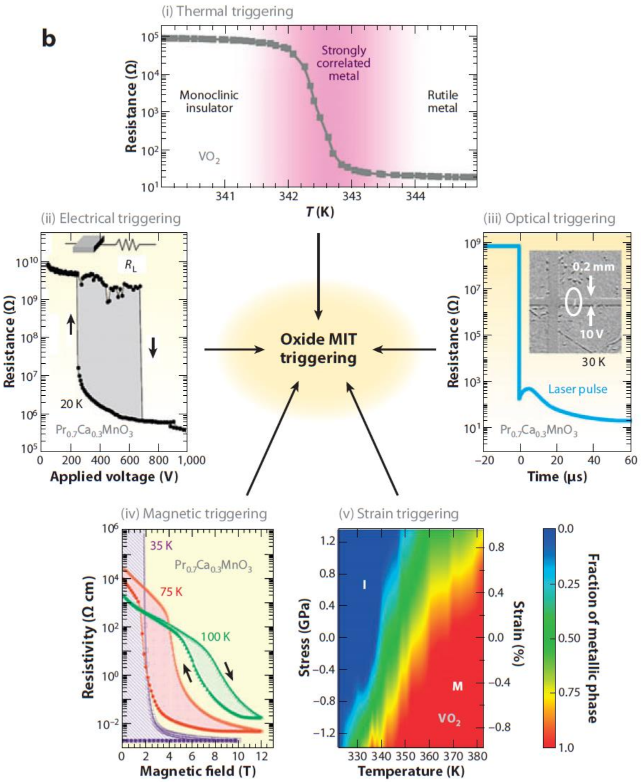
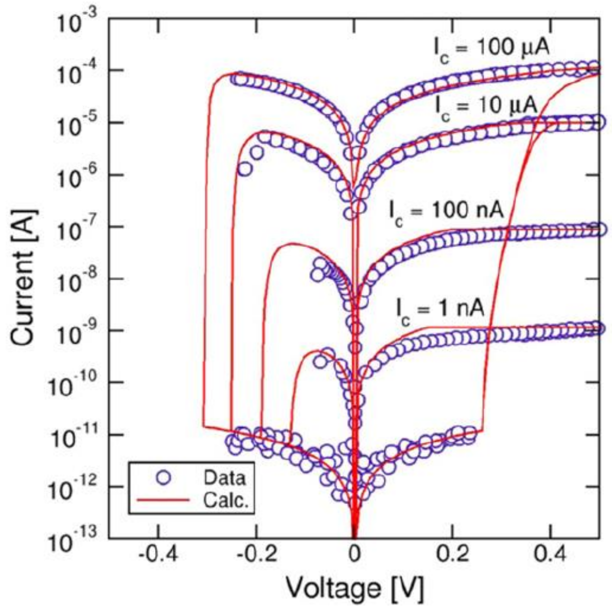
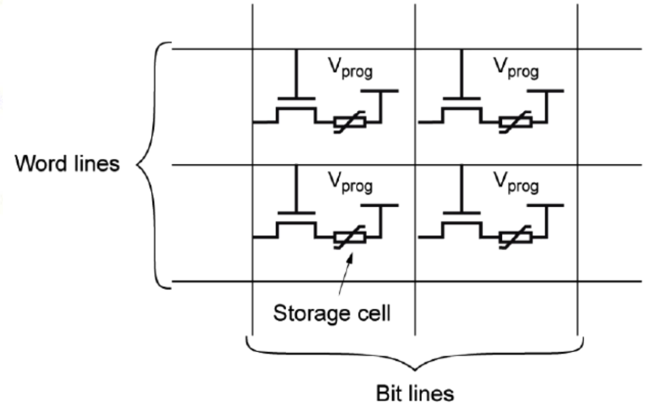
L7: Neuromorphic Computing

