EE746 Neuromorphic Engineering

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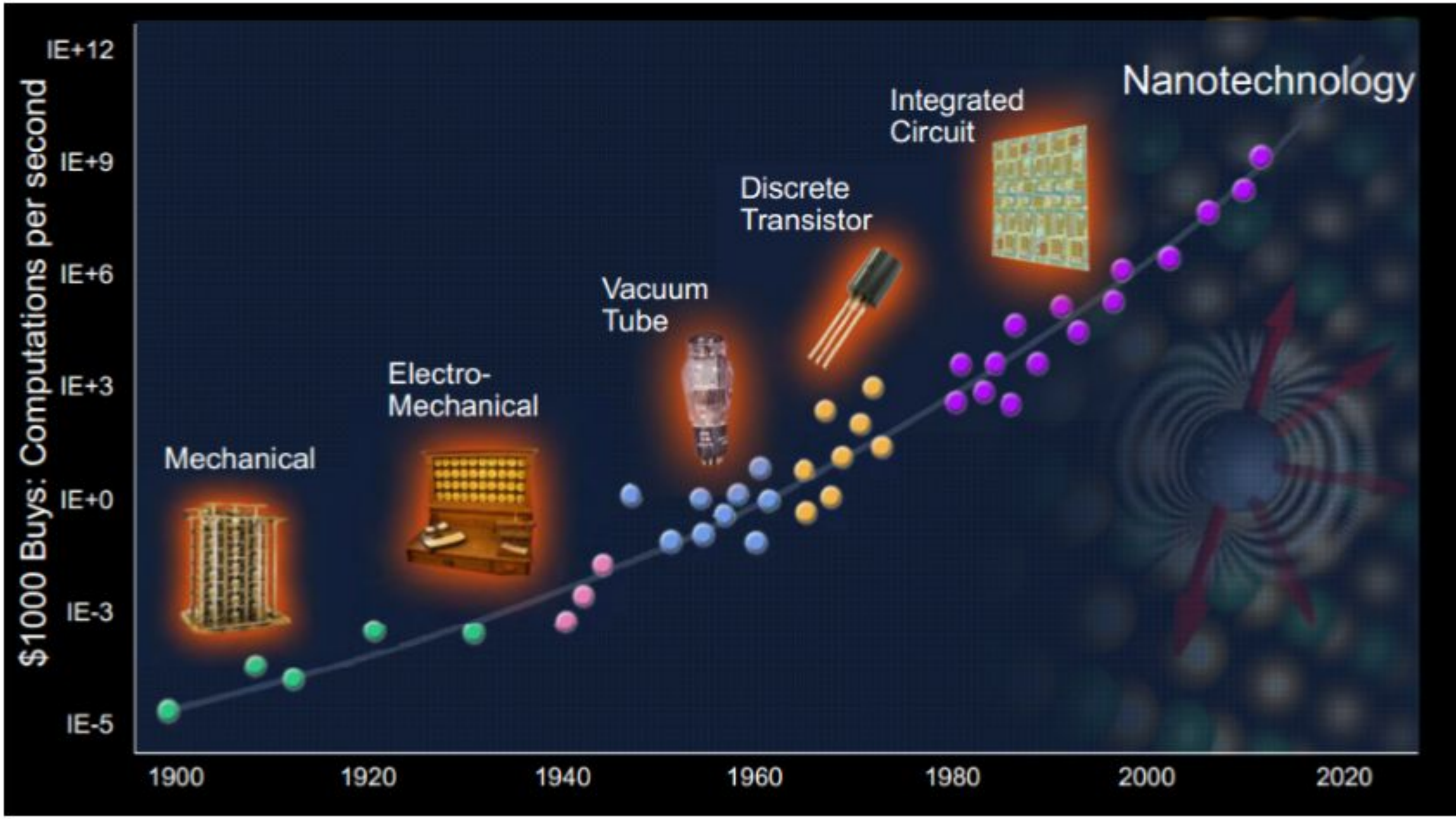
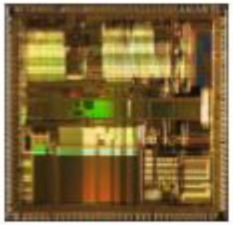
Exponential Growth in Computing

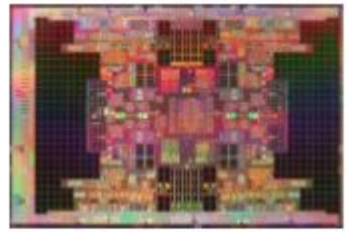


Source: Kurzweil 1999 - Moravec 1998

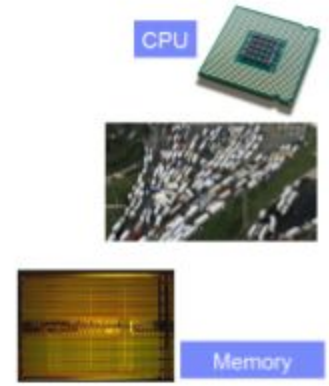
The story of micro-processor data in timescales



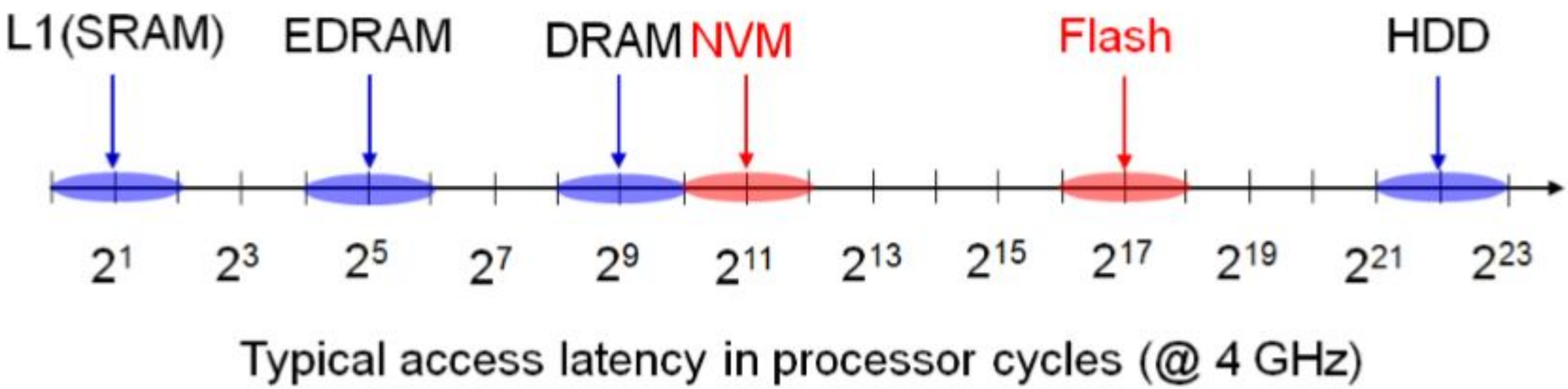
80486, circa 1990
1.2 Million Transistors



Tukwila, circa 2010
2 Billion Transistors



Source: www.intel.com



Prof. M Qureshi

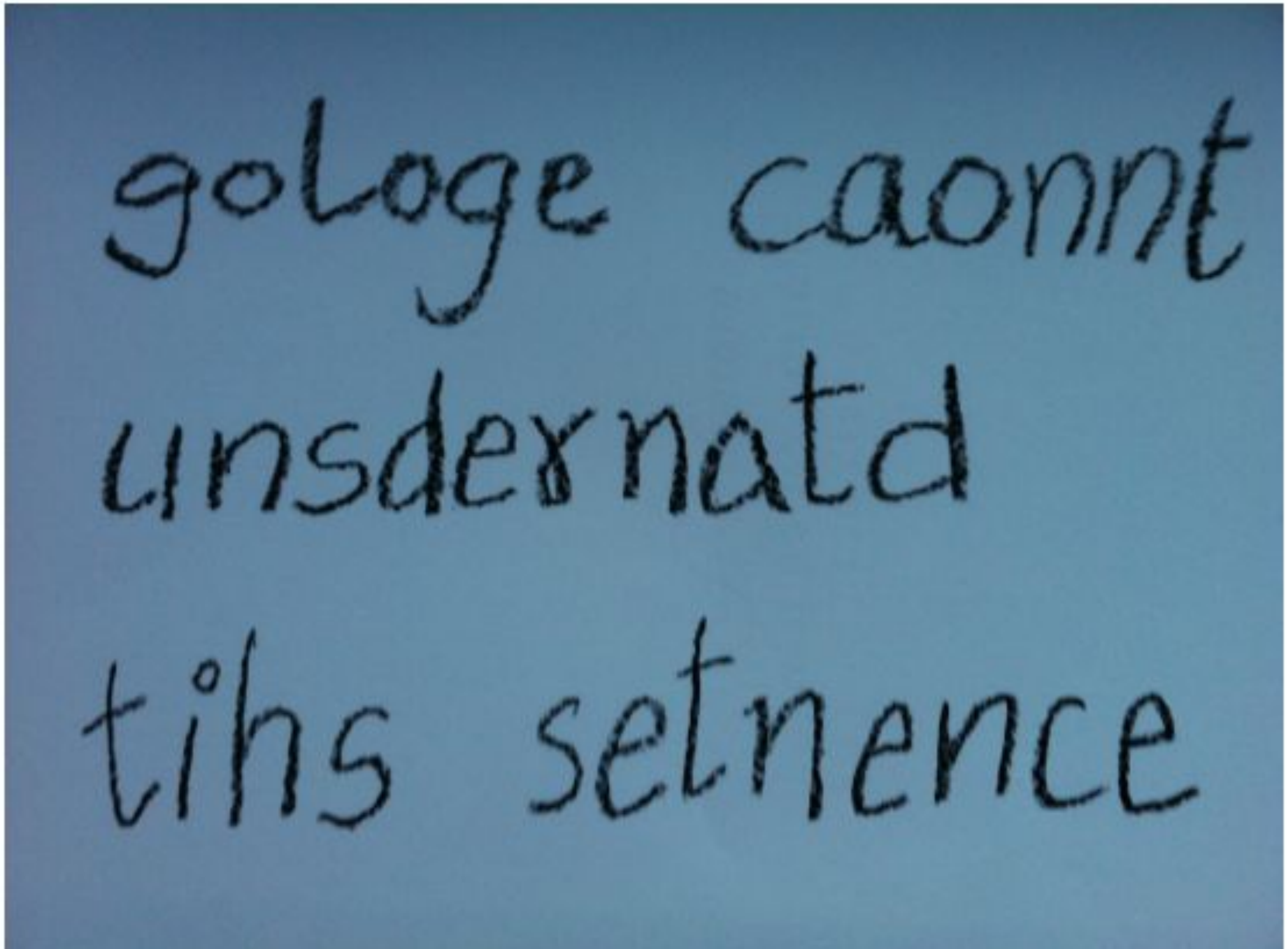
Computation – A comparison

Source: http://spectrum.ieee.org/

17.8 Million Watts
7750 sq. ft.
$\sim 10^9$ ops/J

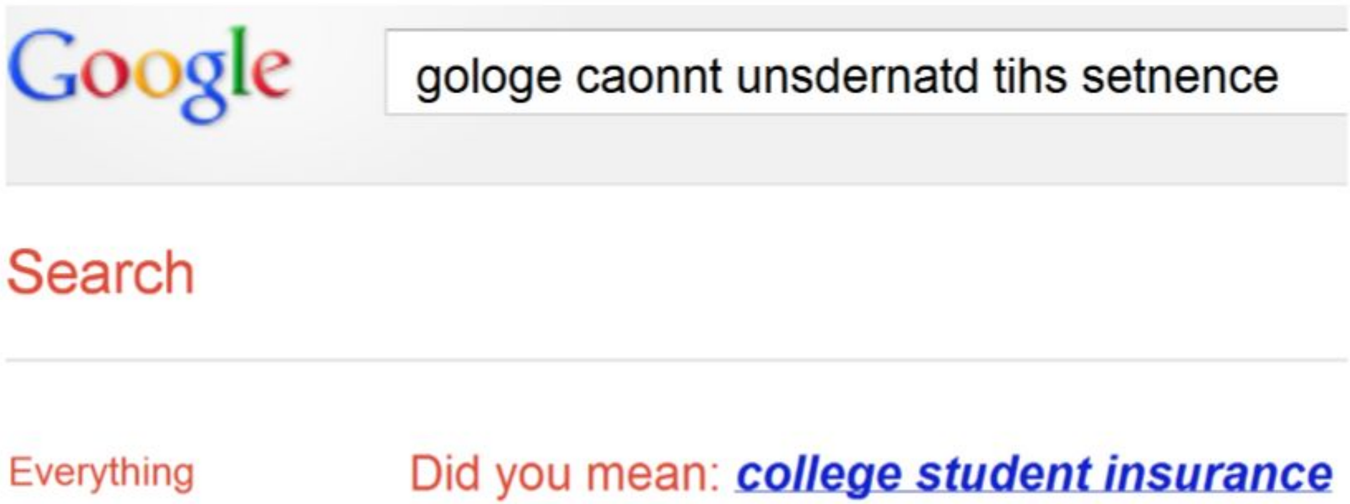
$\sim$ 20 Watts
2 sq. ft.
$\sim 10^{15}$ ops/J

