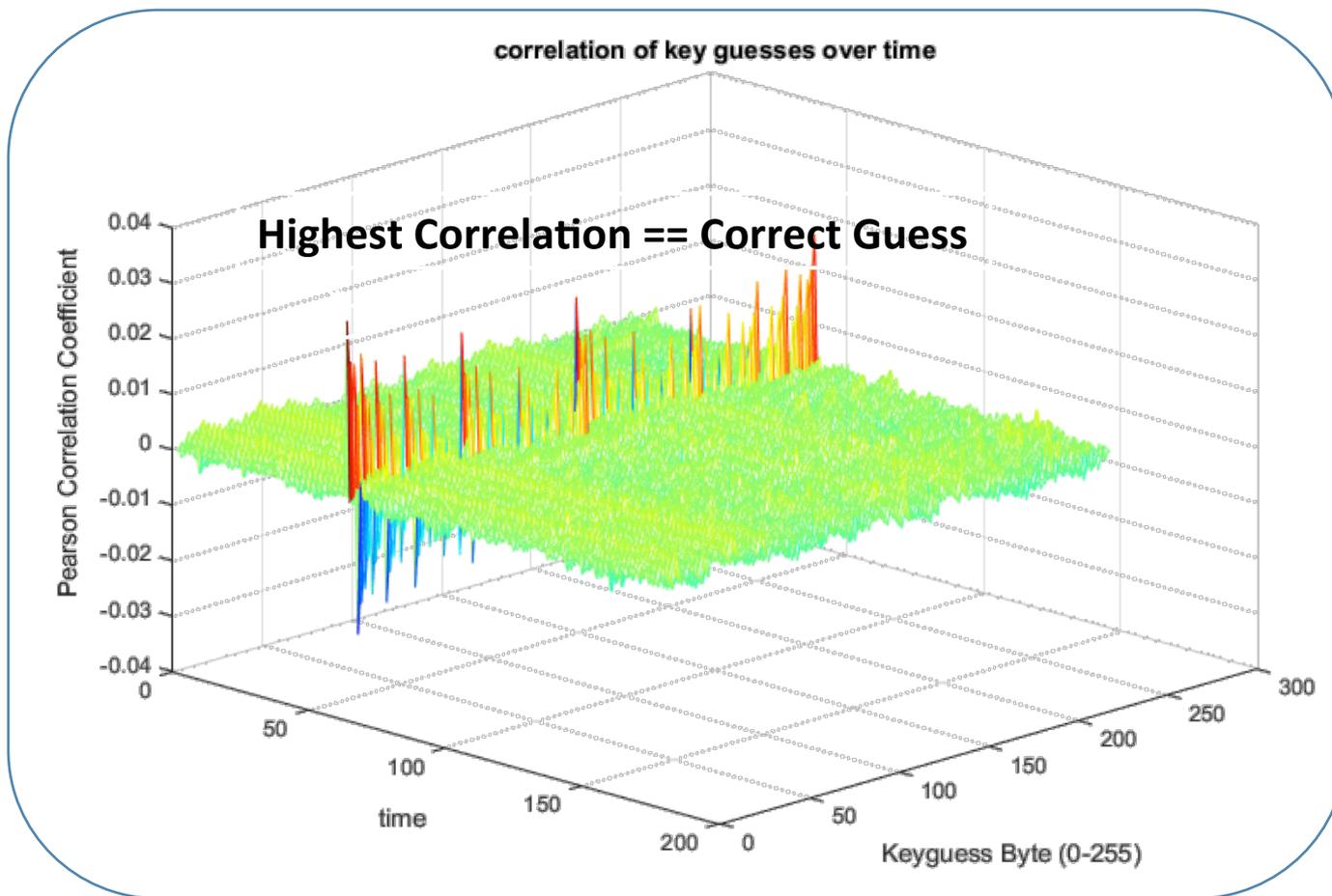
Keccak Algorithm Implementation SHA-3

Single Trace

Multiple Trace



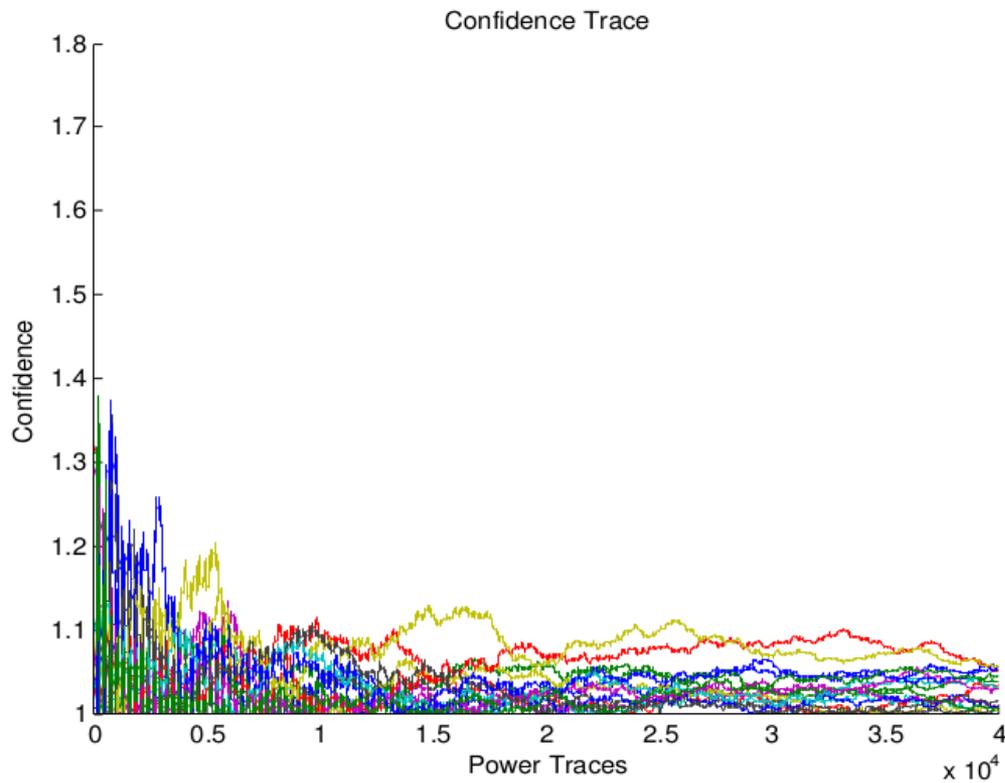
Correlation Power Analysis Attack



Correlation Power Analysis Attack

8:48:1 Network S-Box

Using a Hamming Weight leakage model, no keys were successfully guessed after 40,000 traces



SPIE 2014

Looking Forward

- Circuit models/architectures embedded in small scale systems
 - Simulation complexity of circuit models
 - Neurogenesis/Neuronal Pruning
- Nature vs. Nurture
- It is yet to be seen where neuromorphic/neuromemristive systems will make a large impact
- No (good) standard metrics



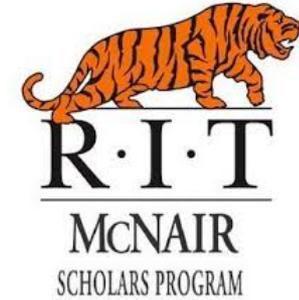
“Once we accept our limits, we can go beyond them” —Albert Einstein

Mind in Motion @ Dr. Miguel Nicolelis
FIFA 2014, Exoskeleton

NanoComputing Research Lab Team



Acknowledgements



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ENERGY