TU1A-1

Brain-Inspired Learning for Intelligent Spectrum Sensing

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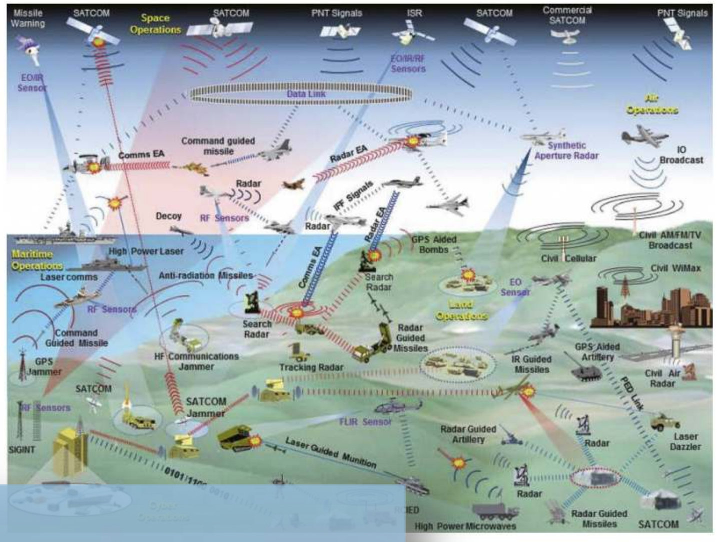
Texas A&M University

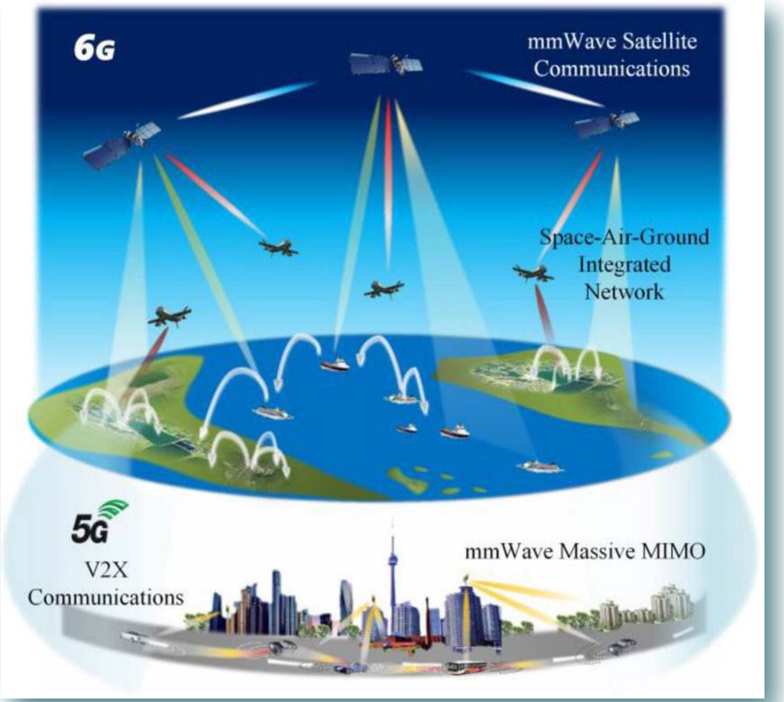
College Station TX

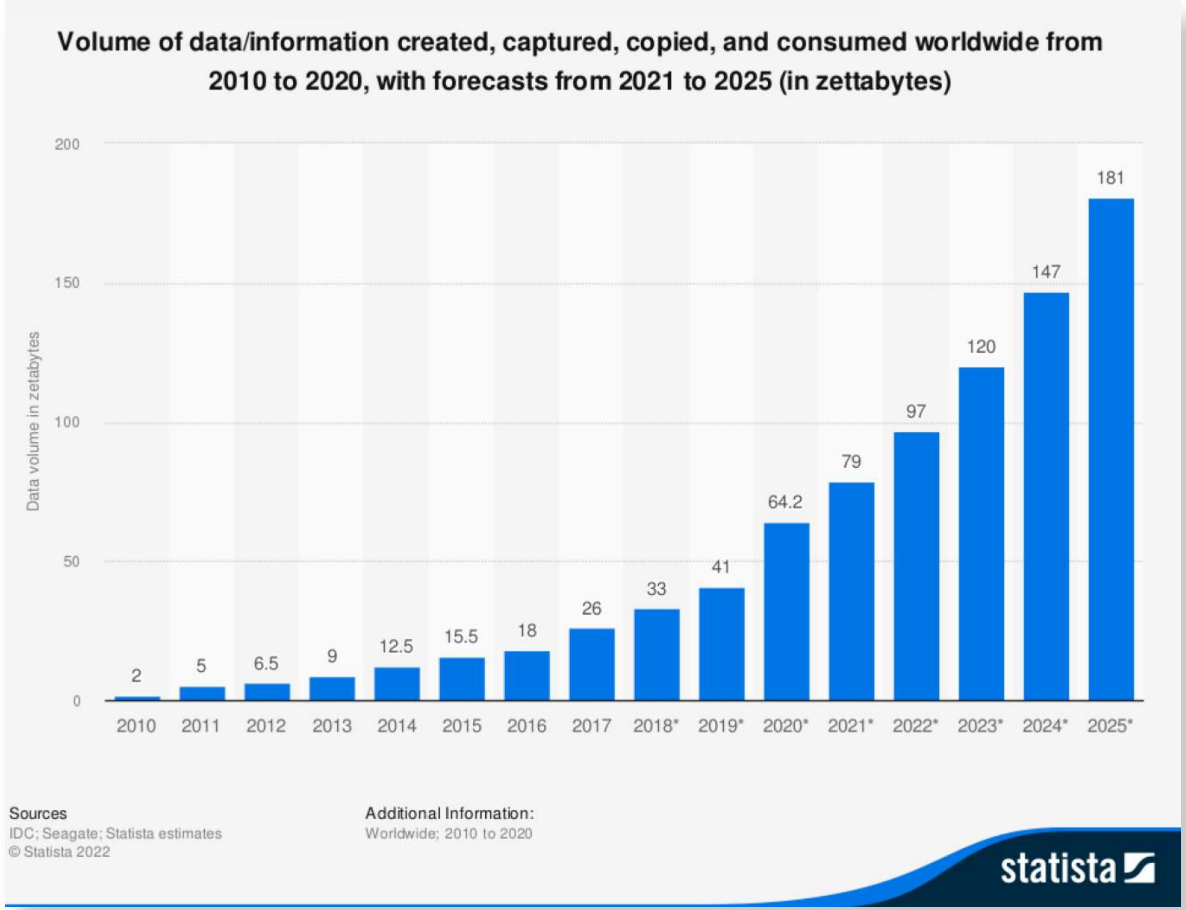
Spectrum on Demand

There are 3 x Earth's Population of active wireless users, according to Cisco, without satellites and military wireless systems