Instructor: Prof. Feng Xiong

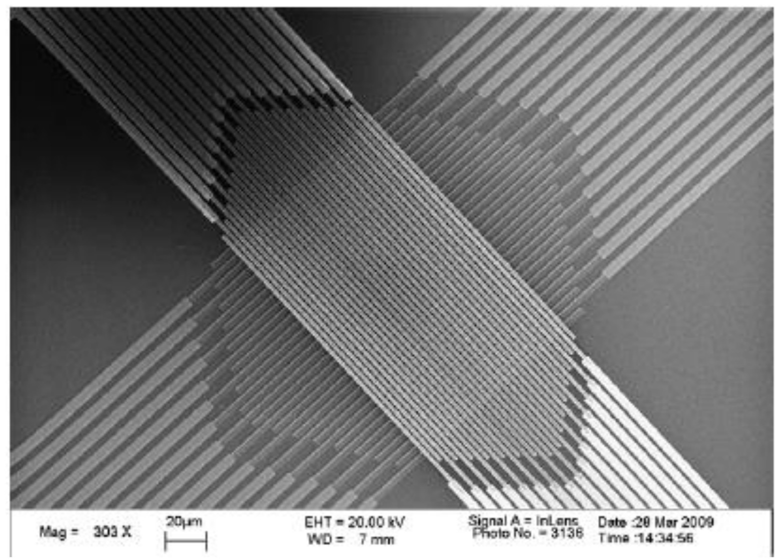
Recap



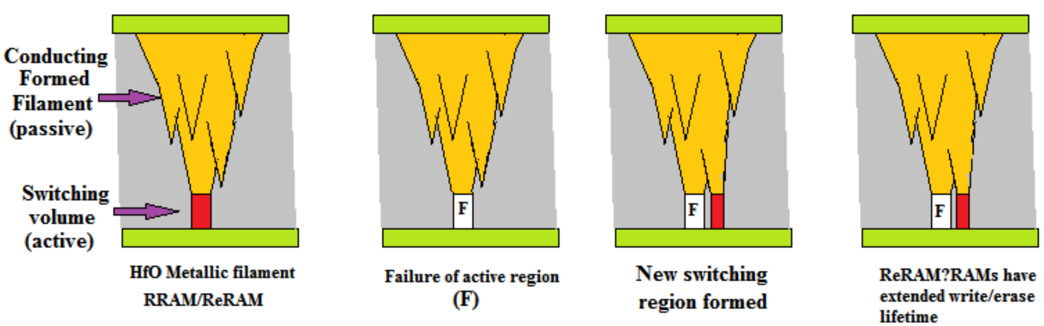




Crossbar array



Scaling implications: Write/Erase endurance requires the existance of a large filament