Si vs. C based computation

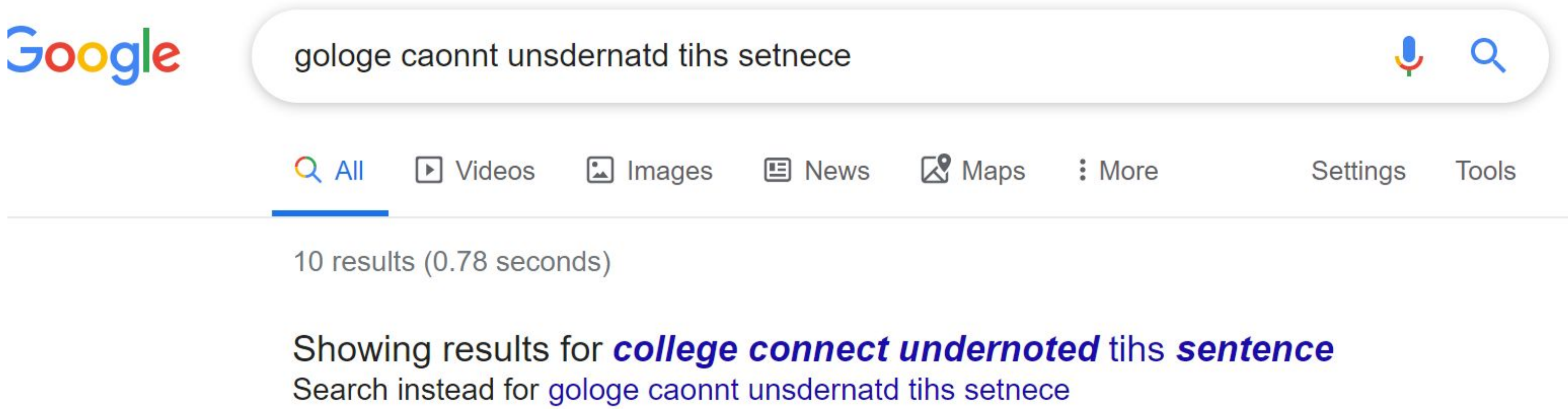


Artificial Intelligence progress

2013



2020



Outline

- How we compute?
- Neuromorphic Engineering - Elements
- Why Neuromorphic engineering? – Opportunities

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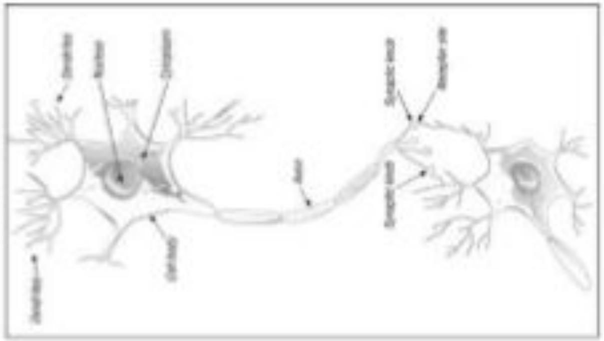
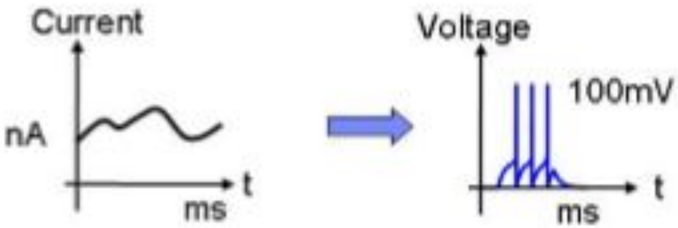
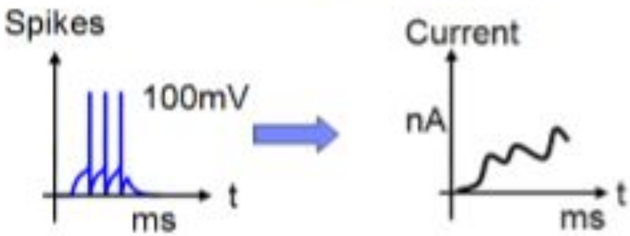
Computation in the Brain





kind of resonance



Spikes are the tokens of information processing

Strength of communication is encoded in the synapse

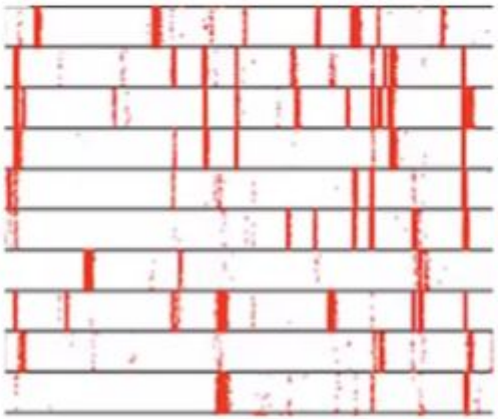
$\sim 10^{11}$ neurons in human brain

$\sim 10^{15}$ synapses in human brain

Inherently 3-dimensional connectivity that changes with activity

Cogito Ergo Sum - I think, therefore I am

source: A. Fairhall



Spatio-temporal Spiking

representation of how we store a picture in our memory

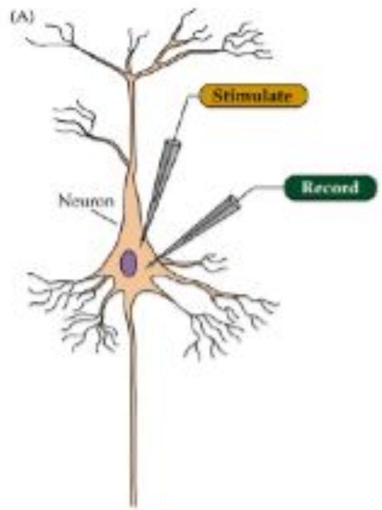
You are your spikes!

What does a neuron do?

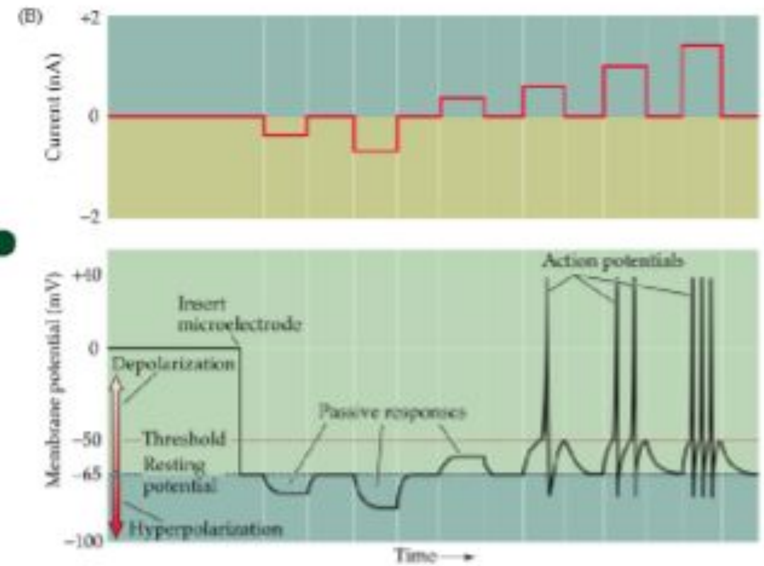
Alan Lloyd Hodgkin

Andrew Huxley

Nobel Prize, 1963.



when there is negative current it behave like a rc circuit but when there is +ve voltage it behaves like a CCO. MORE POSITIVE CURRENT MORE THE SPIKE



Source: Neuroscience, Purves

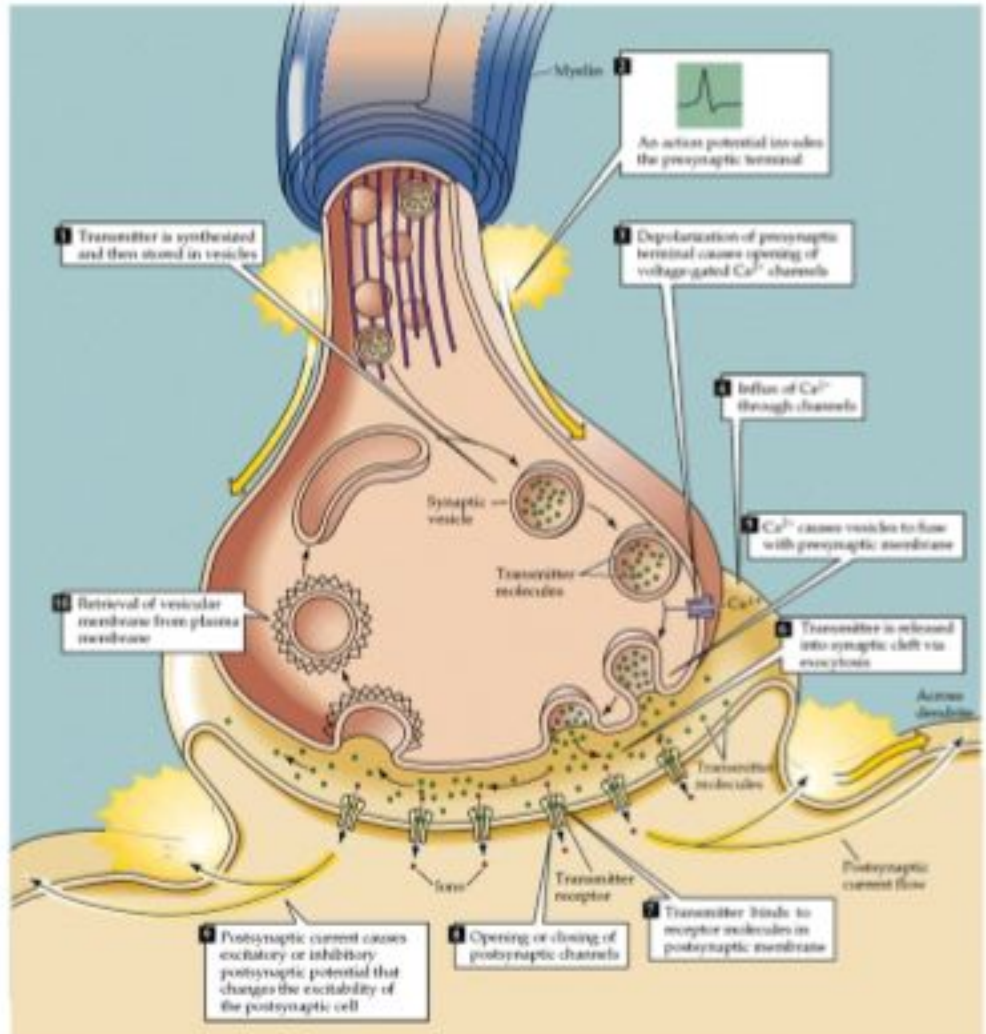
What happens at the synapse?

Charles Sherrington

Nobel Prize, 1932.

Sir John Eccles

Nobel Prize, 1963.