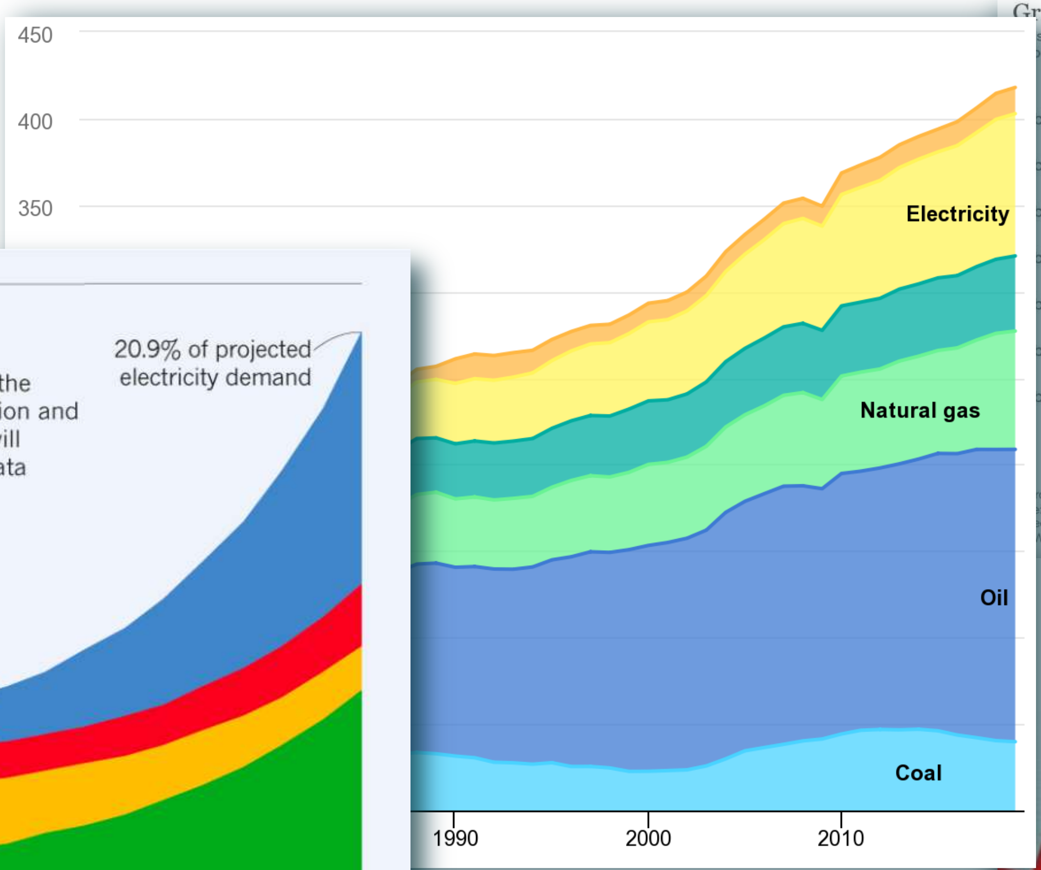


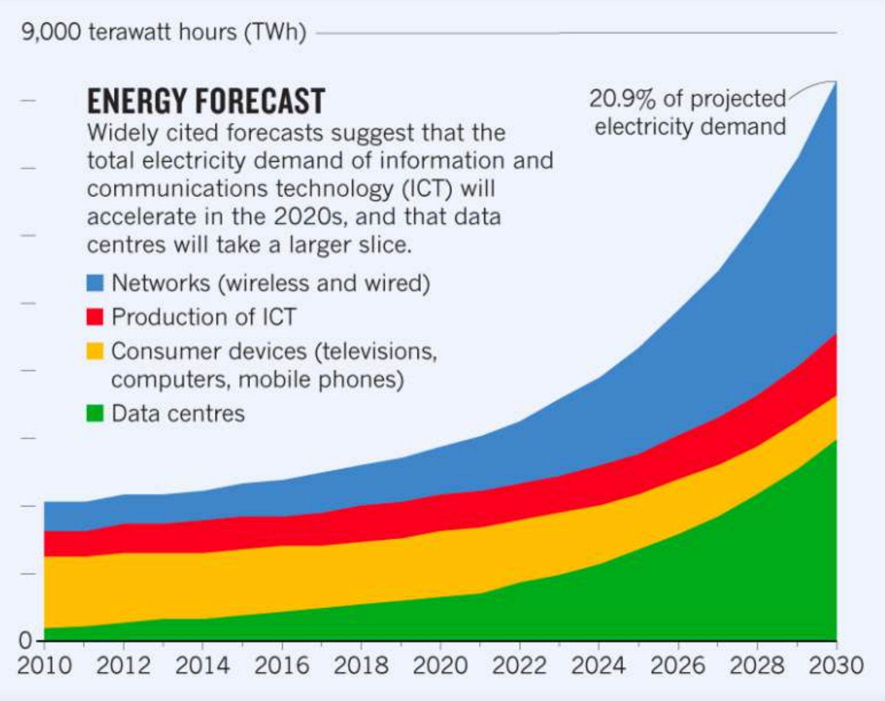
181 Zetta-Bytes (10^{21}) of Data

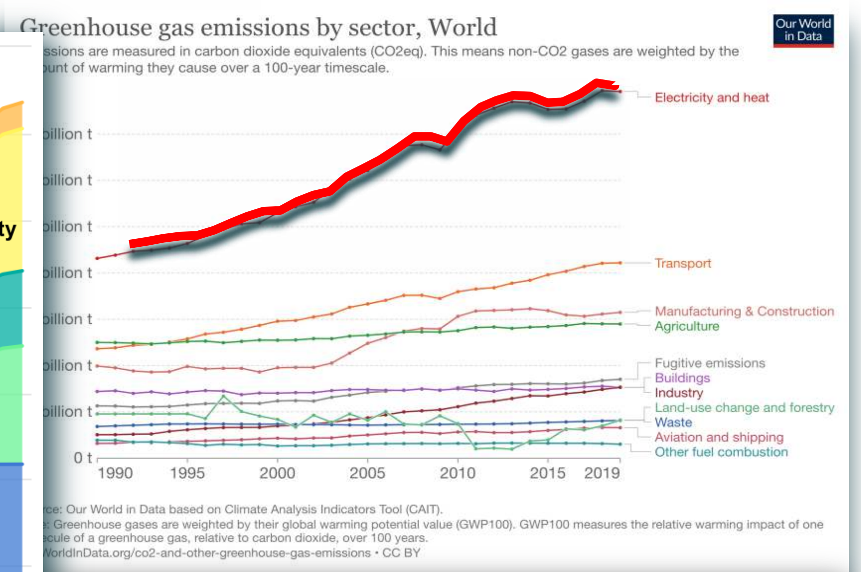




A Stealth Threat







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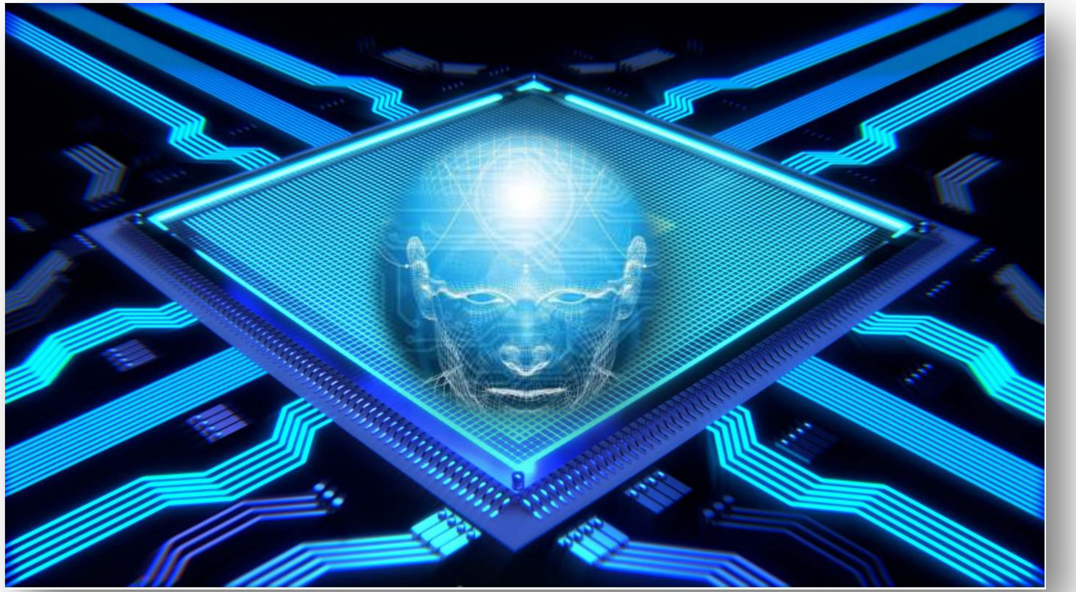
EDGE Intelligence: Response to the Energy Problem



Sensory Intelligence

- The Role of Sensing in Intelligent Systems
- The Architecture of a Neuro-inspired Intelligent System
    1. *Distributed Intelligence*
    2. *From Deterministic Systems to Stochastic*
    3. *An example of an Intelligent Sensor in 5G/6G: an Intelligent Receiver*

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Intelligence an Evolutionary Process

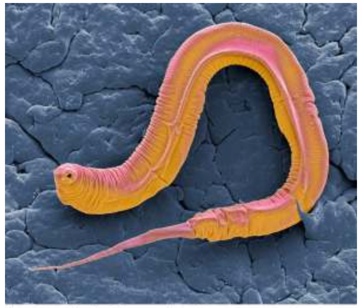
- *Cognition:* is the process of learning from experiences based on a robust set of capabilities and policies or ethics
- *Intelligence:* is the manifestation of cognition resulting in the ability to independently decide

  - *Nature:* Real-time recognition of various species is performed in distributed centers
  - *Distributed Processes:* Locally (on the skin) vs. Centrally (in the Central Brain)

What do we know about Brains?

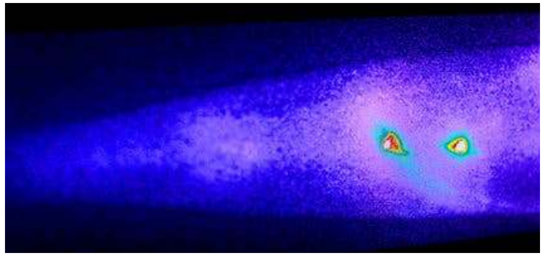
We know that Nature has gifted every
A living organism has a brain that learns
via repetitive actions

From small and simple

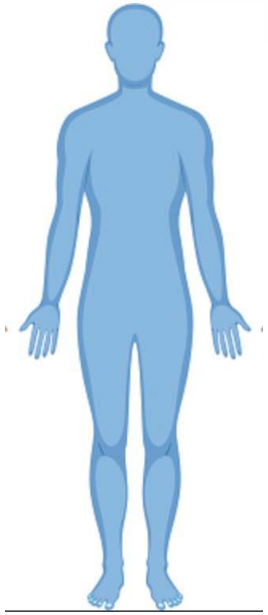


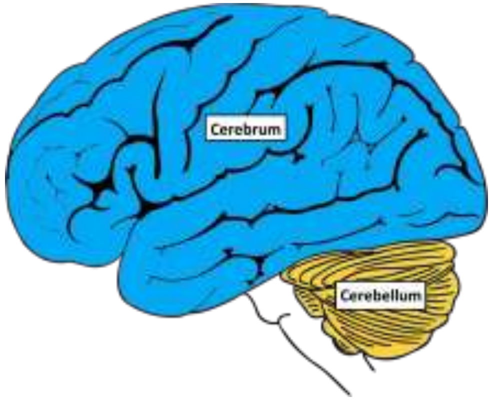
The neural network of the C. elegans roundworm is a mystery no more. Steve