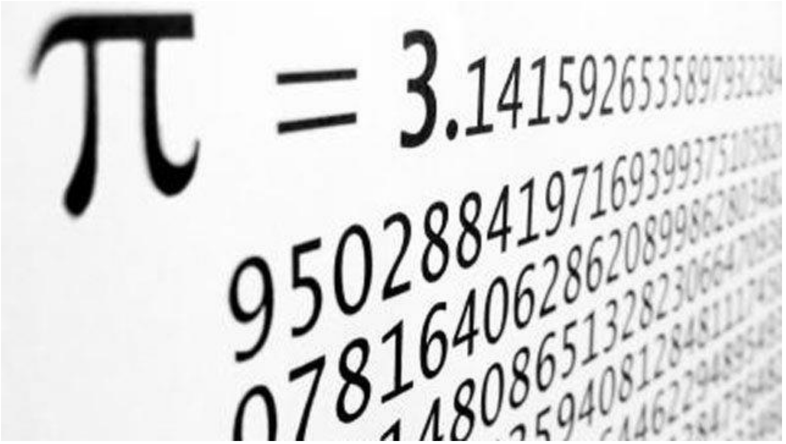


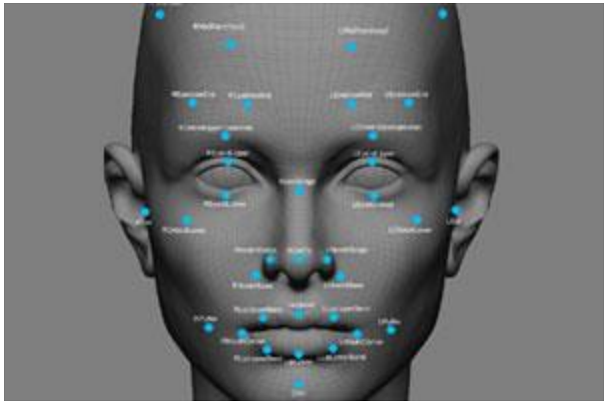
Outline

- Introduction to Neuromorphic Computing
- Biological neural network and synapse
- Synaptic plasticity
- Hebbian Learning
- Spike-timing dependent plasticity (STDP)

Computing Challenge

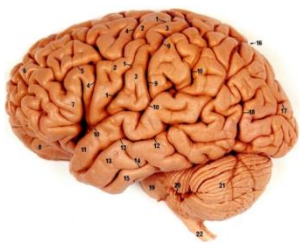
- Computer
  - well structured work
  - computing
  - storage
  - high-speed communication
- Human
  - fuzzy problems
  - image recognition
  - creativity: writing a poem
  - deep level understanding





Energy Consumption

(IBM Watson, *Jeopardy!* champion)



20 Watts

200 kiloWatts

10,000x

Computer Architecture vs Brain

“von Neumann Bottleneck”

Process (CPU) ⟷ Storage (RAM)

Human Brain

10^{10} Neurons
10^{4} Connections
↓
10^{14} Synapses

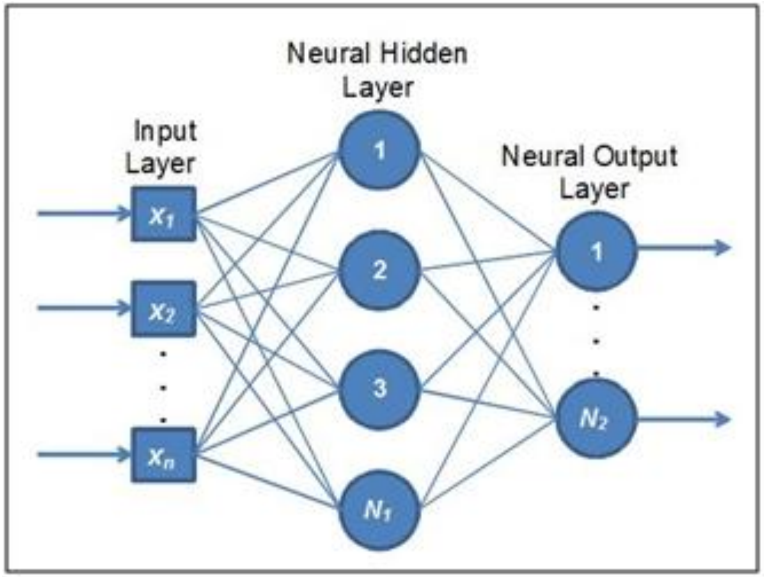
von Neumann Machines
Sequential processing
Only few channels
Fast processing

⟺

Neuromorphic Machines
Parallel processing
High computing efficiency
Large connectivity

High degree of complexity
High power consumption

Neuromorphic Computing



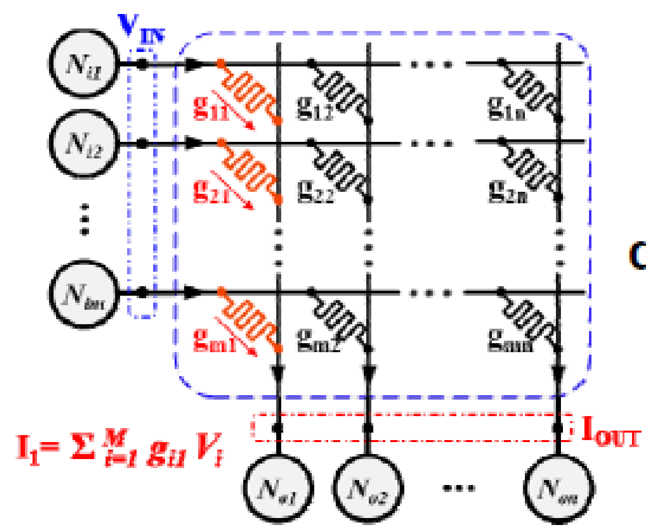
Natural matrix operation

$$[x_1\ x_2\ \dots\ x_m]\begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{m2} & \cdots & g_{mn} \end{bmatrix}$$