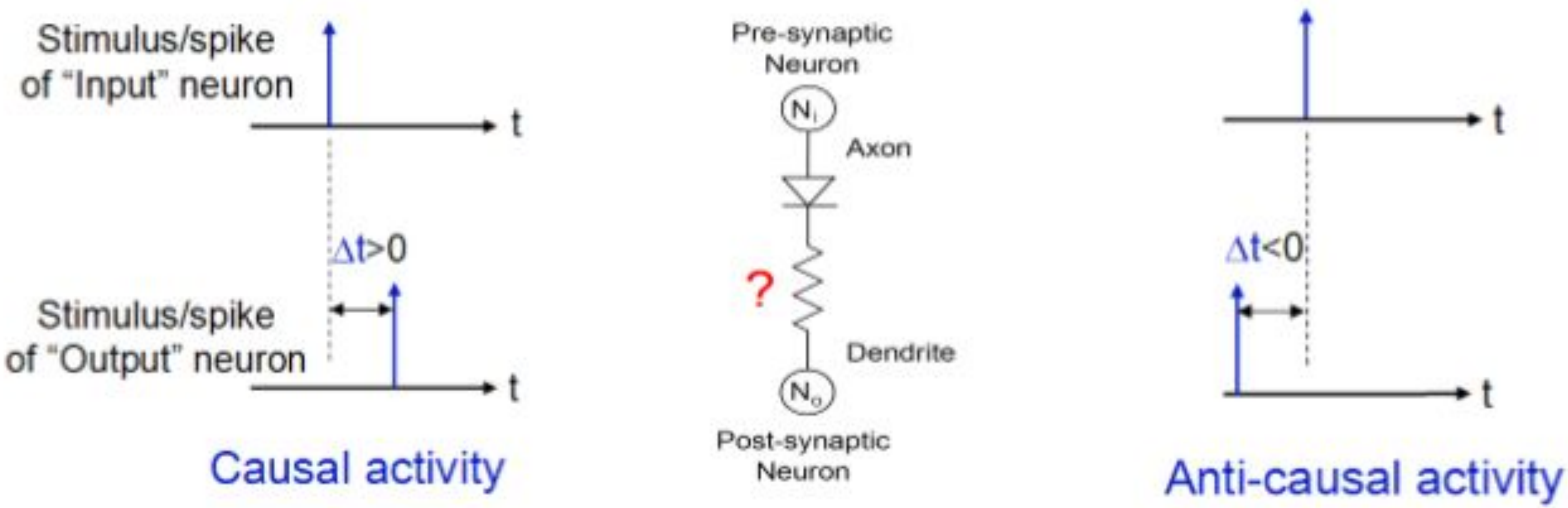


Source: Neuroscience, Purves

What is the basis of intelligence?

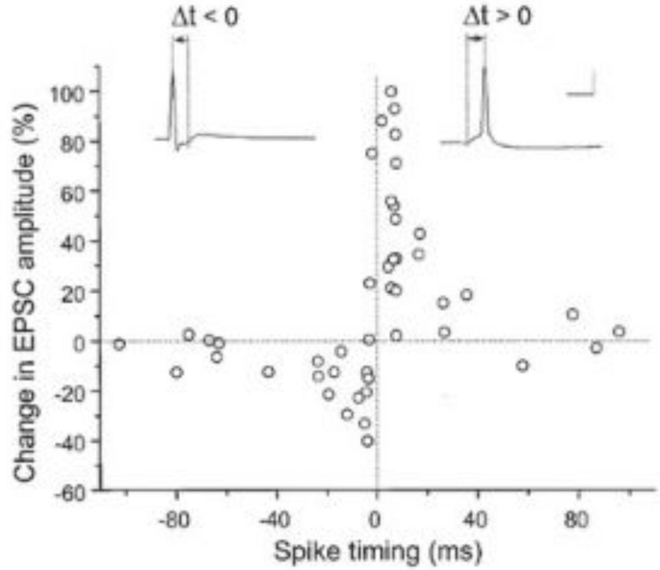
Eric R. Kandel

"Synaptic plasticity emerged as a fundamental mechanism for information storage" – Nobel Lecture, 2000.



effect before the cause

Spike Time Dependent Plasticity (STDP)



Bi & Poo, J. Neuroscience, '98

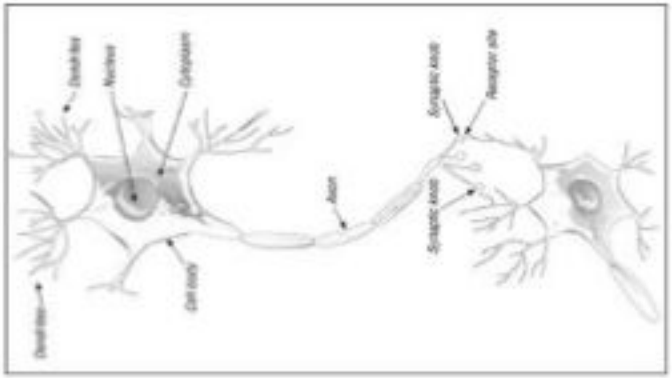
Causal firing $\Rightarrow$ Conductivity increases

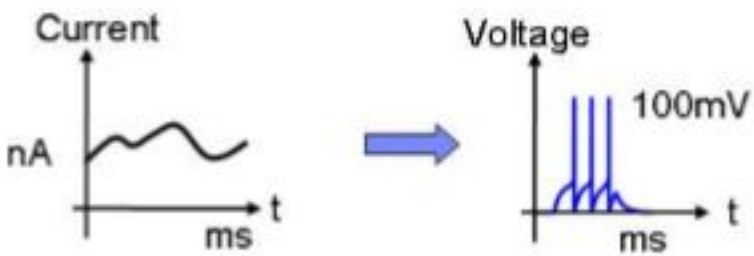
Anti-causal firing $\Rightarrow$ Conductivity decreases

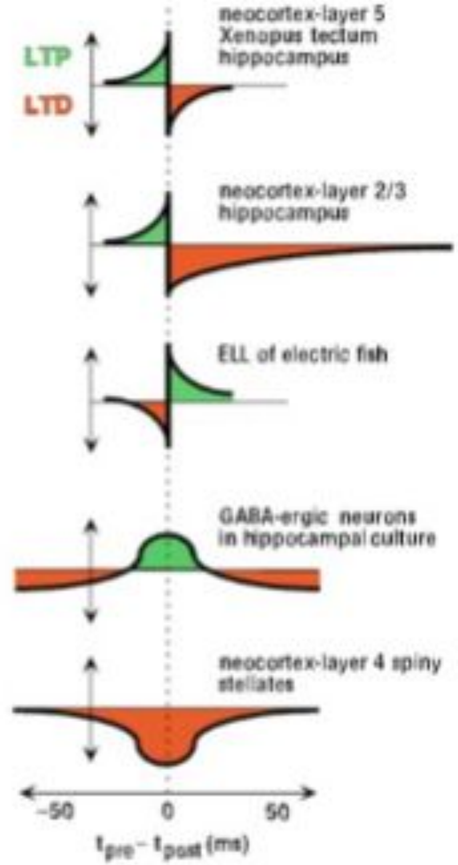
$$\Delta G \propto \exp(-|\Delta t|)$$

Timing correlations in the range of $\pm$100ms.

Learning in Biology







Source: Nature Neurosci. 3:1178-1183.

Low voltage spikes and timing based plasticity is fundamental in biology

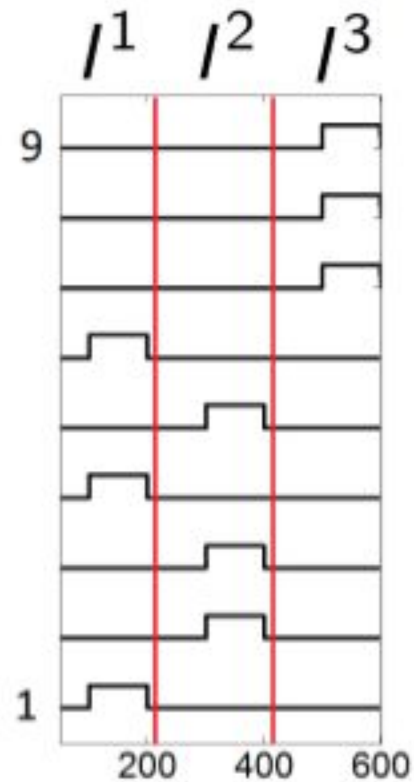
What can a neuro-synaptic network do?

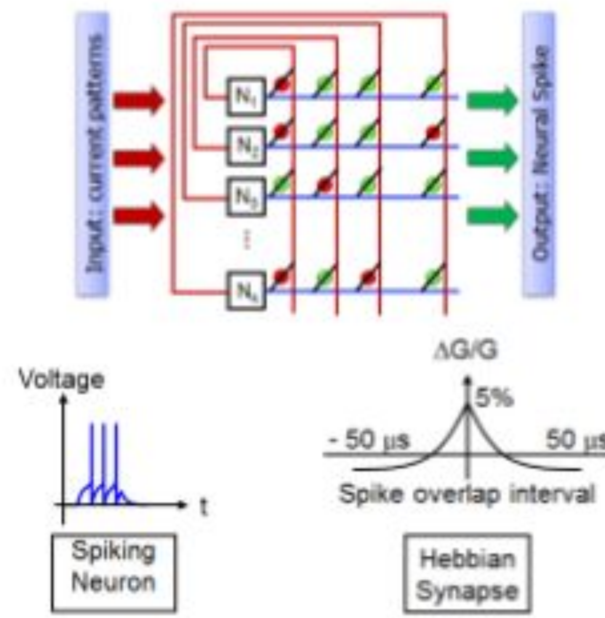
Learnt patterns

- $I^1 = [100101000]$
- $I^2 = [011010000]$
- $I^3 = [000000111]$

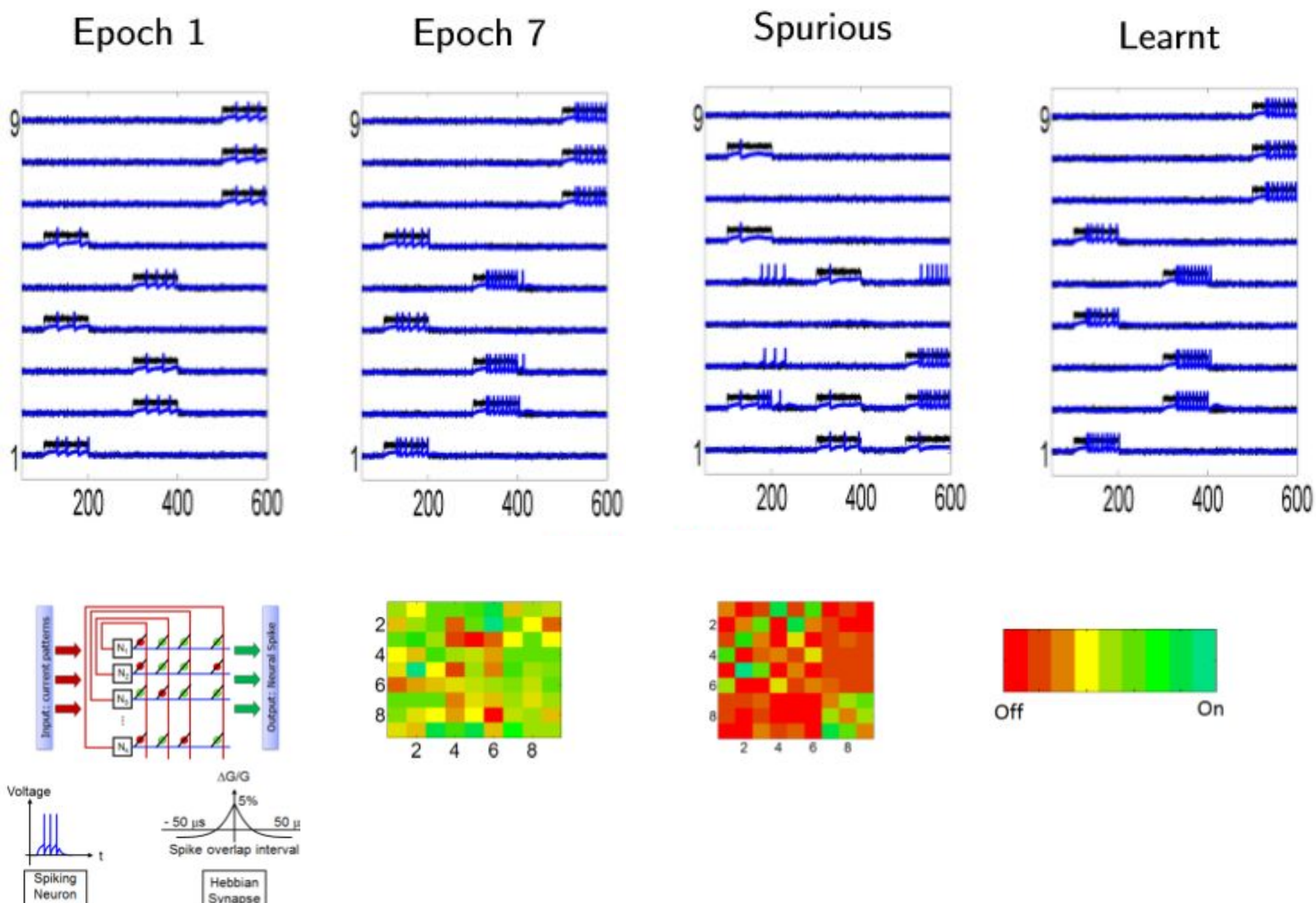
Task: Is $X \in \{I^1, I^2, I^3\}$?