Round Worm
305 Neurons
17,000 synapses

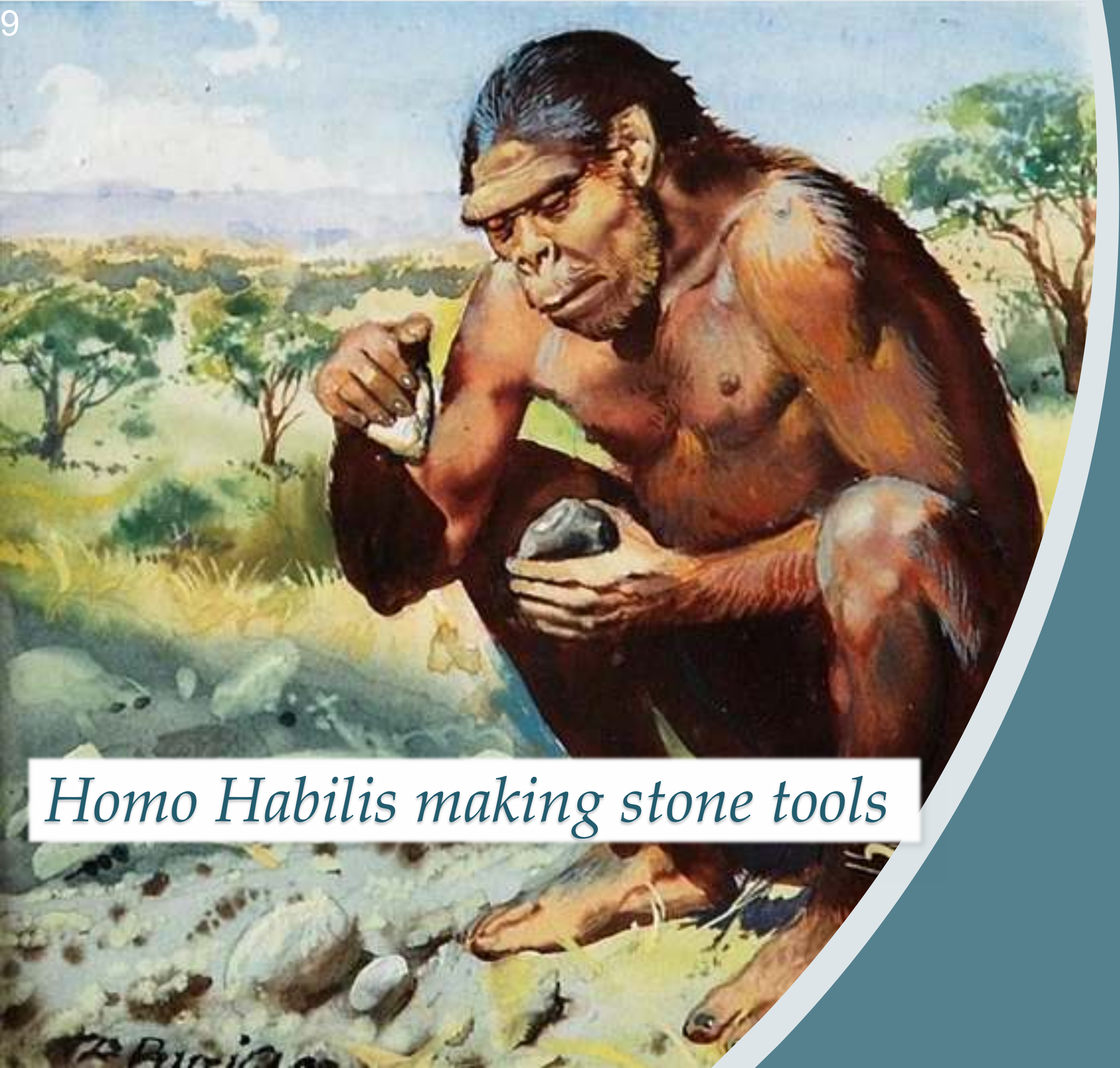


To large and complex





69 billion neurons



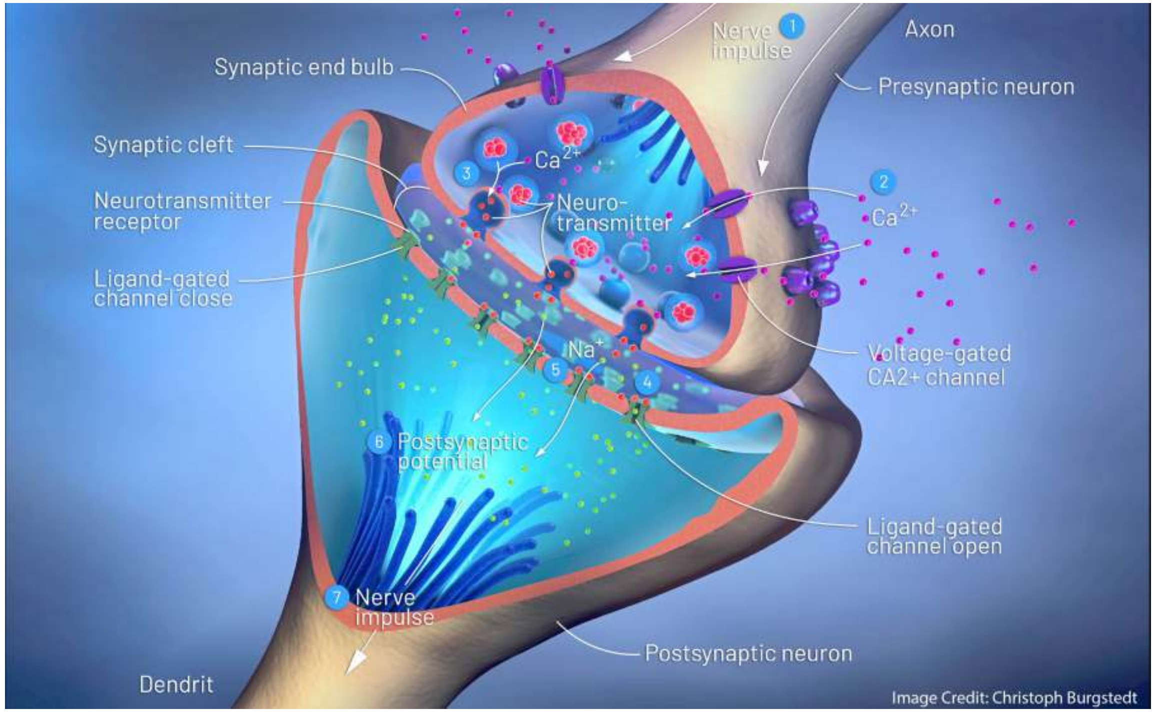
Homo Habilis making stone tools

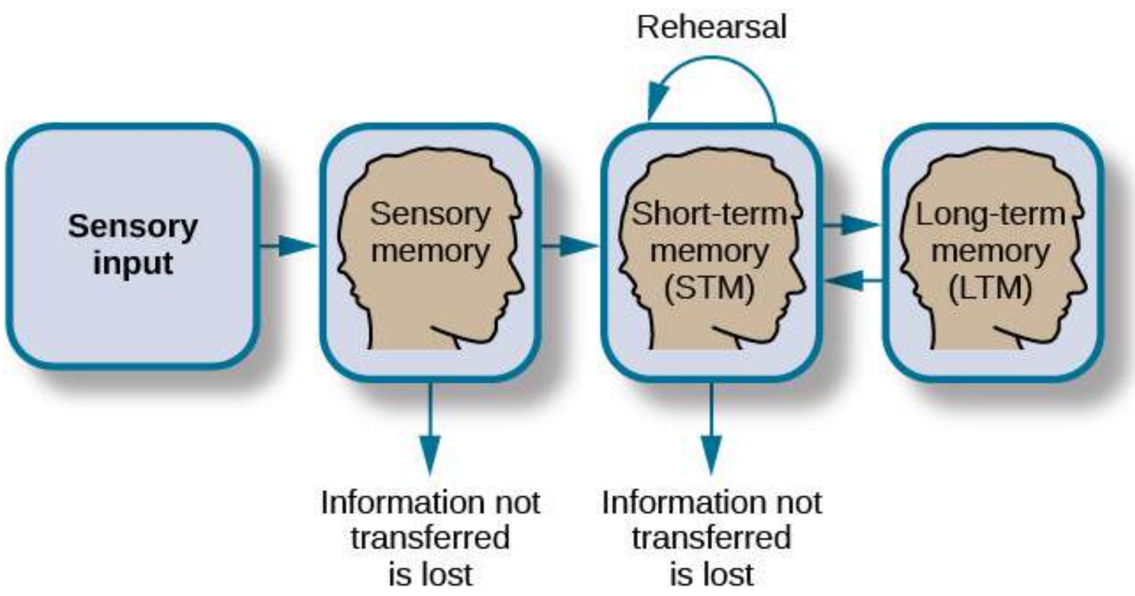
Human Intelligence
vs.
Learning

During the past 1.5 million years of evolution, the repetitive actions required by the stone toll greatly increased the cerebellum's size.

The communication between the cerebellum and cerebral cortex led to the development of working memory, innovation, creativity, and cognitive efficiency.

From Sensory Input to Memory





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The Amazing Field of Neuro-design

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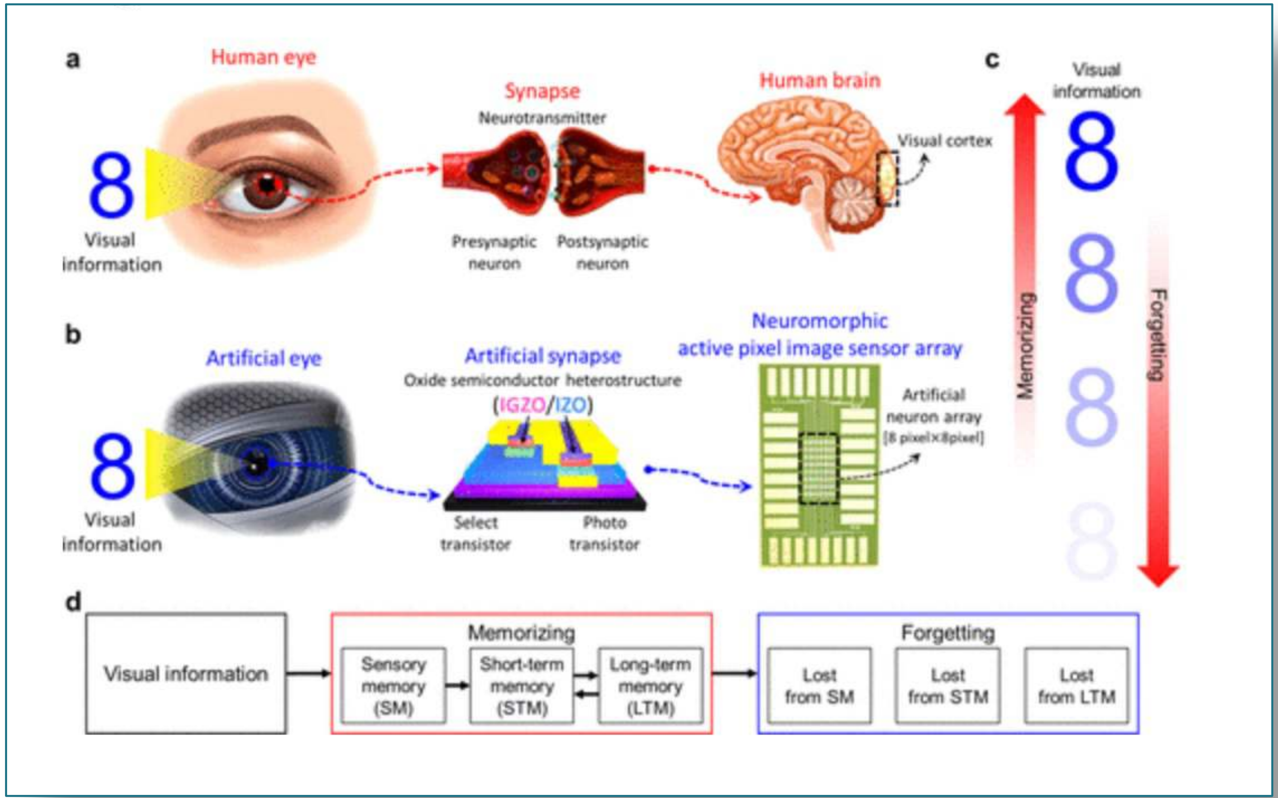