$$\|$$

$$[\ y_1\ \ y_2\ \cdots\ \ y_n\ ]$$

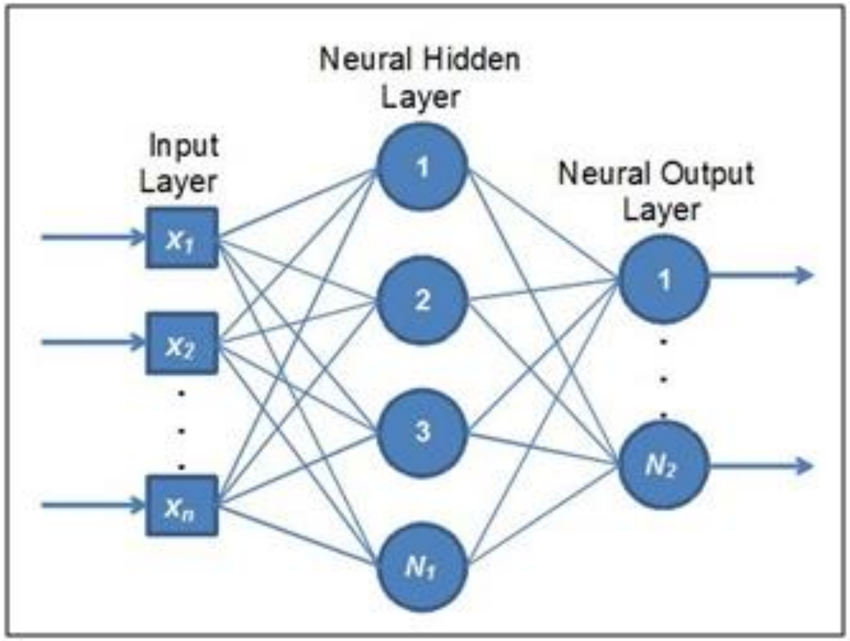
$$y_1 = \Sigma\, x_i \cdot g_{i1}$$



- Mapping a high-dimensional input to a low-dimensional output
- Pioneered by Carver Mead in late 1980s