Key component of pattern recognition.

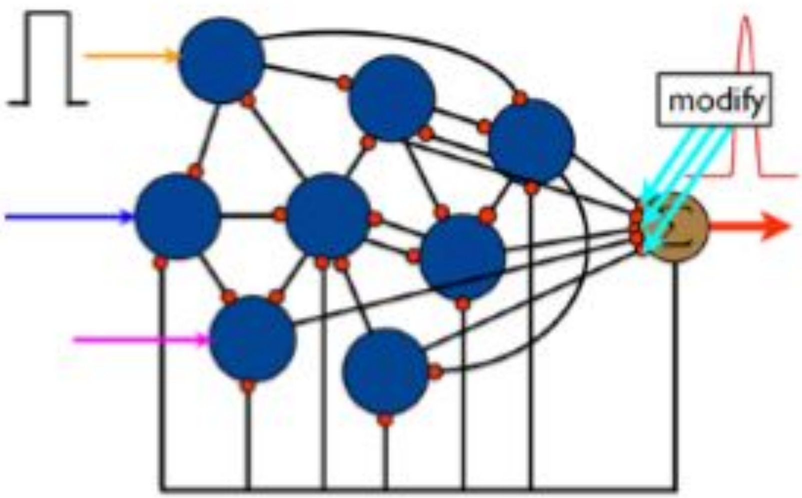




What can a neuro-synaptic network do?

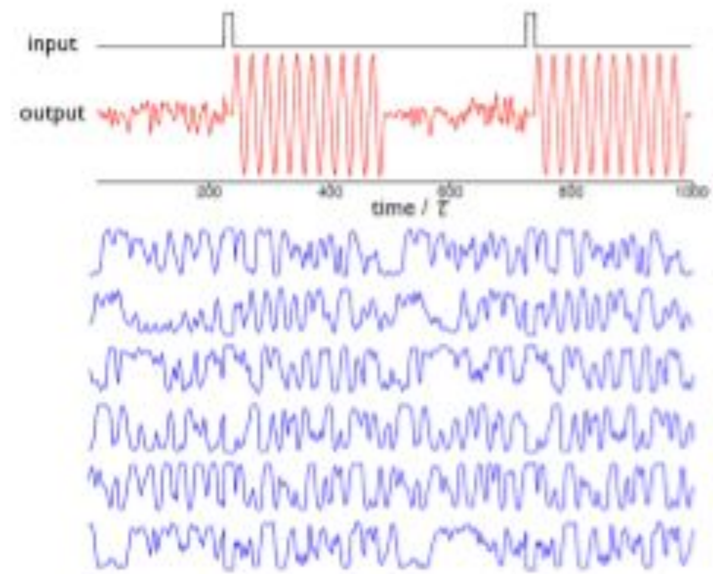


What can a neuro-synaptic network do?



$$\frac{dx_i}{dt} = -x_i + \sum_{j=1}^{N} J_{ij} tanh(x_j)$$

Source: L. Abbott

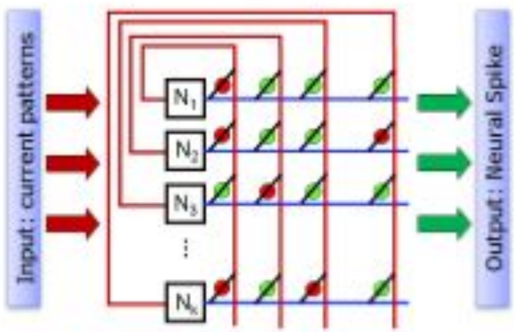


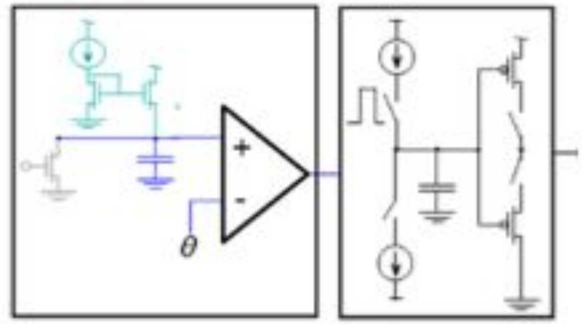
Random Network on Neurons will learn a function

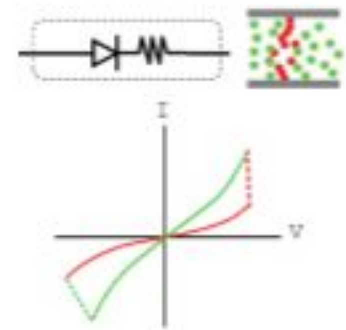
Outline

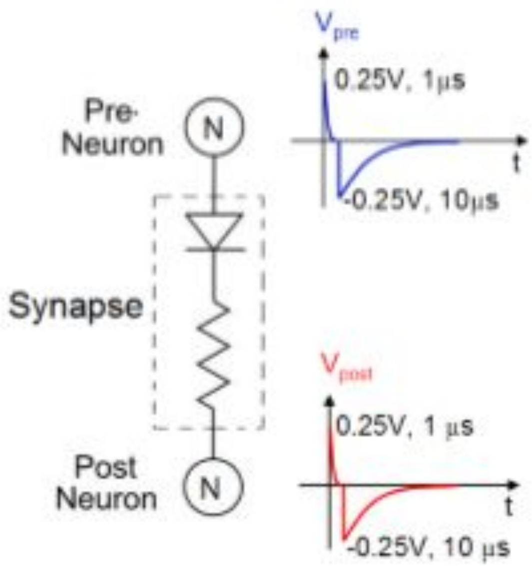
- How we compute?
- Neuromorphic Engineering – Elements
- Why Neuromorphic engineering? – Opportunities

How can we build a neuro-synaptic core?









When a neuron spikes:

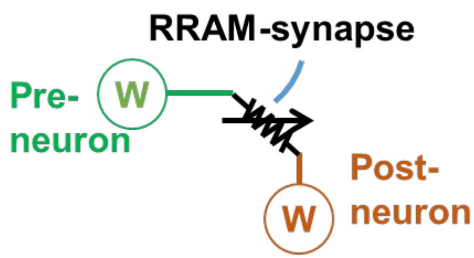
i) V_{pre} is sent along the axon

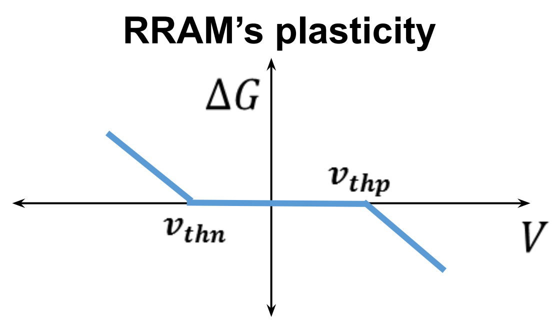
ii) V_{post} is sent along the dendrite

STDP ($\Delta G(\Delta t)$) = RRAMs + Neuronal Waveform

- Waveforms
  - Means of converting timing info to voltage etc

RRAM:
$\Delta G(V)$





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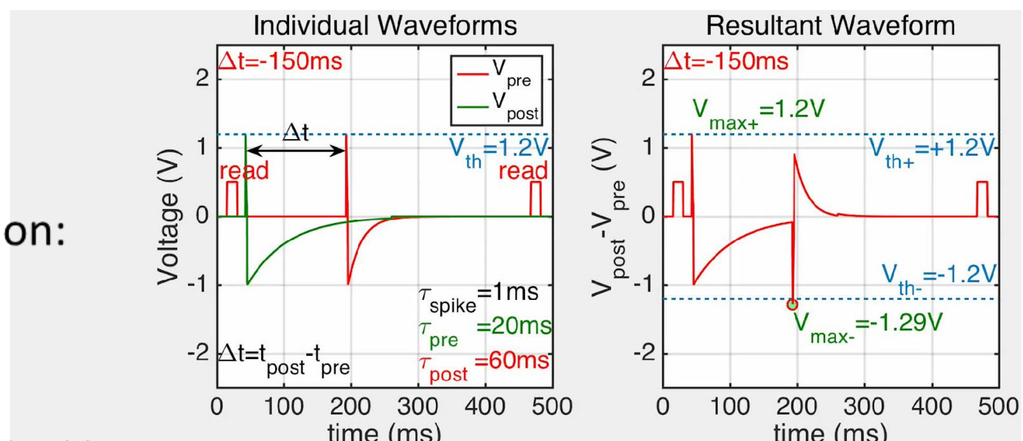
Waveform
Superposition:
$V(\Delta t)$



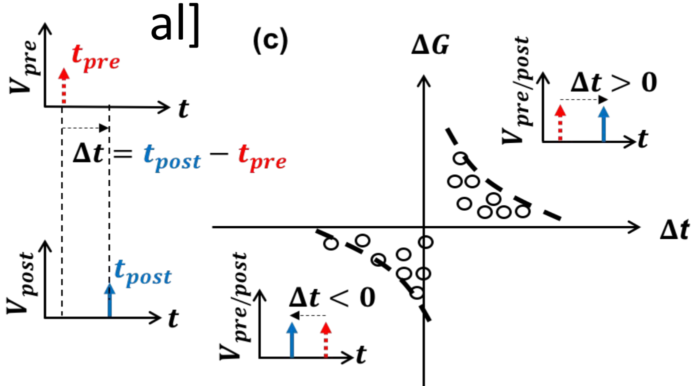
=

STDP: ΔG ($V(\Delta t)$)

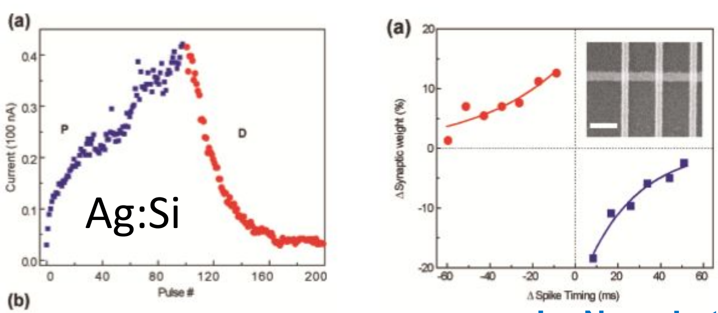
Waveforms produce STDP but replace sharp biological spikes with long waveforms

RRAMs – Analog weights & STDP

- Voltage-pulse-dependent resistances
  - STDP shown successfully by many [Jo et al], [Panwar et al]



