THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

ASIC-based Artificial Neural Networks for Size, Weight, and Power Constrained Applications

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Agenda

- **Nano-Enabled Computing**
- **Neuromorphic Computing**
- **ASIC Artificial Neural Networks**
- **Computational Intelligence Near the Sensor**
- **Neuromorphic Systems and Nanotechnology for Network Security**
- **Concluding Remarks**

Nano-Enabled Computing

Nano-science/technology is an enabling field:

- ❑ Multidisciplinary
- ❑ Applications across technologies

Concentrated on computational architectures:

- ❑ Size, Weight, and Power (SWaP) – Energy efficiency, capture, storage , and distribution
- ❑ Memristive systems
- ❑ Neuromorphic computing
- ❑ Nanoelectronics research and testing
- ❑ Development of hybrid platforms
- ❑ Massively parallel processors

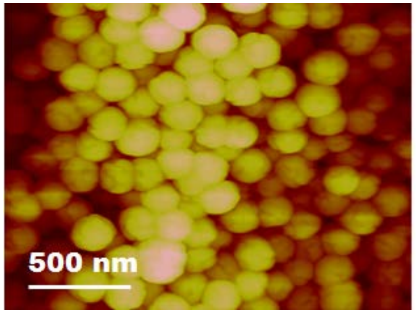
Shaping The Future of Information

Beyond Moore's Law

Mission: Develop advanced computational capabilities through the exploitation of nanotechnologies

Developmental approach:

- ❑ Basic research/needs analysis
- ❑ Modeling and simulation
- ❑ Systems design
- ❑ Fabrication and testing
- ❑ Integration and demonstration



AFM image of gold-coated SiO_2 nanoparticles AFRL – J. Appl. Physics (2012)

Disciplines include:

- Nano-scale Engineering
- Solid State Physics
- Computer Science
- Material Science
- Biochemistry
- High Performance Computing
- Chemistry

Neuromorphic Computing

Computational Intelligence

Autonomously finding patterns and reason in data/environment

Mission: Develop neuromorphic architectures with enhanced autonomy and perception

Emulate the computational methods of the brain:

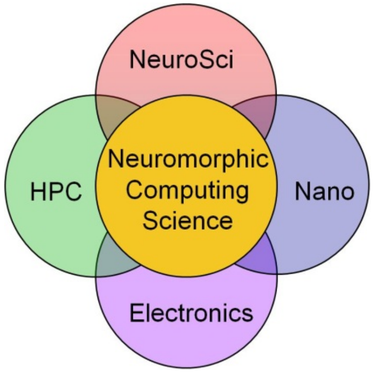
- ❑ **Explore the mechanisms the brain uses for sensory perception, memory, and cognitive capabilities.**
- ❑ **Chip technology based on brain mechanisms and structure, unrestrained by von Neumann architecture.**
- ❑ **Demonstrate SWaP efficiencies**

Multidisciplinary Approach:

- ❑ **Brain function and design**
- ❑ **Artificial Neural Networks**
- ❑ **Large scale modeling**
- ❑ **Memristive system research**
- ❑ **Nano architectures**

Disciplines Include:

- **High Performance Computing**
- **Engineering**
- **Neuroscience**
- **Brain Imagery / Cog. Psych.**
- **Computational Neuroscience**
- **Computer Science**



ASIC Artificial Neural Networks

Fully parallel, silicon based ANN chip

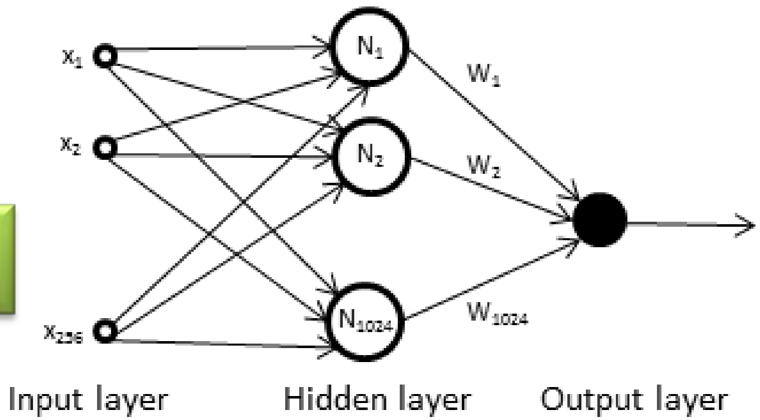
Two nonlinear classifiers:
- **K-Nearest Neighbor (KNN)**
- **Radial Basis Function (RBF)**

Scalable:
- **Same processing time**
- **Low power requirements**

CogniMem Technologies, Inc.