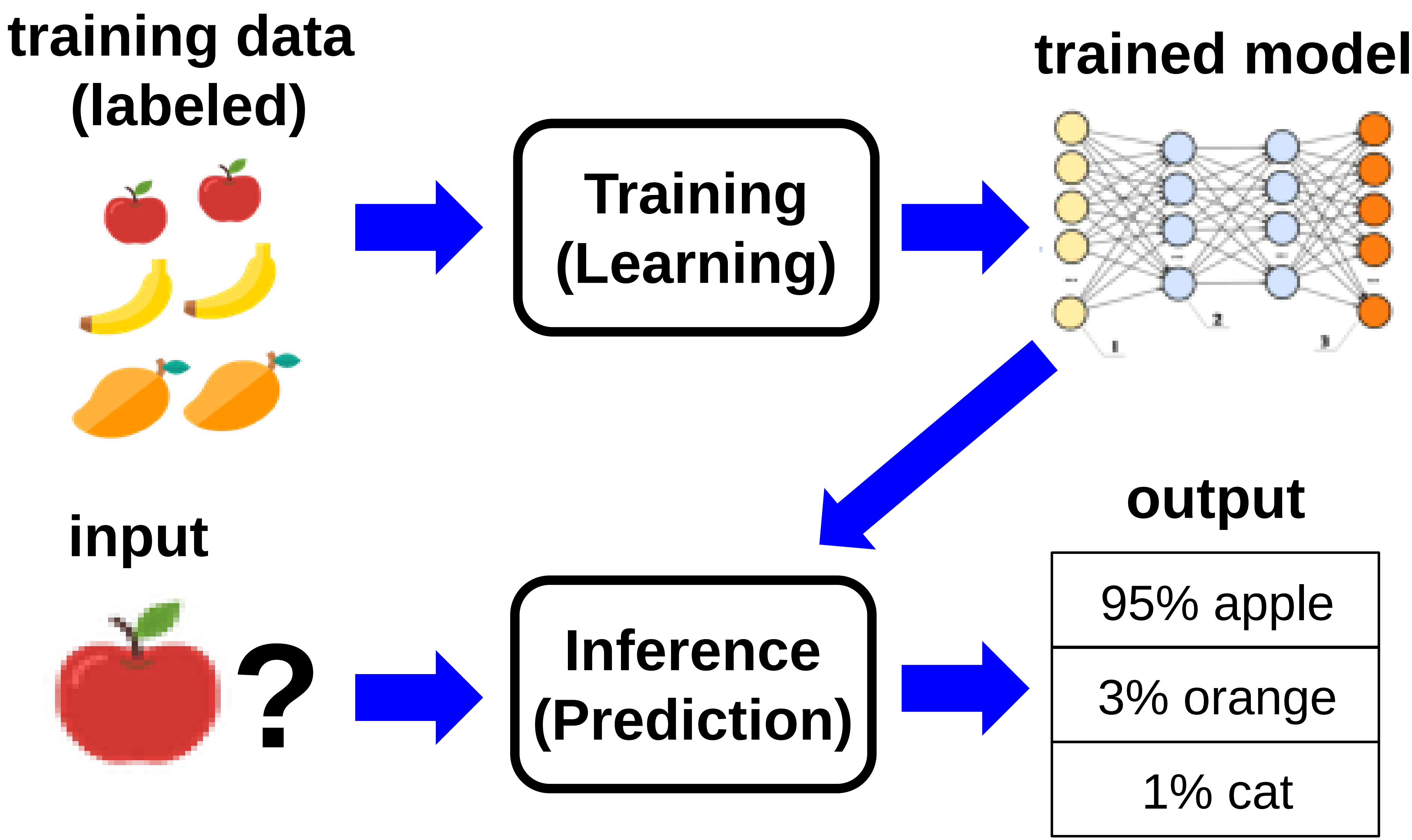
Neural Network

Artificial Neural Network

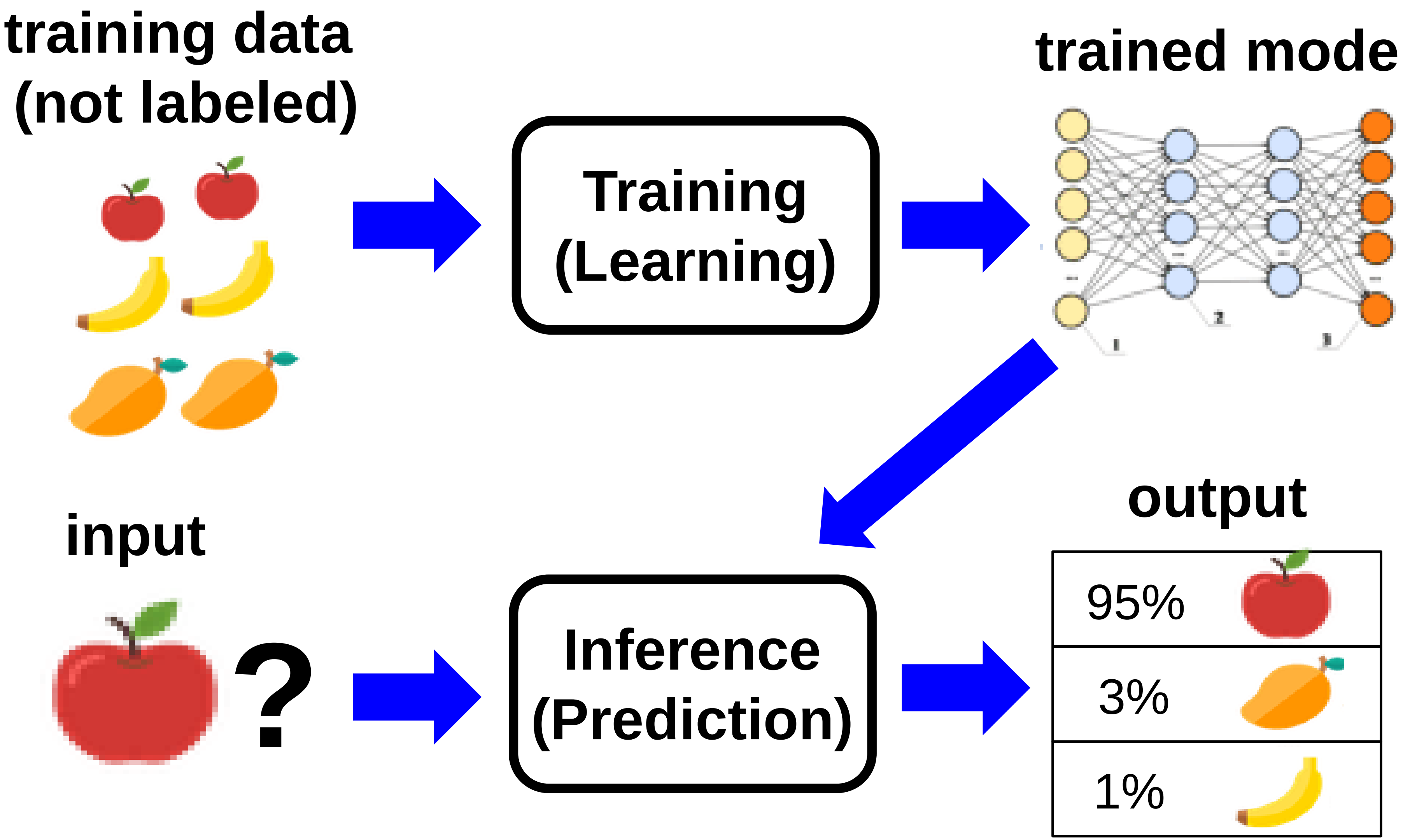


- Brain has ~10^{11} neurons
- Each neuron has ~10^{4} connections to other neurons
- → 10^{15} synapses in our cortex
- Artificial Neural Network (ANN)

Training and Inference (Supervised)



Training and Inference (Un-supervised)