1. Biology(Bi & Poo)



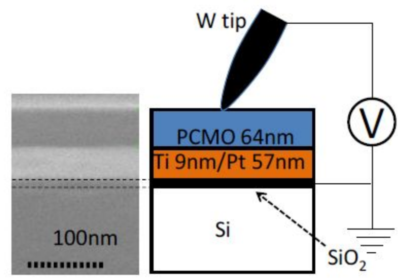
2. Simple STDP

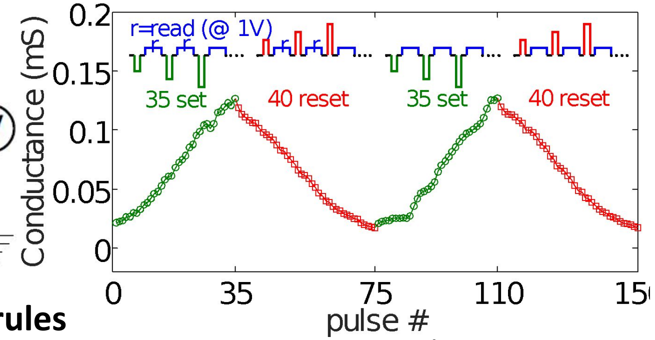
Jo, Nano Lett., 2010

3. Arbitrary STDP

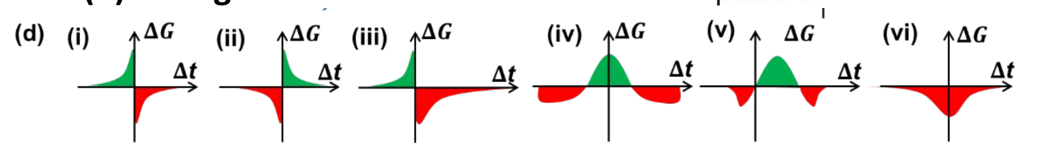
Panwar, EDL, 2017

3 (a) Analog States

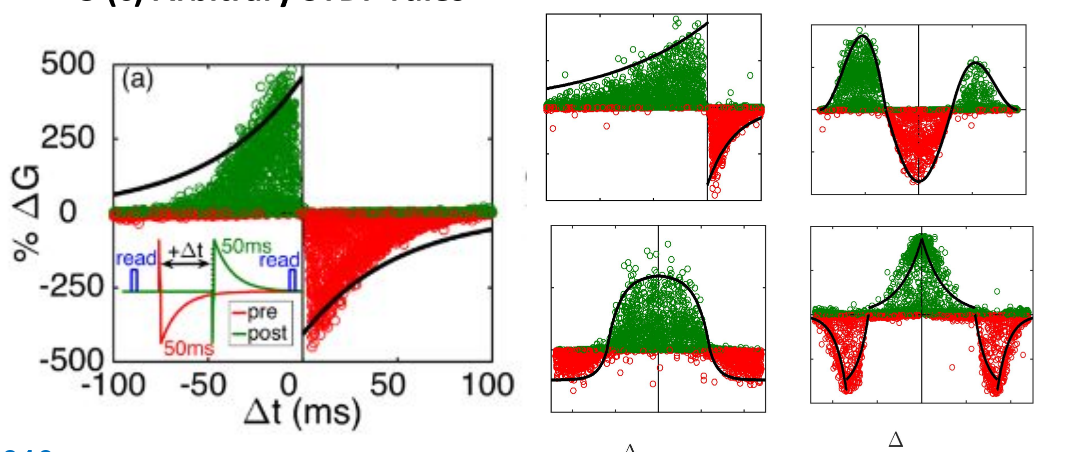




3 (b) Biological STDP rules

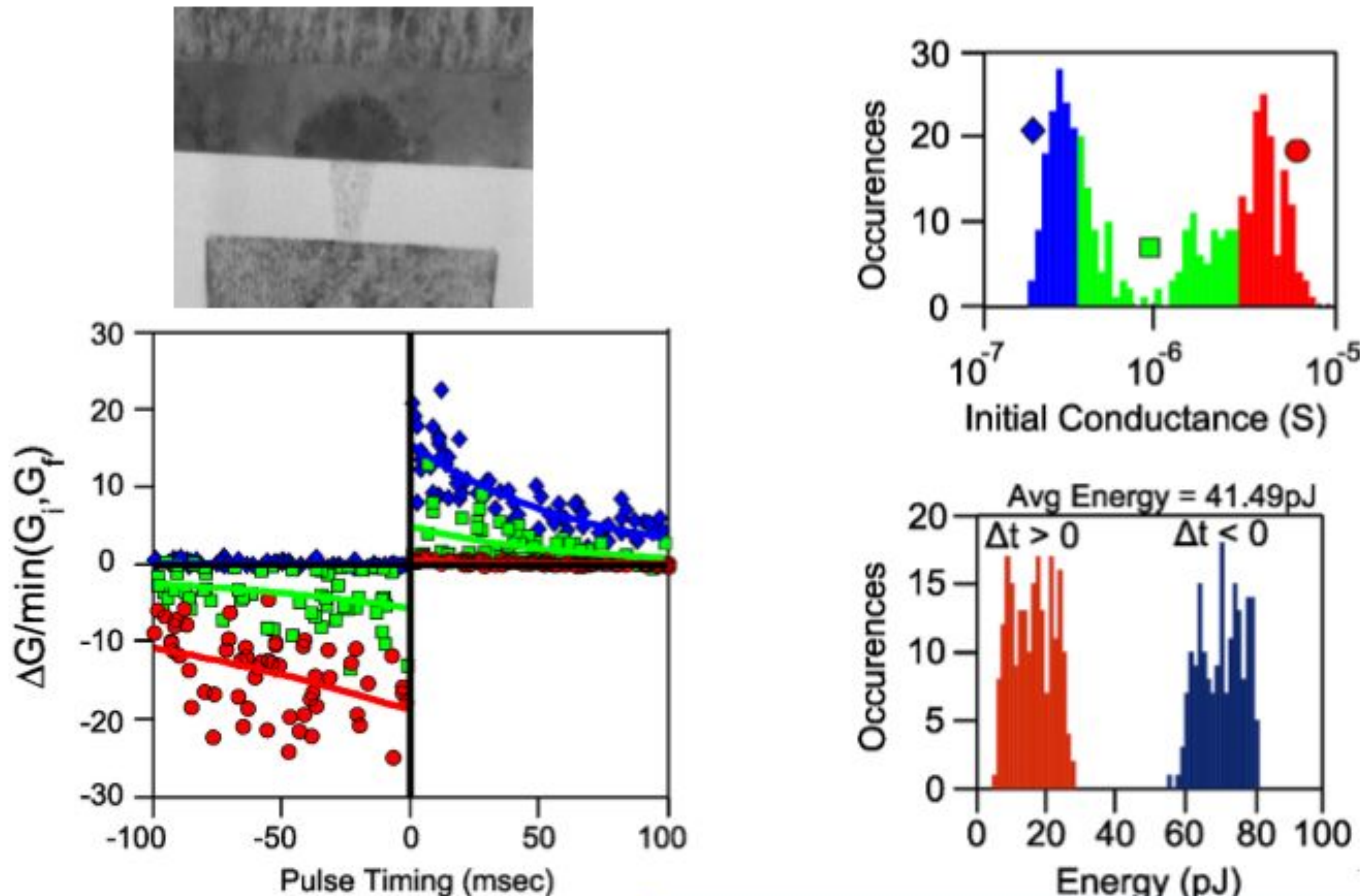


3 (c) Arbitrary STDP rules

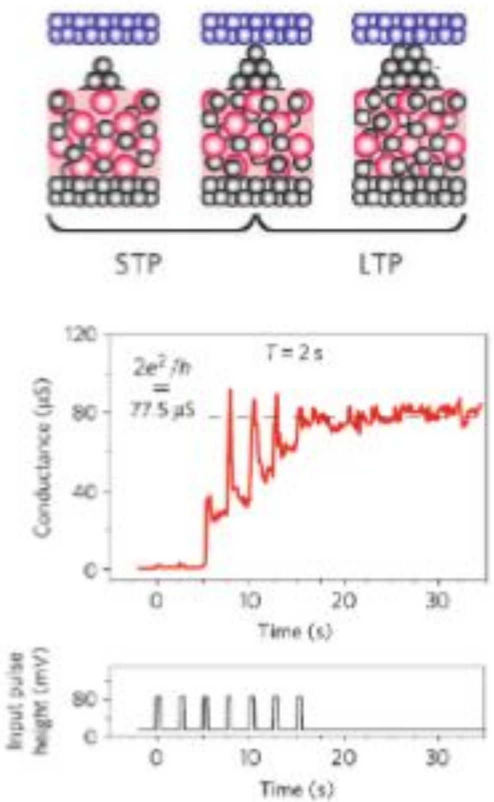


Nanoscale Devices as Synapse

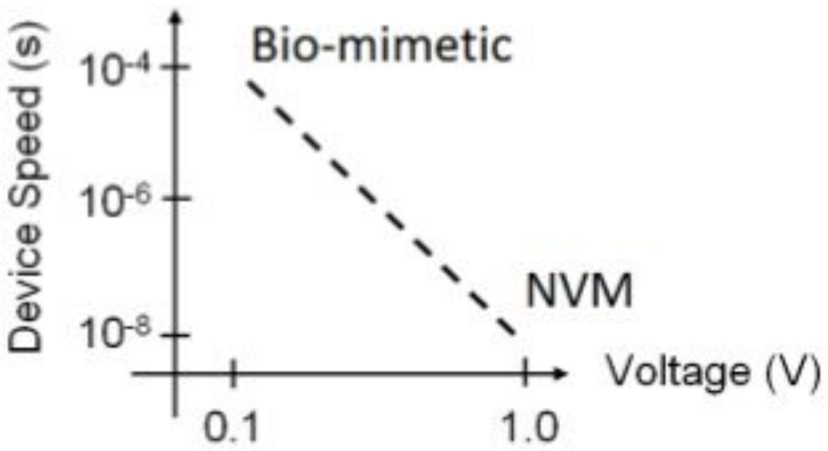
Jackson et al, ACM JETC '13



Exploit nanoscale phenomenon to mimic biology



Source: T. Ohno, Nature Materials, 2011



Can we engineer the building blocks of bio-mimetic computational systems from nanoscale materials?

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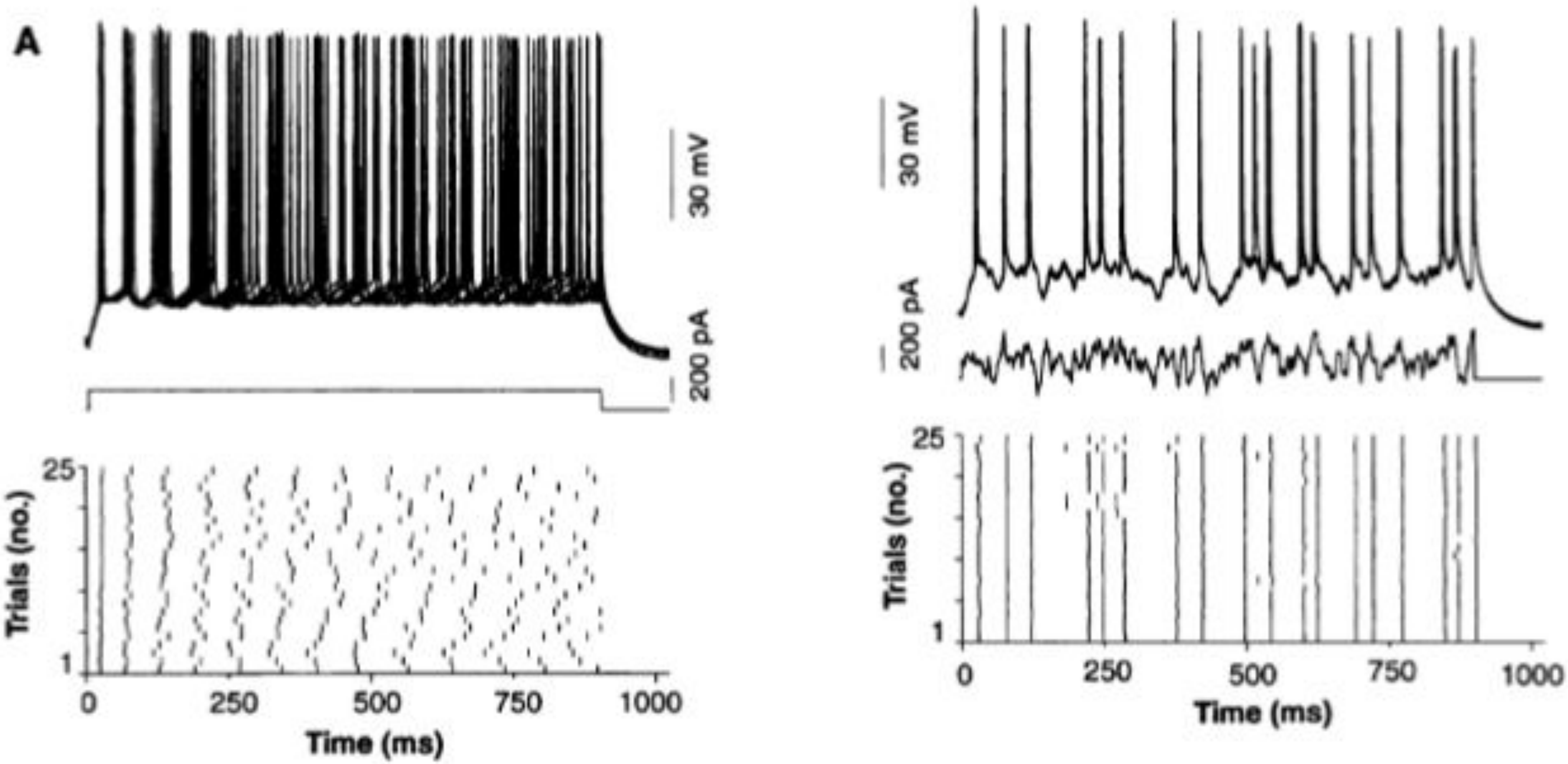
Understanding Biology: Noise/Signal