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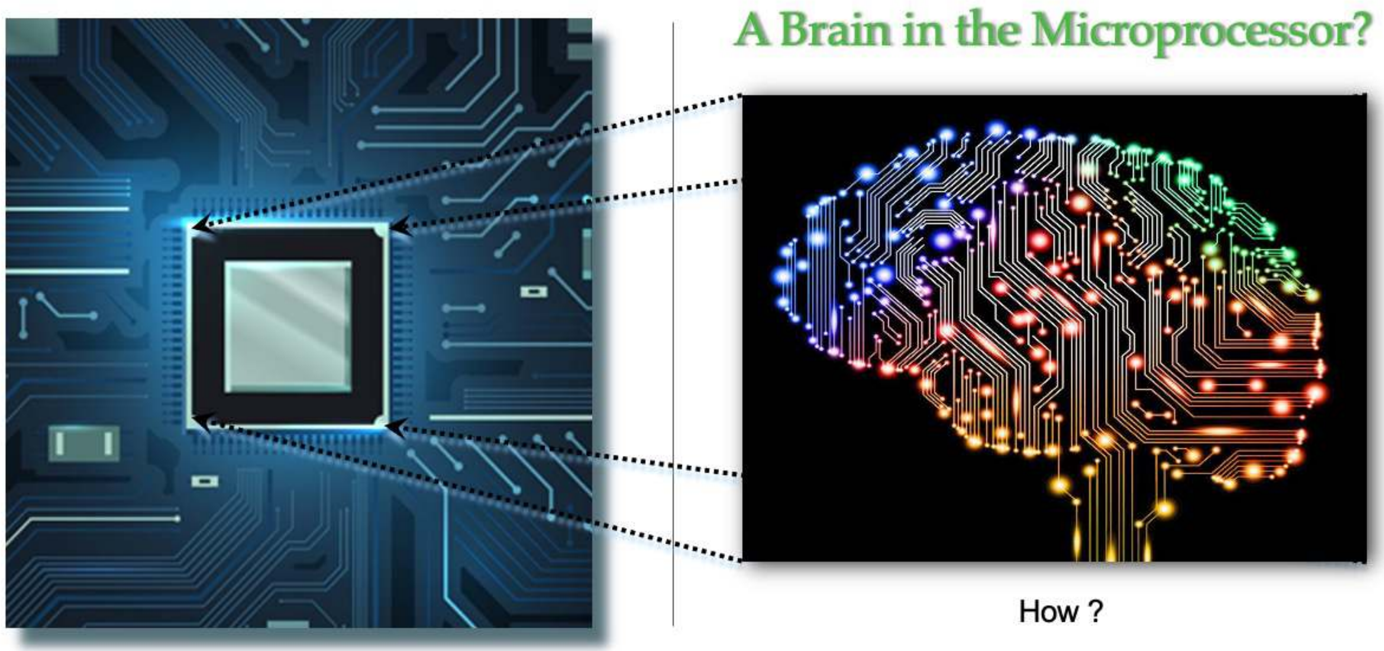
How does the Brain Work?