Mature technology when compared to memristive or synaptic designs

Signature/Pattern Recognition



General topology of Radial Basis Function (Restricted Coulomb Energy Network)

Confidence Interval -- Distance

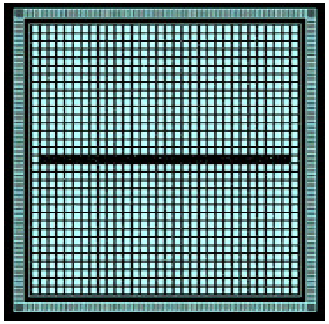
Two methods:

1. **Manhattan**

$$D_{Man} = \sum_{i=1}^{n} \left| V_i - P_i \right|,$$

2. **Lsup**

$$D_{L\sup} = Max \left| V_i - P_i \right|,$$



Plot of the CM1K ASIC
1024 identical & parallel neurons
256 byte signatures, 27 MHz

Future System Innovations:
- **Reconfigurable classifiers**
- **Non-volatile memory**
- **22 nm node fabrication**
  - **Faster processing speeds**
  - **More neurons/chip**
- **Increased neuronal memory**
- **Undo training capabilities**

Issues Facing Computing

Energy Efficient Systems

- DoD is nation's largest energy user
- Efficiency is a force multiplier
- High performance processing is in demand - real time, big data
  - Large power requirements
  - Large cooling requirements
- Autonomous Systems
- Computational Intelligence

Condor Cluster (AFRL)

1748 PlayStations, 500 Teraflops
300 to 320 kilowatts
Confabulation/Brain-State-in-a-Box

Extreme Scale Computing

- Energy/Power challenges
- Biggest obstacle to Eflops (Exa) is power
- Modern supercomputer
  - 4 - 6 MW
  - Enough to power over 5000 homes
- Eflop computer requires ~ 1 GW
  - Hoover Dam
  - Nuclear Power Plant
- IBM WATSON - 90 servers & 85,000 Watts
- Human Brain - 20 Watts
- More challenging when applied to:
  - SWaP constrained applications
  - Mobile platforms
  - Processing at the sensor

An MQ-1 Predator unmanned aircraft (USAF)

MARCbot IV
(Robotic Systems Joint Project Office)

Intrusion Detection for Remote and Mobile Platforms

The Sensor and Processing Disconnect

Biological Model

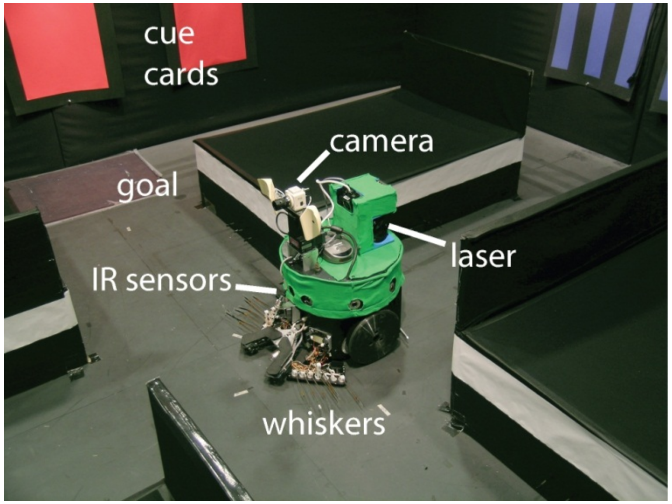
- Many sensors with parallel operation
  - Heavy on sensory processing
  - Relatively weak individual processors
- Low SWaP

- A fly for example
  - ~ 80000 sensory input sites
  - 338000 neurons
  - 98% neurons for sensory perception
  - Extreme flyer with little resource requirements

Current Technology Model

- Few sensors
- Relatively few but powerful processors
- Millions of lines of code
- Little measurements--heavy calculations

- F-35 for example
  - Handful of sensors
  - Nearly 6 million lines of code
  - 3 computers each with 2 PowerPC chips
  - Cooling required (uses SWaP)