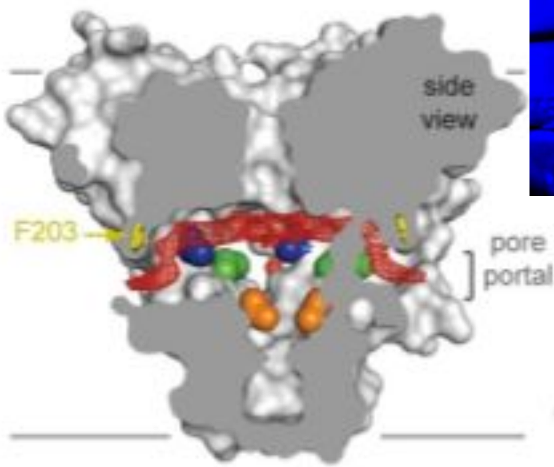


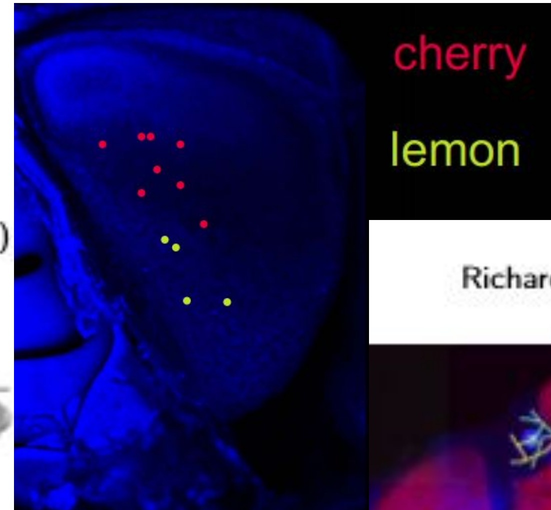
Z. Mainen et al, Science Vol 268 '95

Rate coding vs. temporal coding.

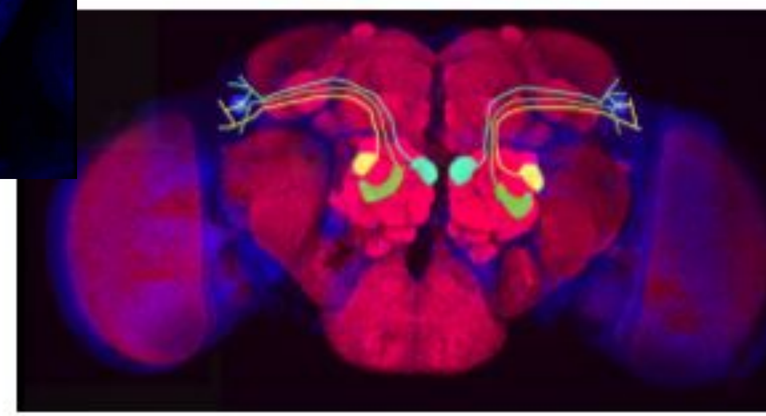
Challenge: To Connect sensing to perception

Nature 475, 353-358 (21 July 2011)





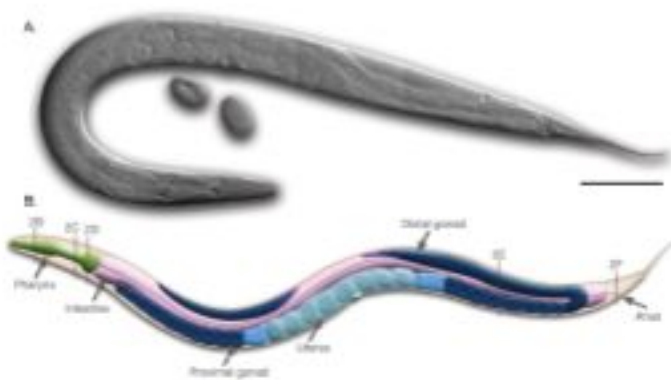
Richard Axel - Nobel lecture, '04



How does the brain build a meaningful representation of the world from stochastic signals?

Are these connection maps set from birth? Do they evolve during infancy?

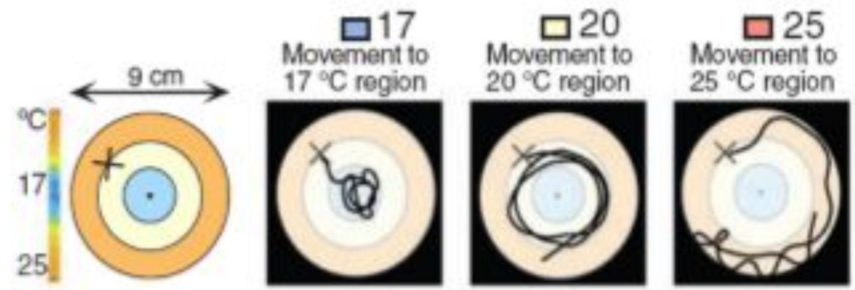
Bio-inspired computation – perception to decision

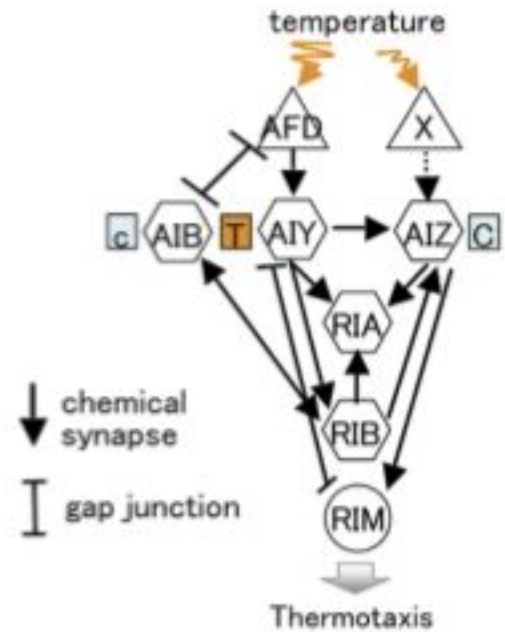


C. Elegans (1 mm long)

- 302 neurons
- $\sim$ 8700 synapses

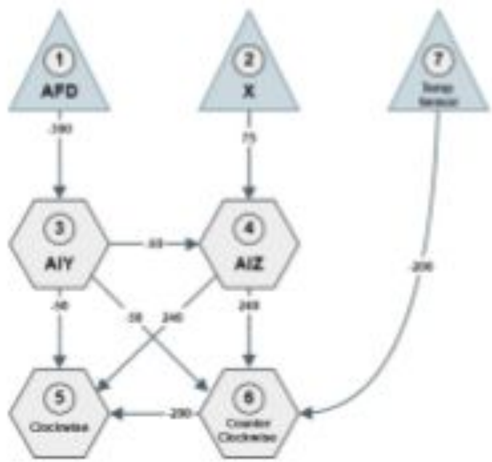
I. Mori et al, Neurobiology '07

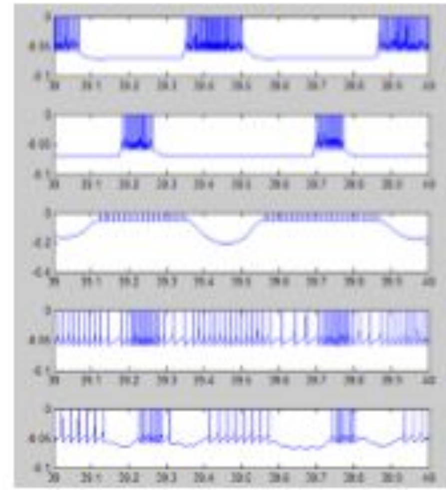




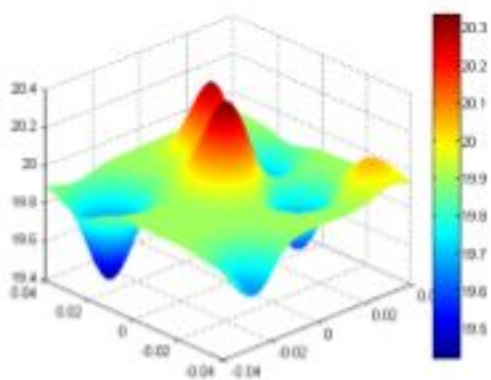
Smallest network capable of learning?