Hardware

+

Embedded Software

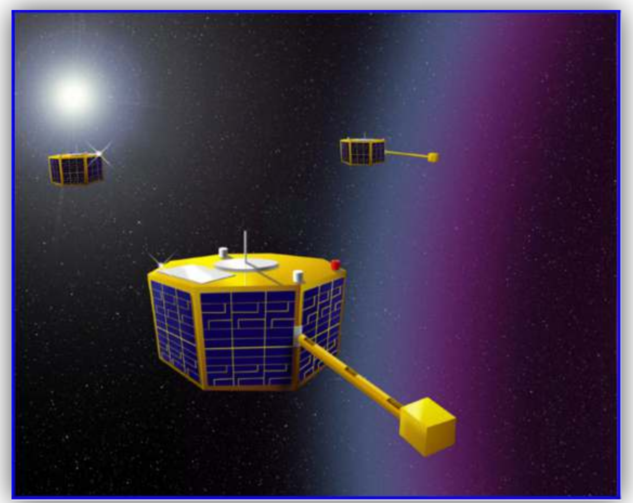
+

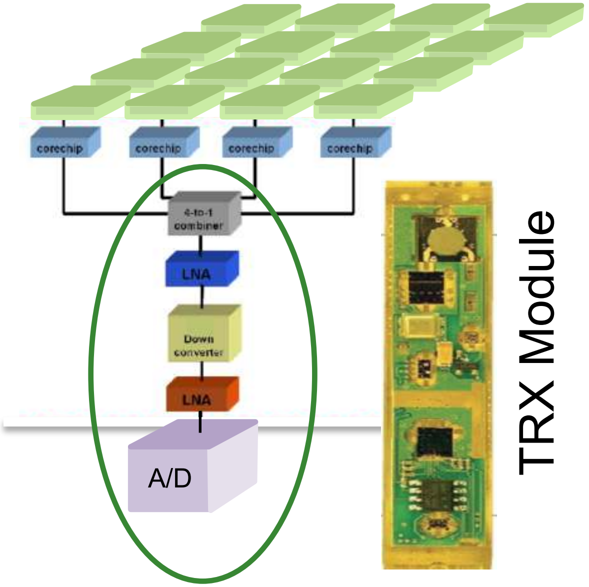
Hierarchical Policies

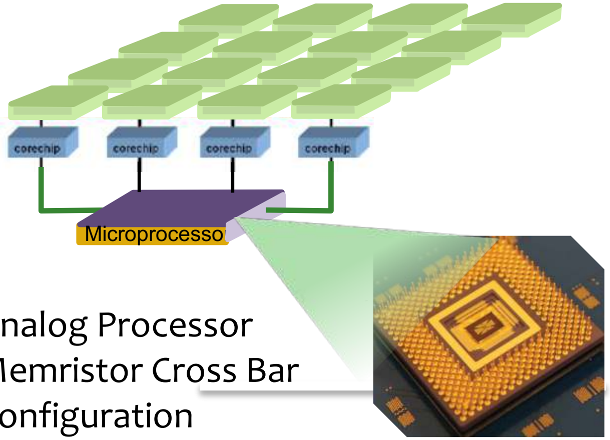
↓

Unsupervised Learning

Deterministic vs. Stochastic Systems







Analog Processor
Memristor Cross Bar
Configuration

Deterministic Engine

Analog Signal → RF Front End → Unique output

Controlled Operating Conditions

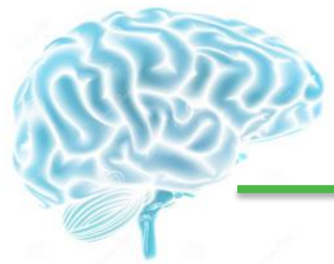
Stochastic Engine

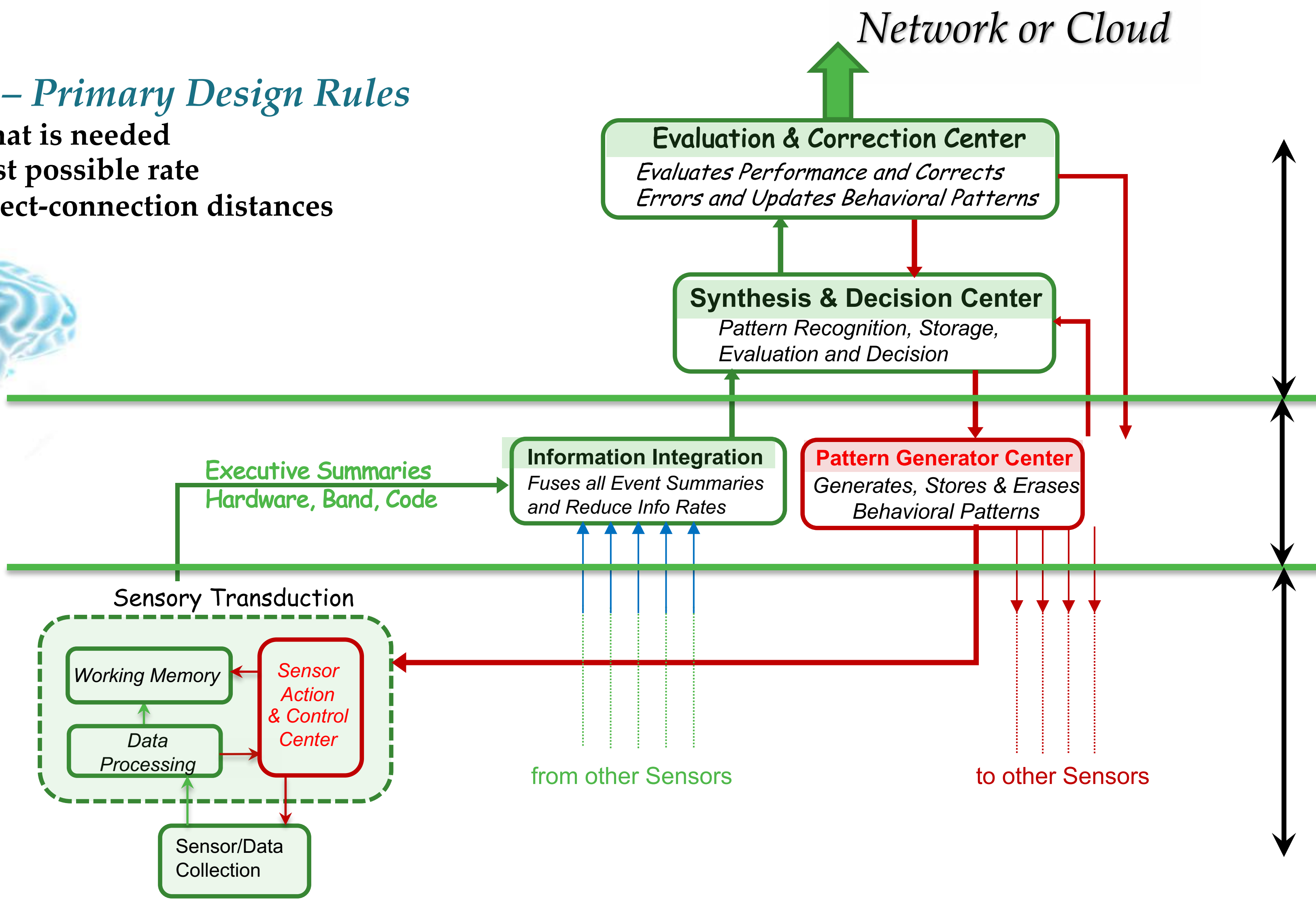
Analog → Micro-processor → Statistical

Operating Conditions randomized by uncertainty

Distributed Intelligence Architecture

Human Brain – Primary Design Rules
- Send only what is needed
- Send at lowest possible rate
- Minimize direct-connection distances





Platform
Decision Making and Action

Platform
Information Fusion

Sensors
Data to Information

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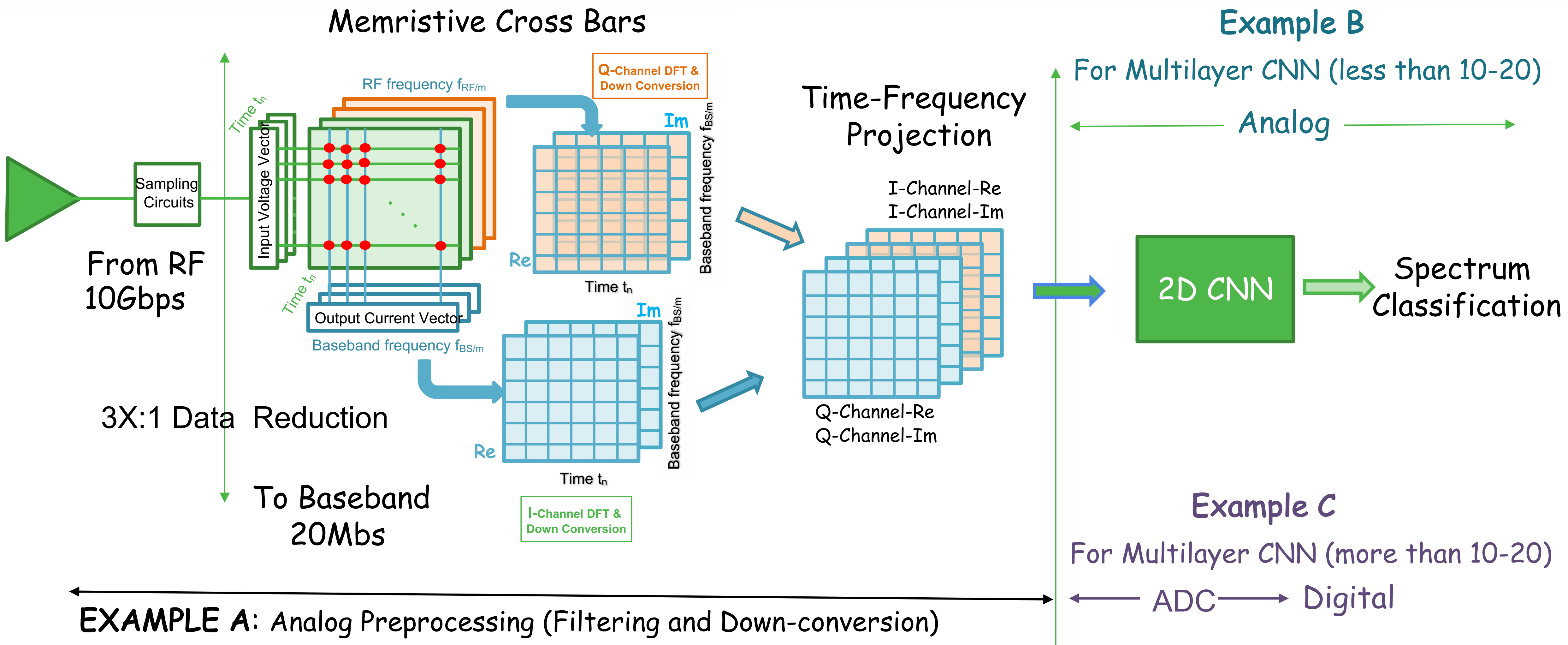
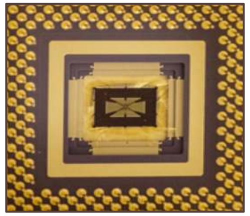
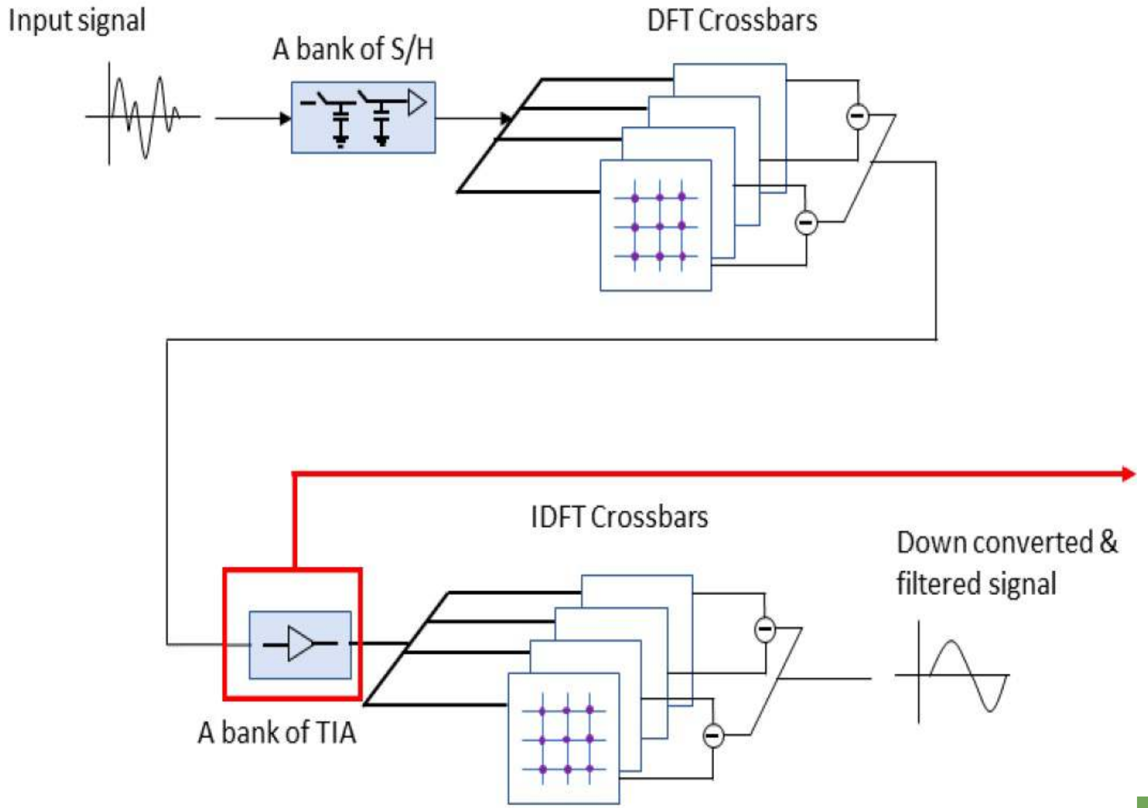
Sensory Transduction: 100X to 1000X reduction in Bits/sec

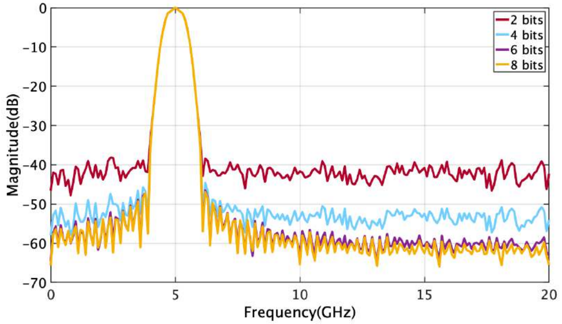


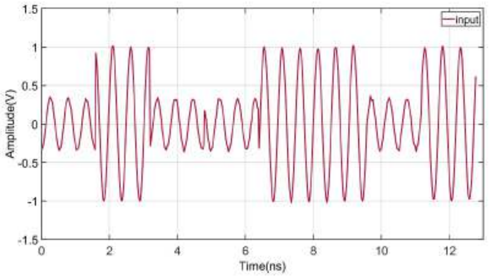
Intelligent Spectrum Sensing



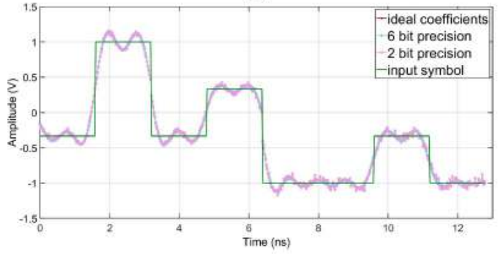
Cross-Bar Filter



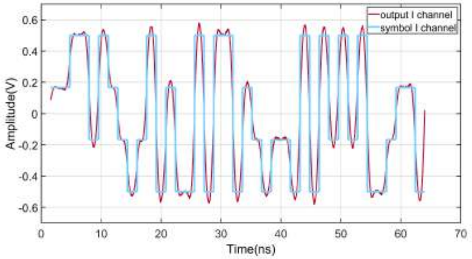




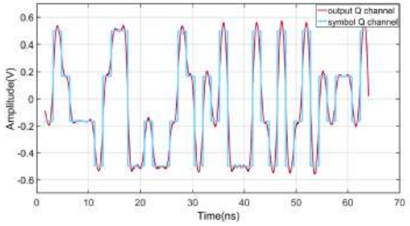
(a)