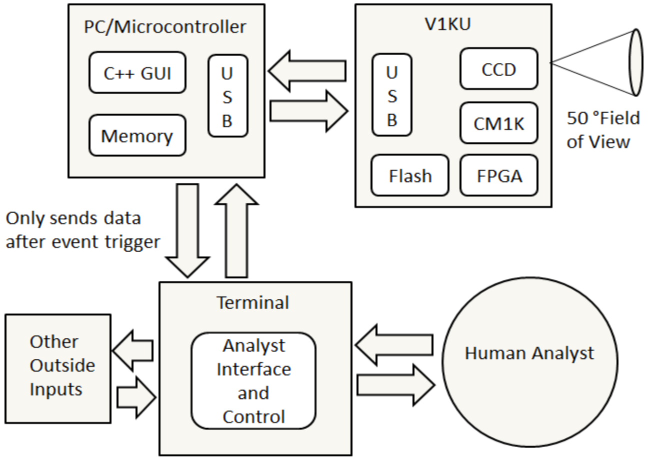
Brain Based Device in a dry land version of the Morris water-maze (The Neurosciences Institute)

F 35 Lightning II Joint Strike Fighter (USAF/AFMC)

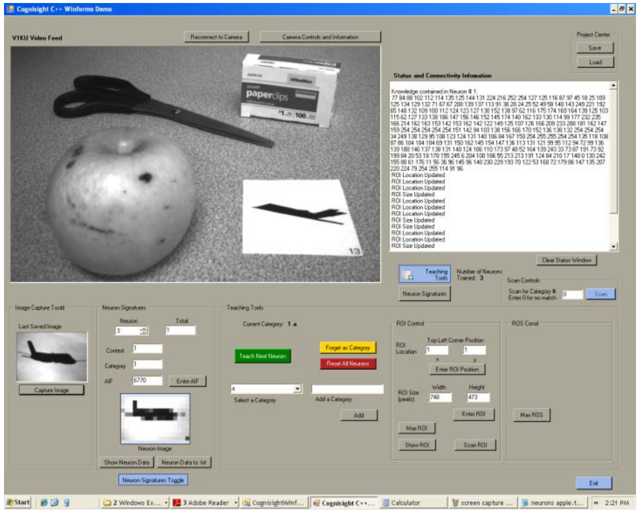
Computational Intelligence Near the Sensor

Mission Extension through Energy Efficiencies

- **Mobile wireless systems consume power**
- **Tedious data monitoring burdens analysts**
  - **Increased infrastructure required**
  - **Higher costs**
  - **Logistical burdens**
- **Hardware-based artificial neural networks on the platform**
  - **Communications hardware placed into standby**
  - **Frees the Analyst**
  - **Extends mission life**
  - **Notifies proper channels when triggered**



A block diagram depicting the system configuration



Screenshot showing the GUI interface

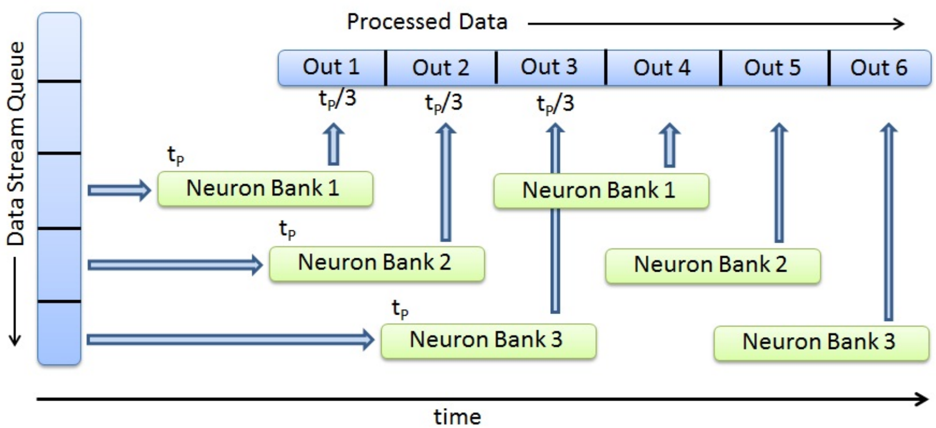
Change Detection System Test

- **Laboratory entrance way monitored by video for 36 hour period**
- **Simple single neuron network**
- **Trained to recognize closed door**
- **Notifies security upon unrecognized signature**
- **Identifying 26 intrusion events**
  - **Zero false positives**
  - **Zero missed occurrences.**

Processing Methods

Single Instruction Multiple Data (SIMD)

- Multiple processors performing the same operation but staggered in time
- Data throughput parallelism
- Banks of identically trained neurons
- Increased data rates
- Utilize surplus neurons for increased speed



The SIMD Process

Multiple Instruction Single Data (MISD)

- Many operations on same data at the same time
- Functional parallelism
- Each neuron in a bank has it own unique target signature
- Increased functionality and speed

Multiple Instruction Multiple Data (MIMD)