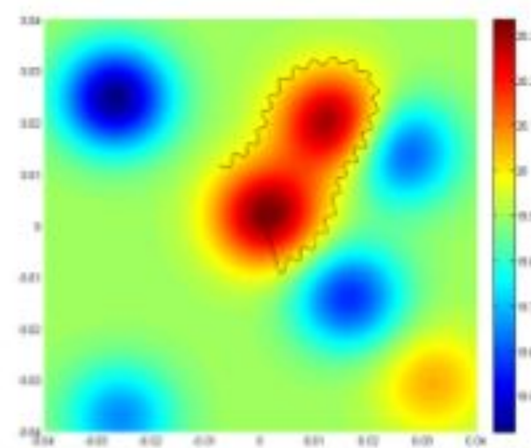
Bio-inspired computation





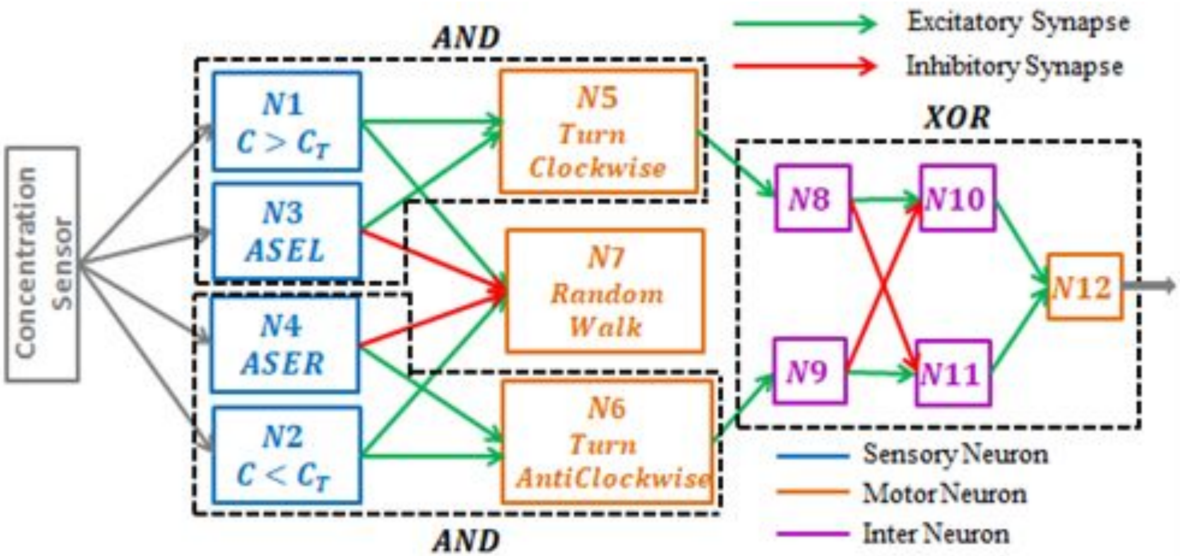
NOISE PROFILE USED



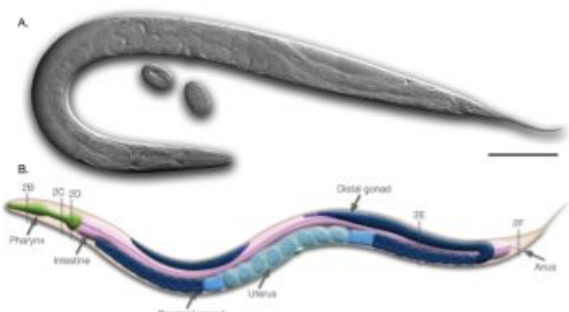


Arjun Rao, Ashish Bora, Sai Bhargav Yalamanchi, Akshat Kadam

Chemotaxis Neural Network



S. Santurkar et al IJCNN 2016
S. Shukla et al ICANN 2018



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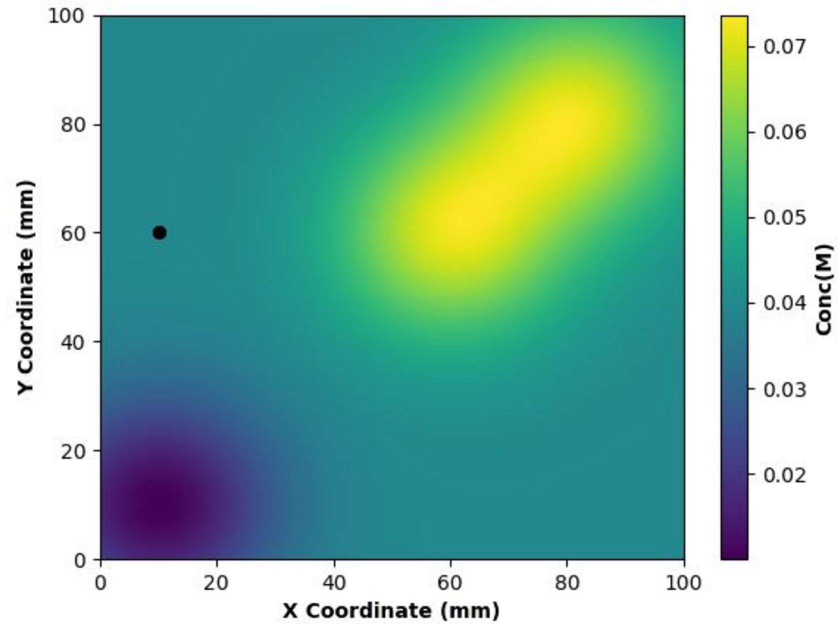
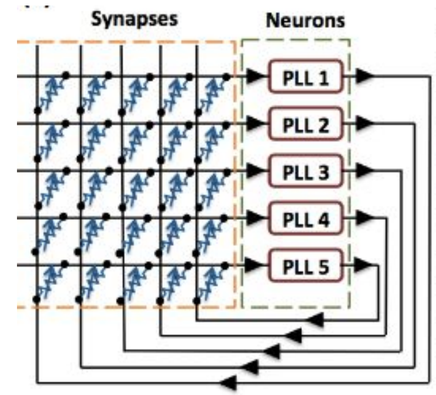
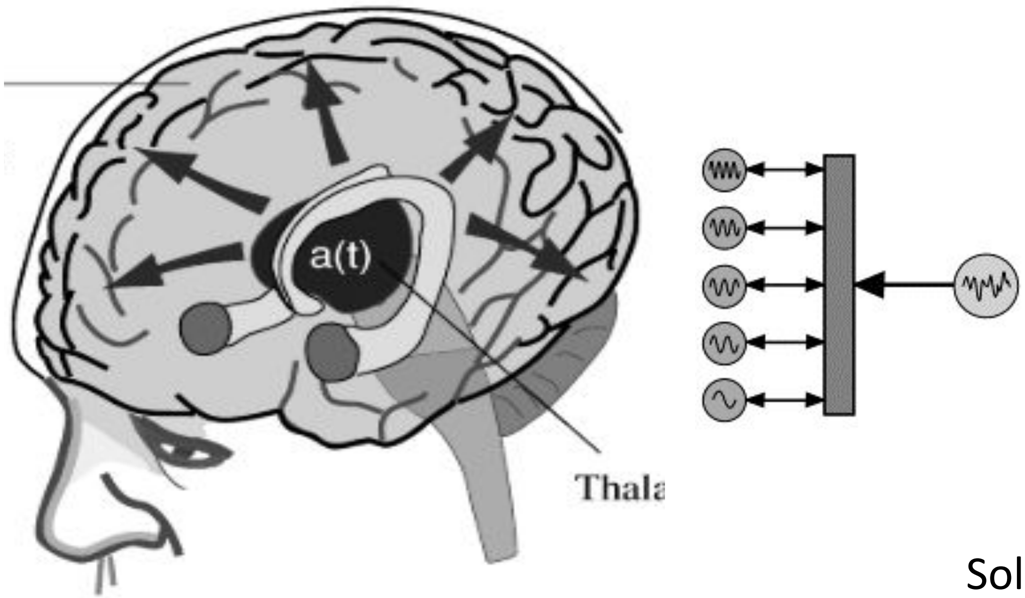
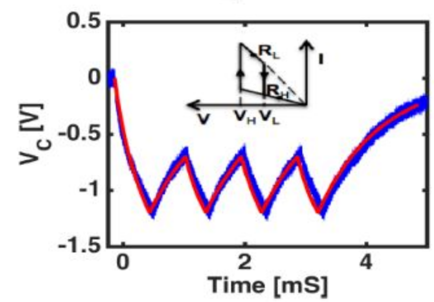


Solving NP Hard Problems

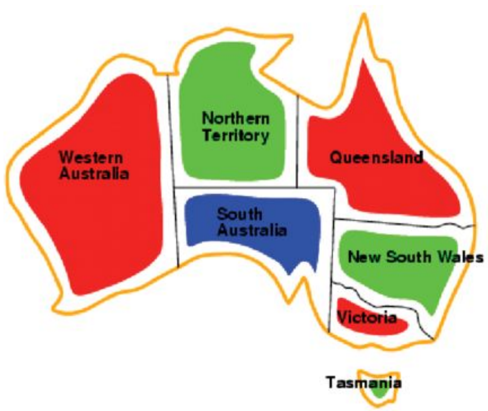


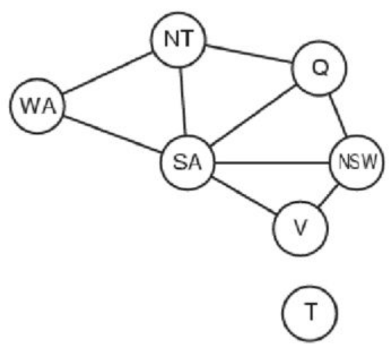


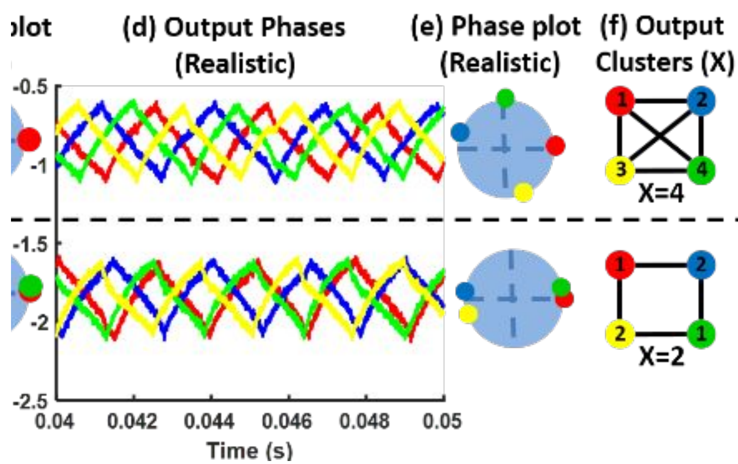


Solving a graph coloring problem

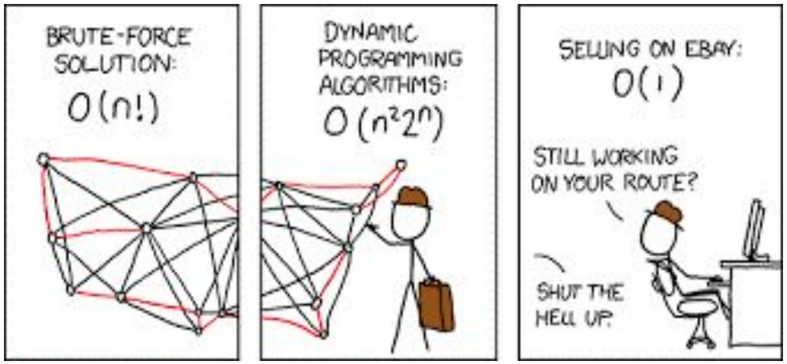
Coupled Oscillatory Neurons solve problems in parallel!

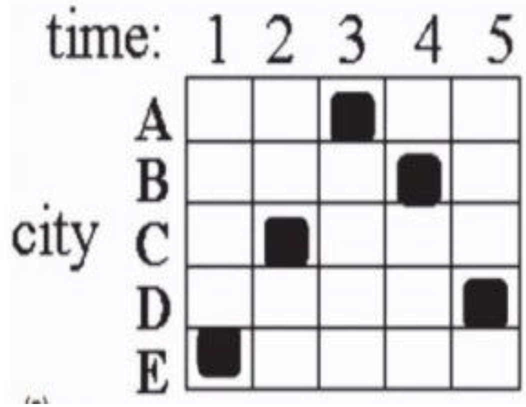


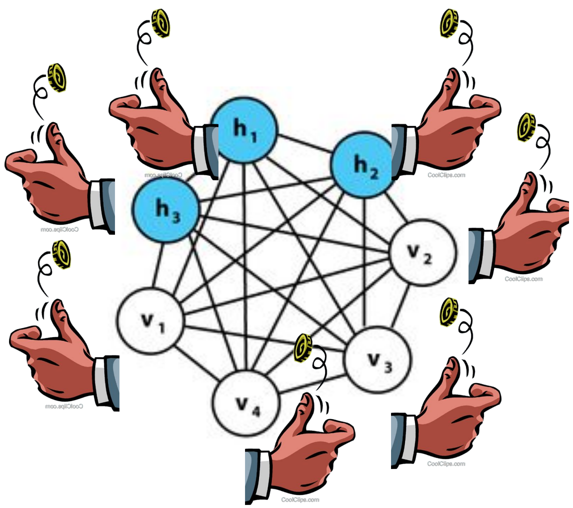


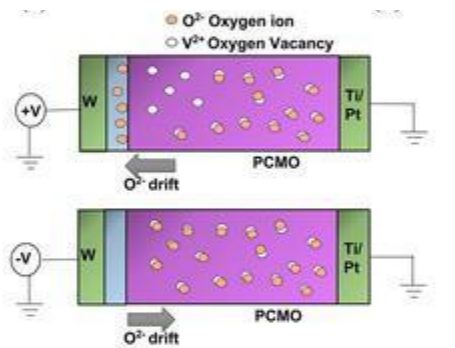


Boltzmann Machine

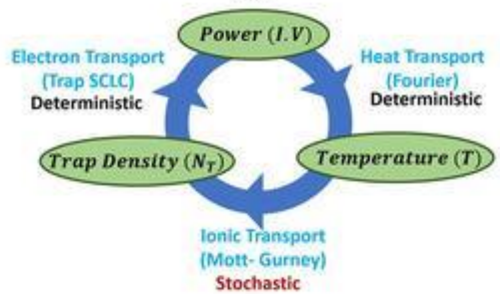








(c)



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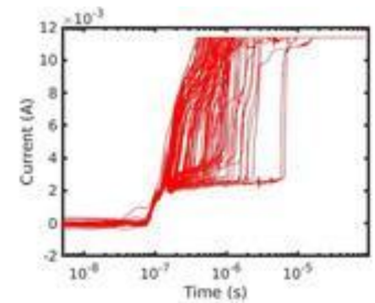
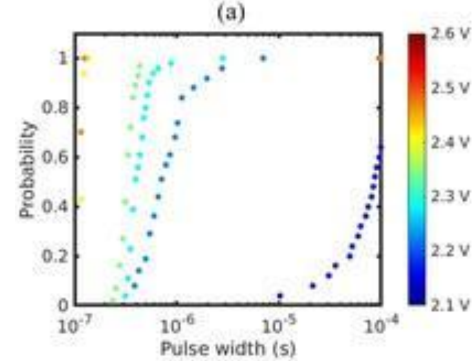
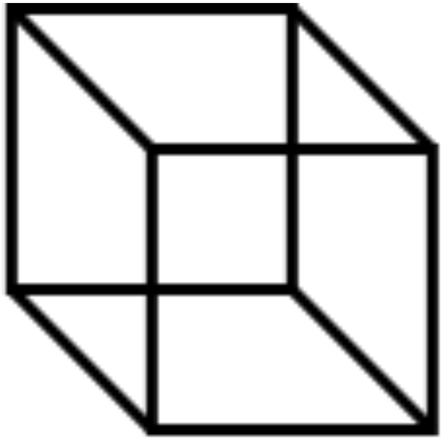


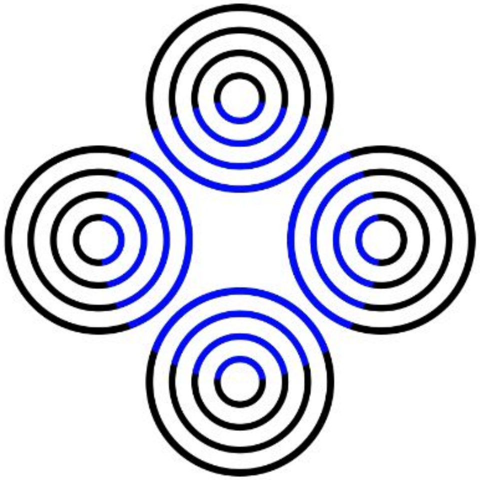
(a)