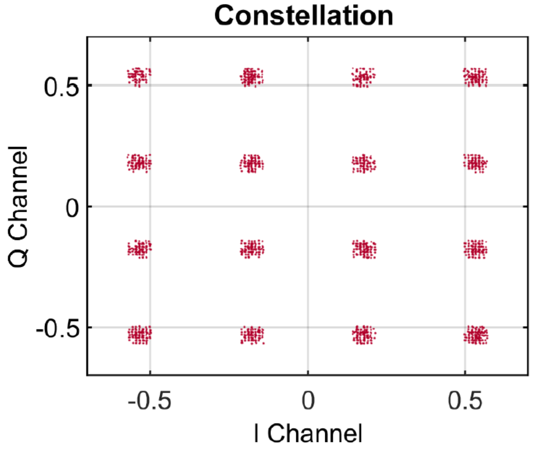
(b)



(a)

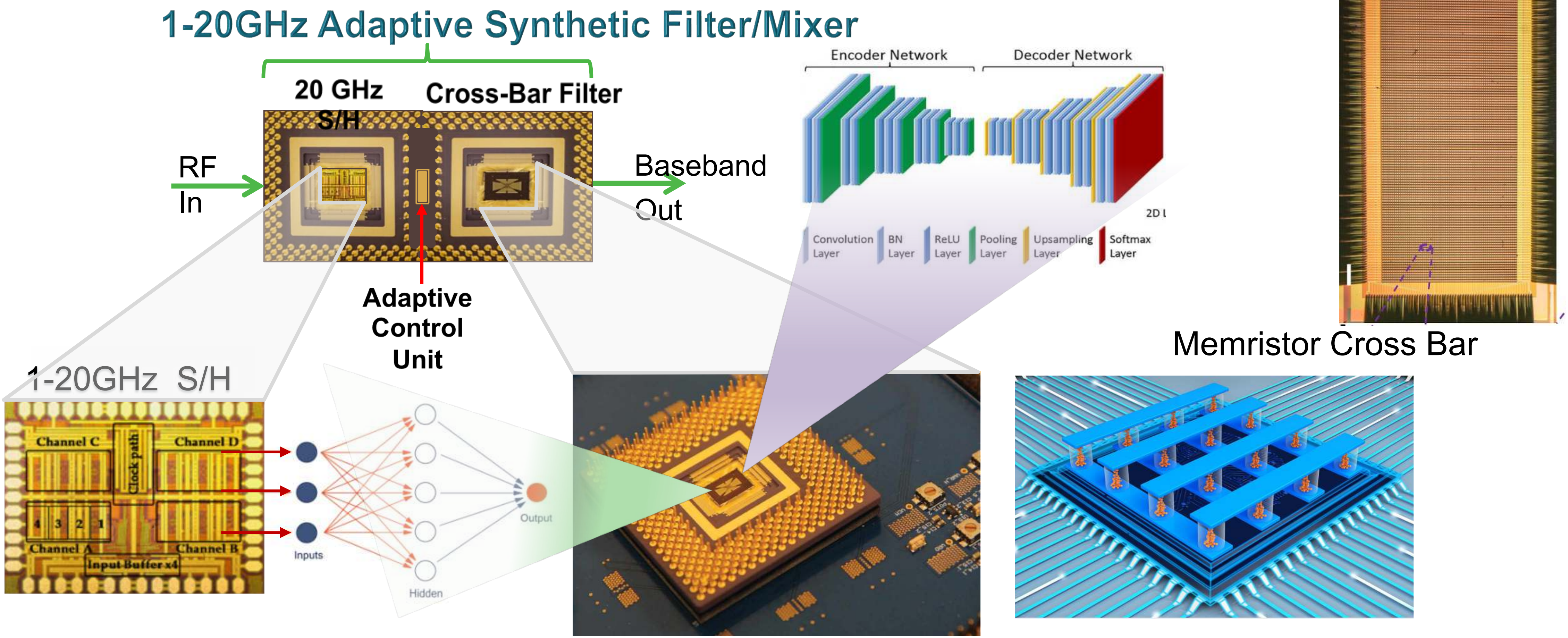


(b)



(c)

How do we Embed AI in Hardware?



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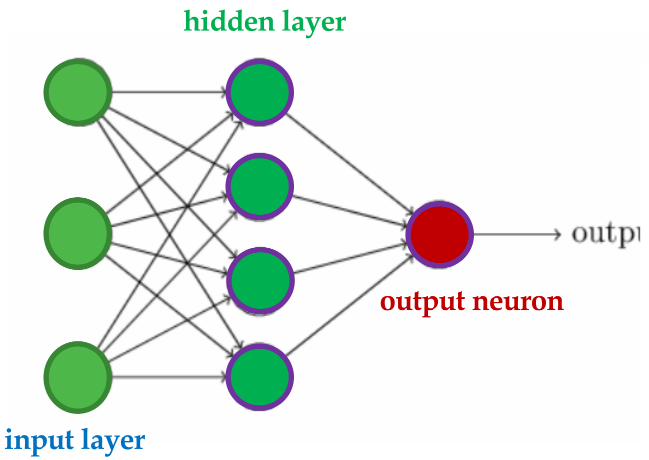
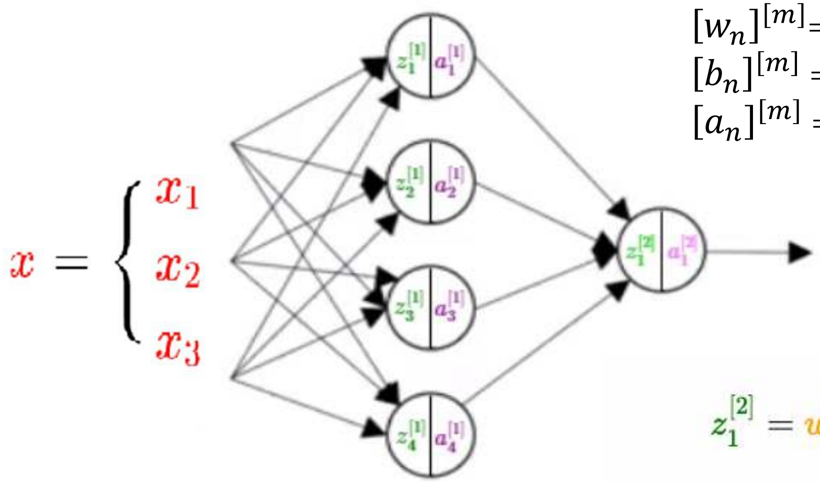
Single Layer Neural Network

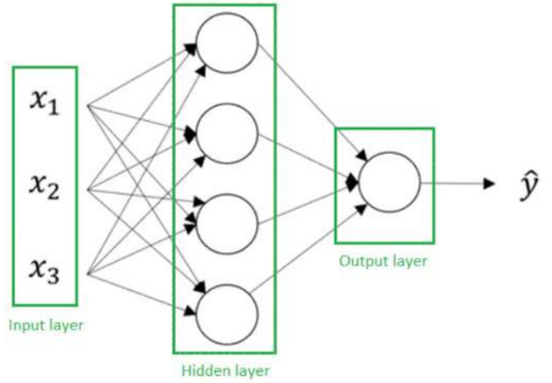




$[w_n]^{[m]}$= matrix of weights
$[b_n]^{[m]}$ =neuronal bias coefficients
$[a_n]^{[m]}$ = activation vectors

$$z_1^{[2]} = w_1^{[2]T} a^{[1]} + b_1^{[2]} \qquad a_1^{[2]} = \sigma(z_1^{[2]})$$

where $a^{[1]} = (a_1^{[1]}, \ldots, a_4^{[1]})^T$ and $w_1^{[2]} = (w_{1,1}^{[2]}, w_{1,2}^{[2]}, w_{1,3}^{[2]}, w_{1,4}^{[2]})^T$



$$\begin{cases} z_1^{[1]} = w_1^{[1]T} x + b_1^{[1]} & a_1^{[1]} = \sigma(z_1^{[1]}) \\ z_2^{[1]} = w_2^{[1]T} x + b_2^{[1]} & a_2^{[1]} = \sigma(z_2^{[1]}) \\ z_3^{[1]} = w_3^{[1]T} x + b_3^{[1]} & a_3^{[1]} = \sigma(z_3^{[1]}) \\ z_4^{[1]} = w_4^{[1]T} x + b_4^{[1]} & a_4^{[1]} = \sigma(z_4^{[1]}) \end{cases}$$