- Many sensors processed simultaneously
- Perceptual parallelism
- Distributed memory
- Biologically inspired

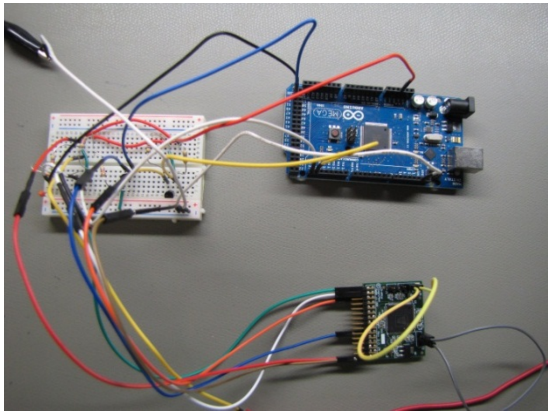
Serial Processing

- Allows for hierarchical structures
- Redundancy
- Decision trees
- Self learning

Neuromorphic Systems and Nanotechnology for Network Security

Network Monitoring

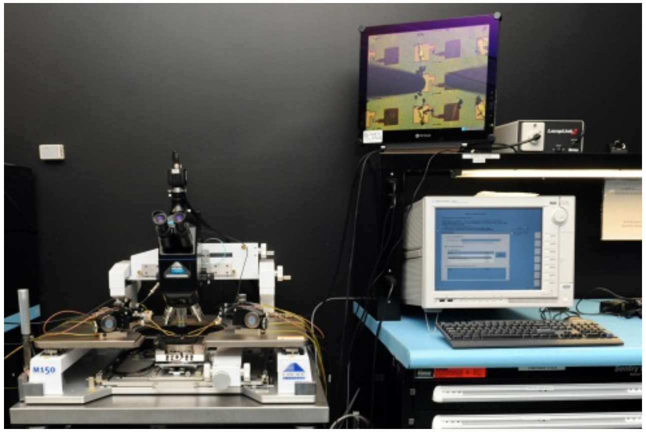
- Single Instruction Multiple Data for high speed monitoring
- Area of influence tuning to detect slightly altered signatures
  - Many attacks are alterations to known signatures
  - Detect key signature characteristics to alert analyst
- Energy efficient methods (~25 watts for 100,000 neurons)
  - Field applications
  - Mobile platforms
  - Security on the deployed system
- Exploit ability to self-teach and learn from experience & user interaction
  - Field trainable
  - Systems can teach and modify each other



Prototype of 1024 neuron data monitoring system using a CogniMem PM1K, Arduino microcontroller, data interface circuit

Unique System Identification

- Memristor-based unique chip identifier
- Physical Unclonable Functions (PUFs)
- Random number generator
- System/chip/device identification



Probe station & B1500A analyzer

100,000 Plus ANN

- Test & Evaluation big data analysis
- Control system for complex platforms
- Same technology for network security
- Find a signature among 100,000 in 10 μs
- Scalable to 1 million+ neurons
  - 0.13 Peta operations per second equivalent
  - 250 mW per 1,000 patterns

Collaborations with Services, Agencies, and Institutes

AFRL Directorates

- Space Vehicles Directorate
- Materials and Manufacturing Dir.
- Sensors Directorate

Industry

- SEMATECH
- Bio Inspired Technologies
- M. Alexander Nugent Consulting
- CogniMem Technologies, Inc.
- ICF International

Academia

- Boise State University
- Cornell University
- Polytechnic Institute of New York
- Rice University
- Union College
- University at Albany (CNSE)
- University of Pittsburgh

AFOSR

- Big Data Neuromorphic Computing
- Nano-memristor R&D
- Nano for Compressive Sensing

OSD

- The Neurosciences Institute (NSI)
  Brain-Based Devices for Neuromorphic Computer Systems

DARPA

- SyNAPSE Program
- Physical Intelligence Program

ARL

- Network Science Division
  Adelphi Laboratory Center
  Network security
  Intrusion detection

Concluding Remarks

- Initial phase focused on exploiting emerging memristive technology
- Additionally, commercial off the shelf technologies are being utilized to
  - Address near term applications
  - Understand architecture and system level issues
  - Guide future memristive technology research and development
- Application focus
  - Addressing shortfalls of the processing, exploitation and dissemination chain
  - Enhanced computer architectures for the test and evaluation community
  - Computational intelligence closer to the sensor
  - Cyber
    - Network monitoring
    - Unique system identification
    - Mission resiliency
    - Risk mitigation / vulnerability reduction