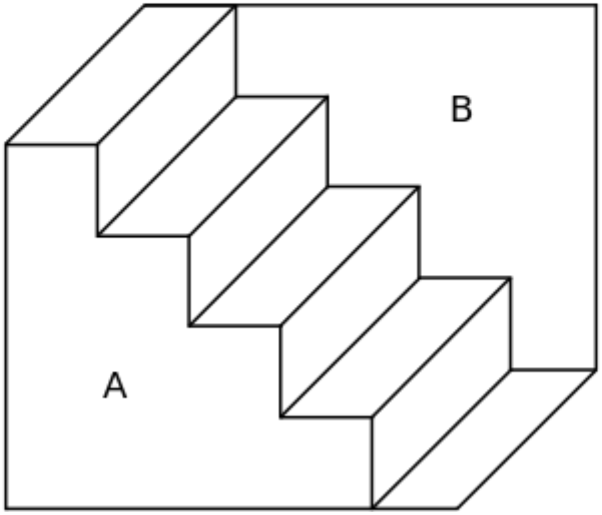
Multi-stable Perception/Illusion



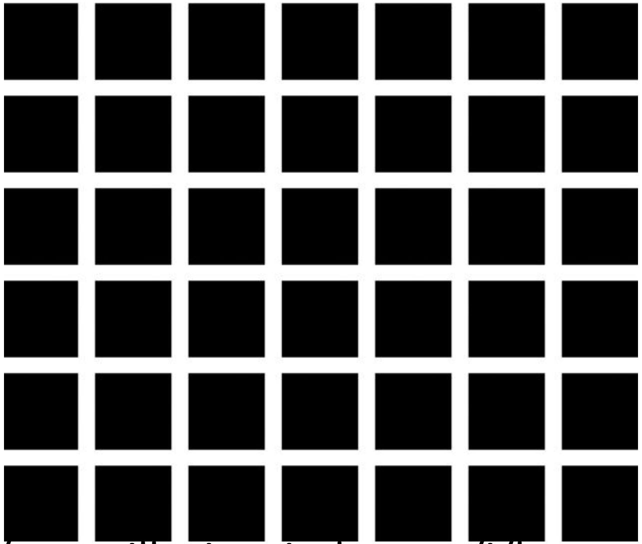
https://en.wikipedia.org/wiki/Necker_cube



https://www.illusionsindex.org/i/neon-color-spreading



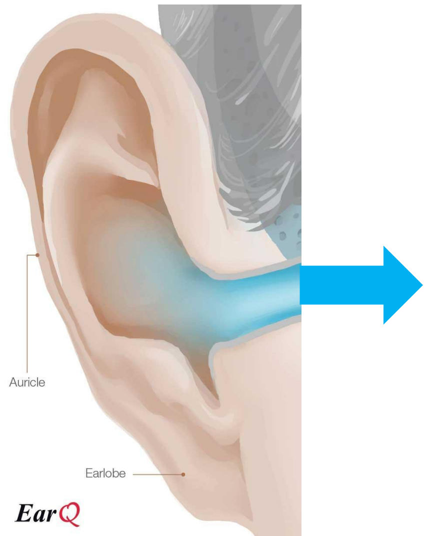
https://en.wikipedia.org/wiki/Schroeder_stairs

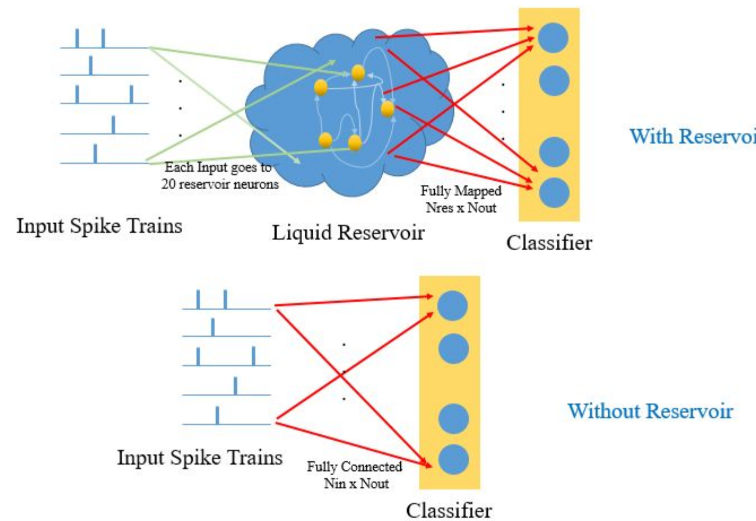


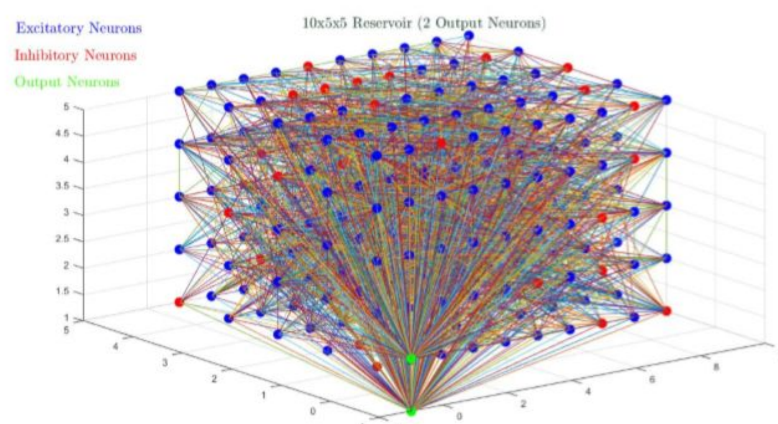
https://www.illusionsindex.org/i/hermann-grid

Liquid State Machine

A Gorad IJCNN 2019 https://arxiv.org/abs/1901.06240



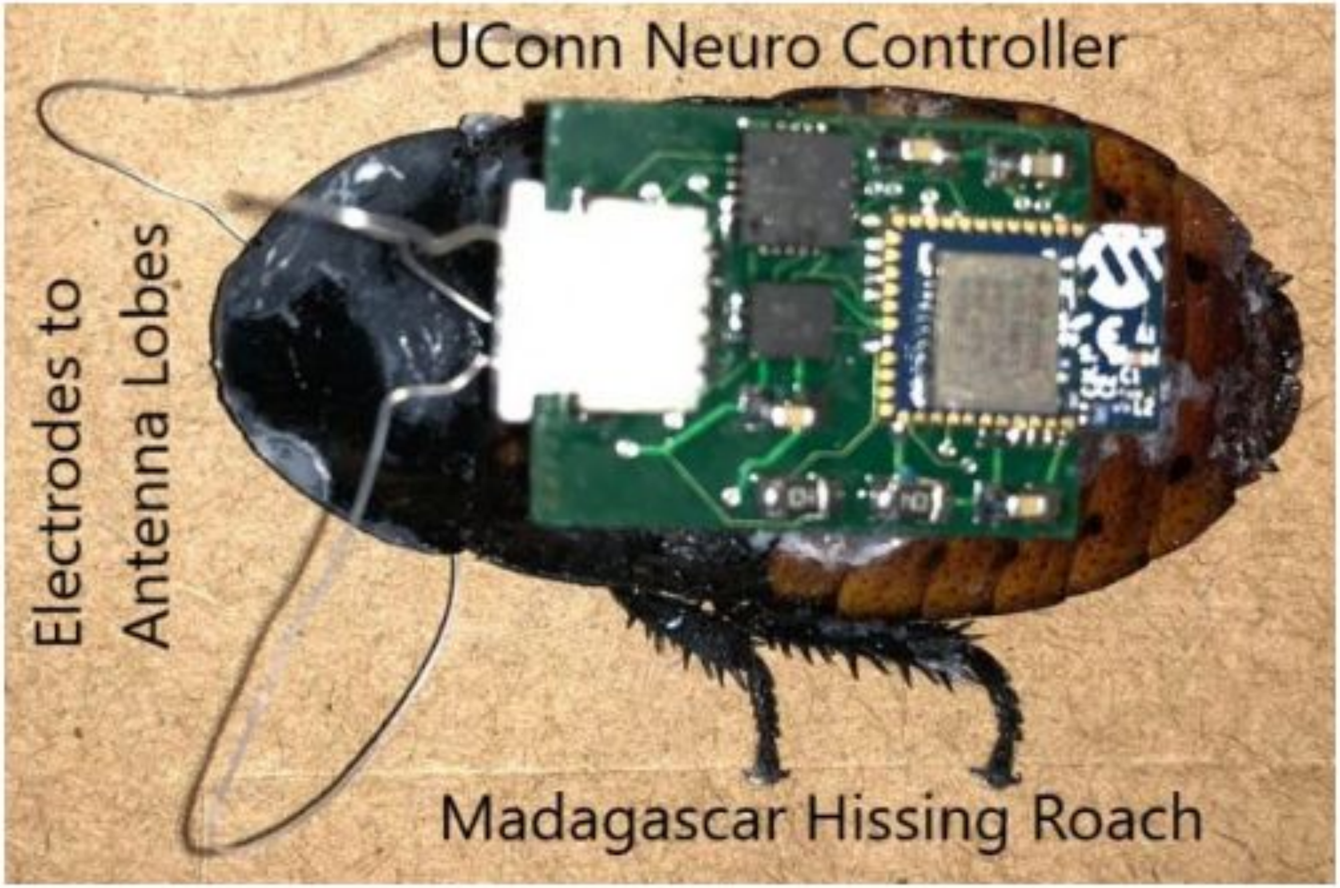




A random array of neurons produce temporary memory for speech recognition

Controlling an Insect

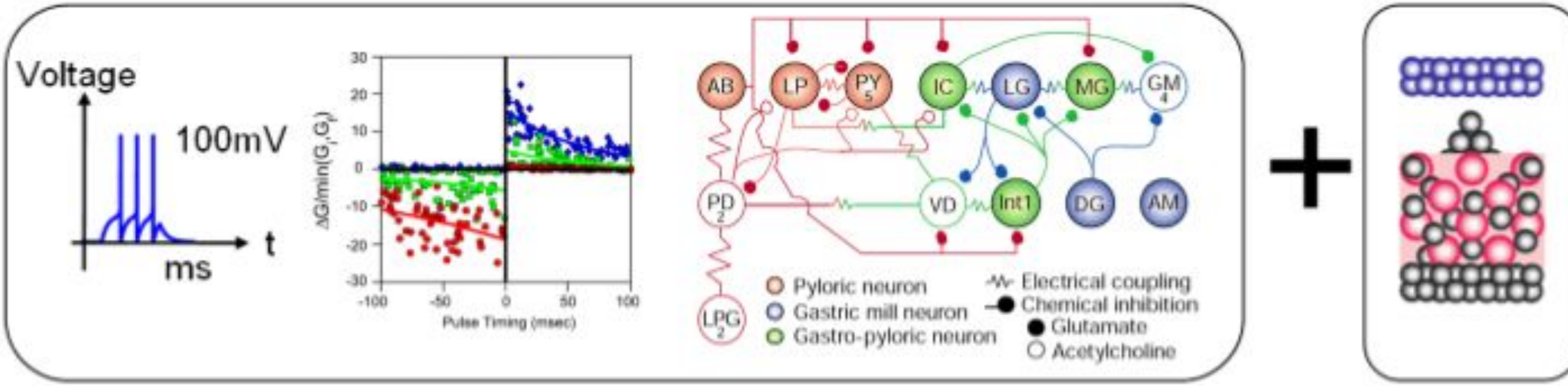
https://today.uconn.edu/2018/09/cyborg-cockroach-someday-save-life/



A cockroach with an implanted neurocontroller. (Image courtesy of the Dutta Lab)

An understanding of neuroscience enables the control of biological agents

Bio-mimetic Information Processing




Personalized medicine /prosthetics


Exa-scale computing


Physical Security


Autonomous Navigation

Course Content

- Goal:
  - Develop models for each element of SNN – neuron, synapse etc.
  - Replication algorithms for recognition and learning
- Need to be able to code in MATLAB
- Course Content
- 3 Home-works
- 4 Exams
- 1 Project to implement learning & recognition tasks
  - Handwriting
  - Video
  - Audio
  - Navigation