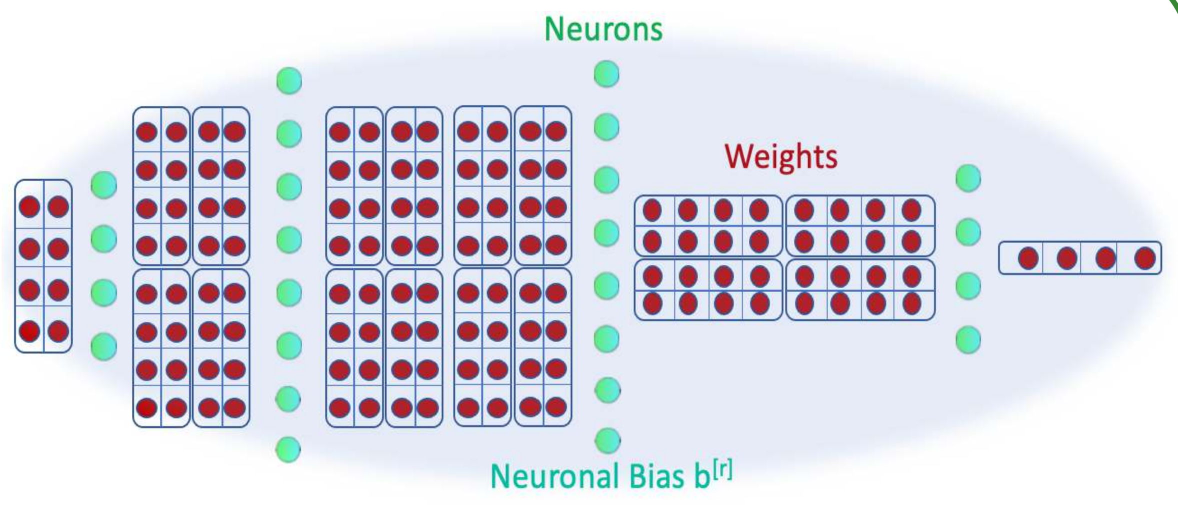
Characterization of a Non-Linear System

Similar Approach to the Koopman Operator Theory

Non-Linear System

Input

$[x_k \quad]$



Output

$y = a^{[m]}$

Linear Weights with Nonlinear Activations

$$
\begin{cases}
Z^{[1]} = W^{[1]}\mathbf{X} + b^{[1]} \\
A^{[1]} = \sigma(Z^{[2]}) \\
Z^{[2]} = W^{[2]}A^{[1]} + b^{[2]} \\
A^{[2]} = \sigma(Z^{[2]})
\end{cases}
$$

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Koopman Operator for Non-Linear Systems

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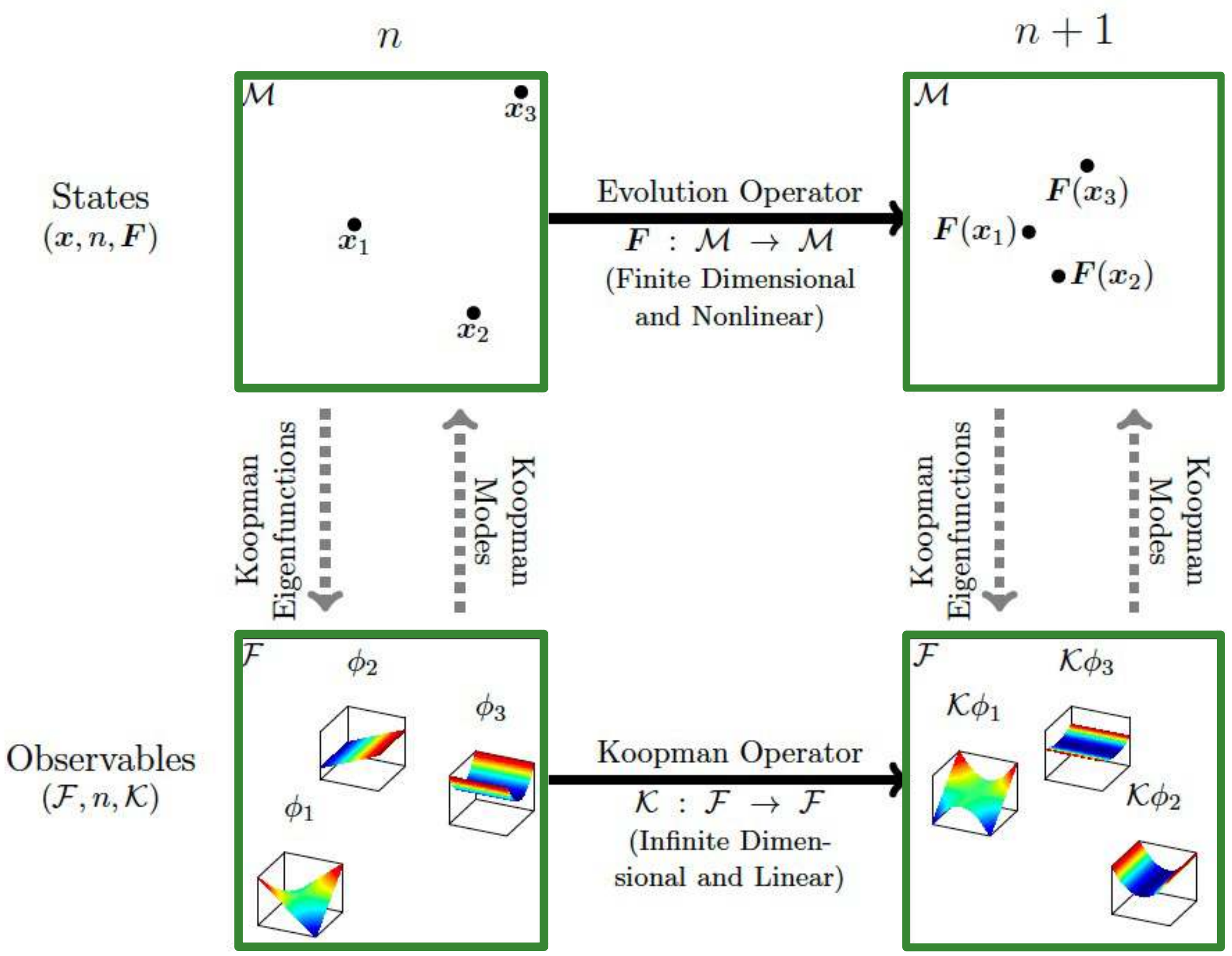
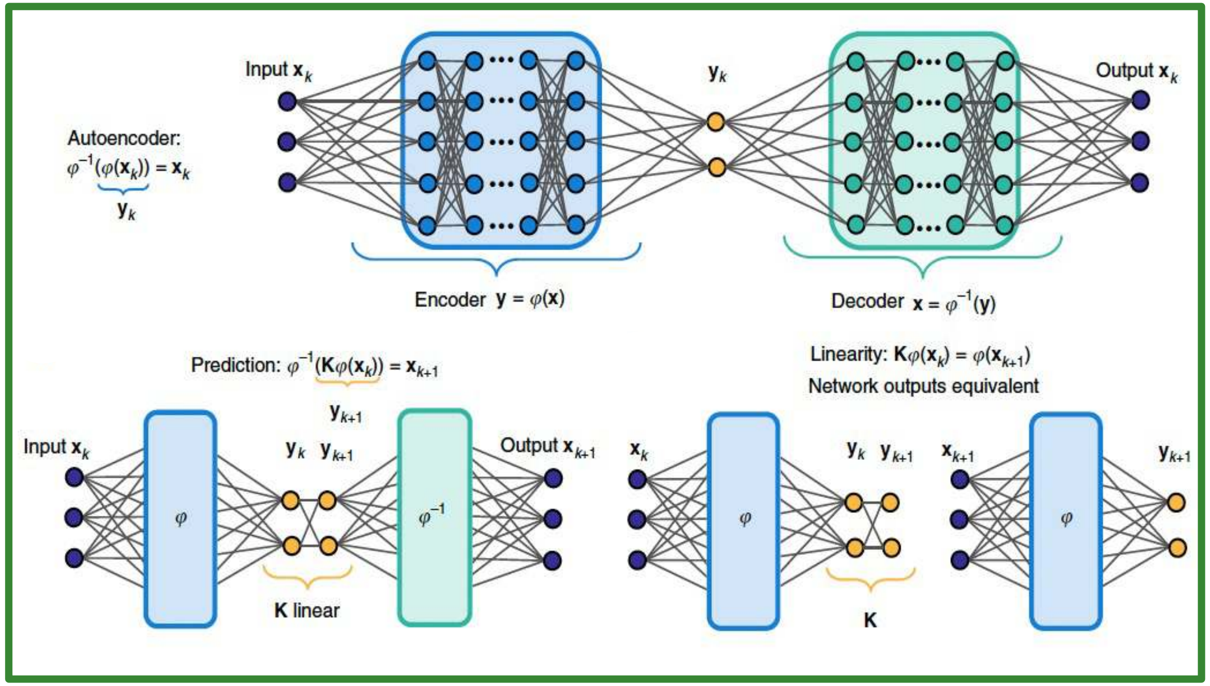
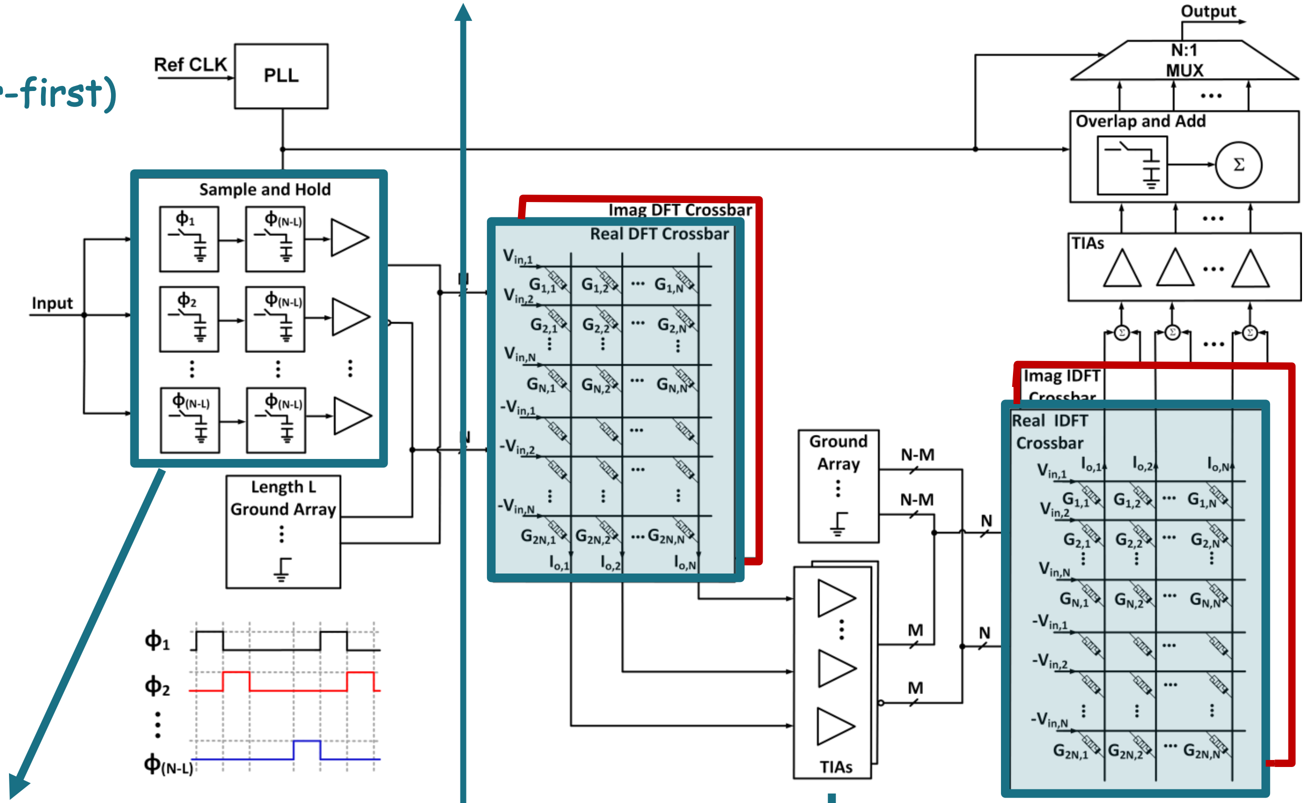
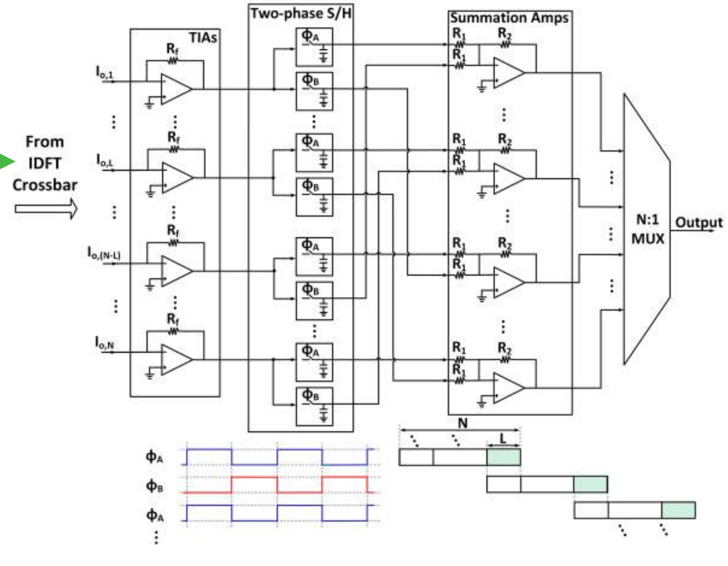
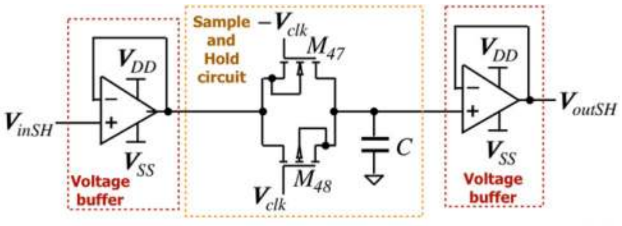


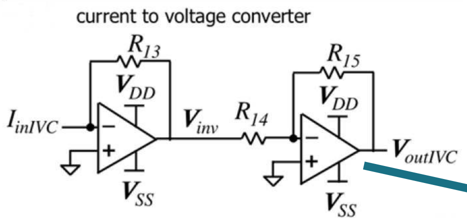


S/H Circuitry
(similar to a mixer-first)

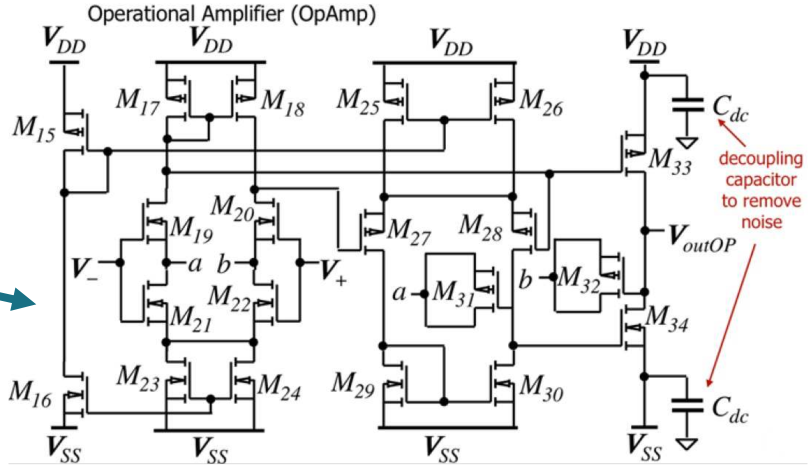




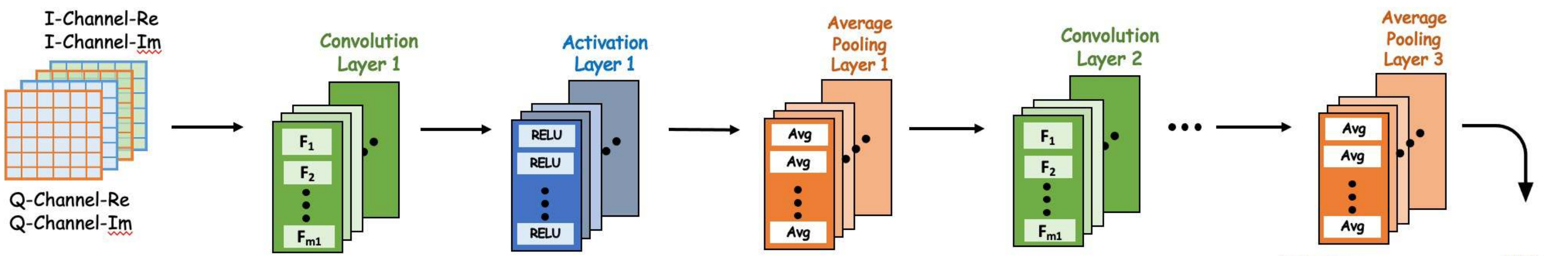
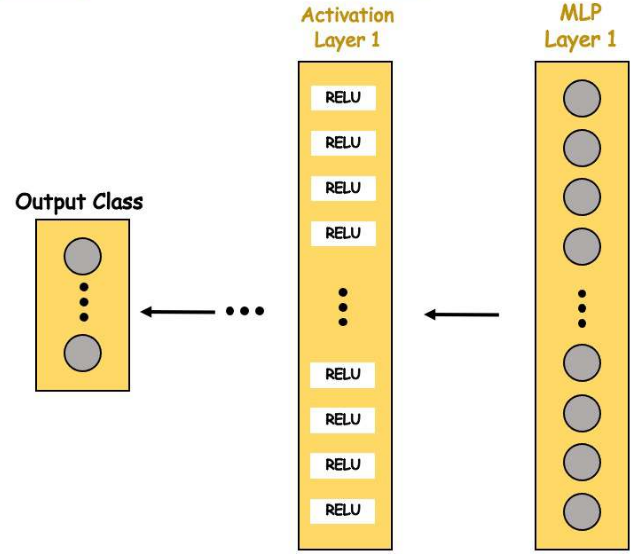




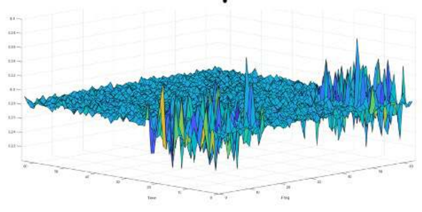
Analog Preprocessing using Memristive X-bar Configurations



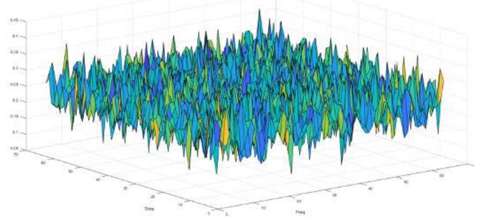
2-D CNN in the Digital Domain- Accuracy >99%

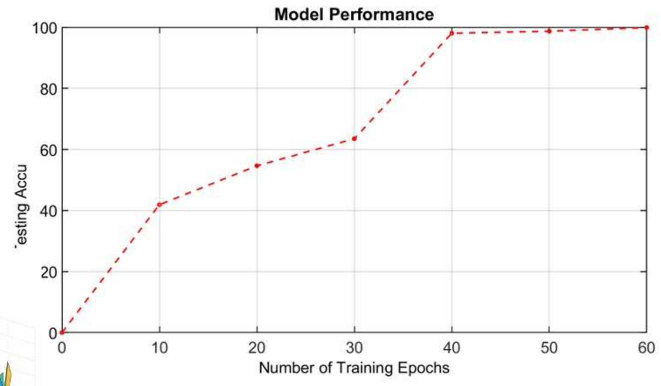



LTE Freq-Time



Wi-Fi Freq-Time





Future Applications

Data to Information

Co-design Analog and Digital Hardware with Neuro-inspired Algorithms for Processing, Memory and Sensor Control. **Demonstrate 3X:1** (bits/sec to samples, events or spikes/sec)

Information Fusion

Layer 2- Information Integration and Control: Transform analog and digital data into information bits; fuse information and identify event correlations; develop and store behavioral patterns. **Demonstrate 1X:1** (bits, samples, events or spikes/sec to Information bits/sec)

Decision and Evaluation

Layer 3-Decision and Evaluation Layer: Design **n**euro-inspired algorithms for synthesis, perception, decision and evaluation. **Demonstrate** further reduction of information **1X:1** bits/sec