Training Process

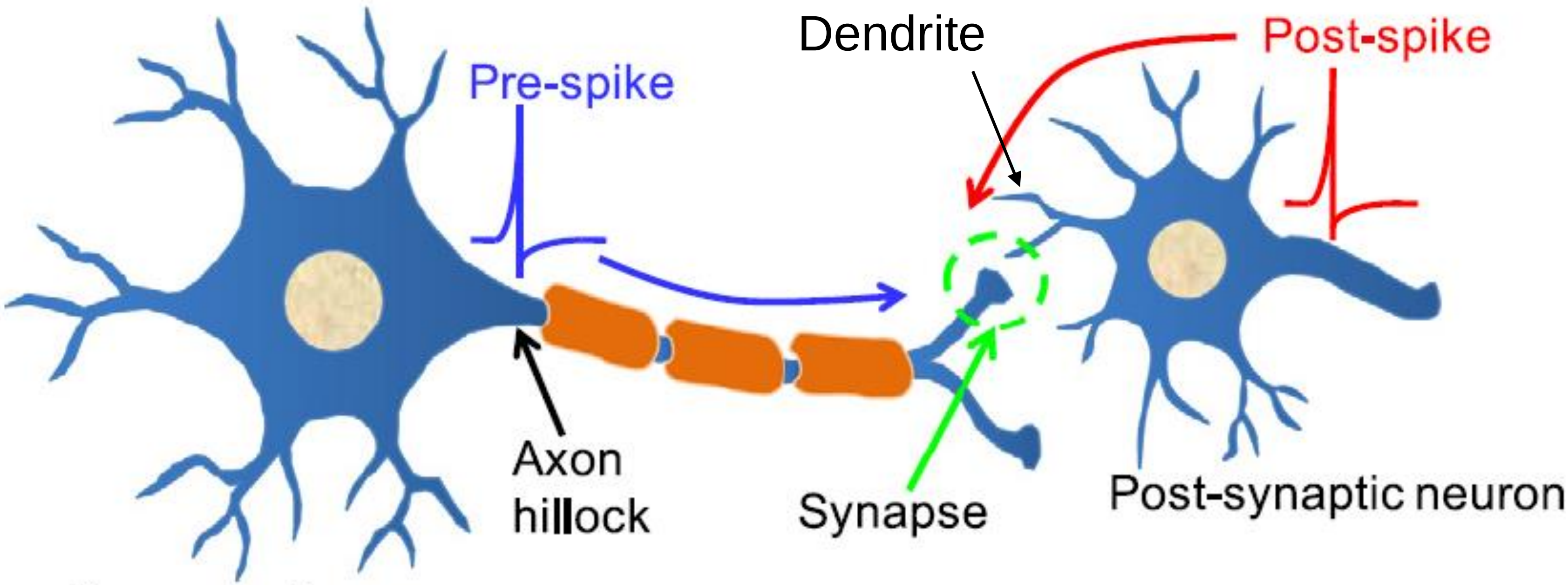
AlphaGo

Google DeepMind

DeepDream

- Training and labeling can be energy and cost expensive
- Excels when the labelling/training cost is low (e.g. GO)
- Applications: self-driving, facial recognition, industrial 4.0

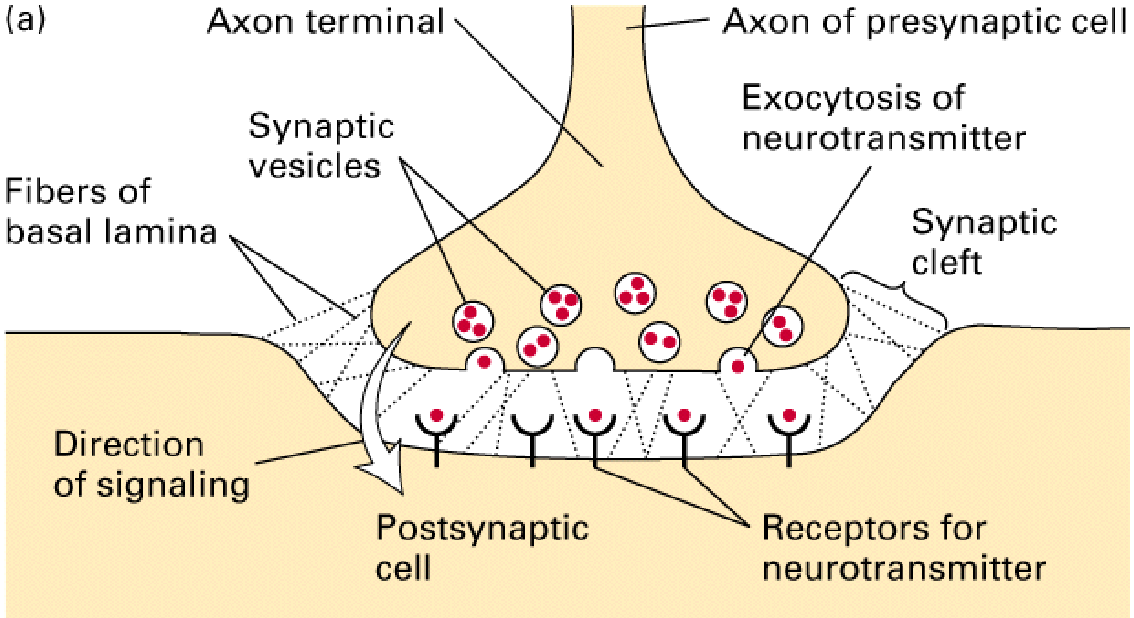
Neurons and Synapses



Kuzum et al., Nanotechnology, 2013

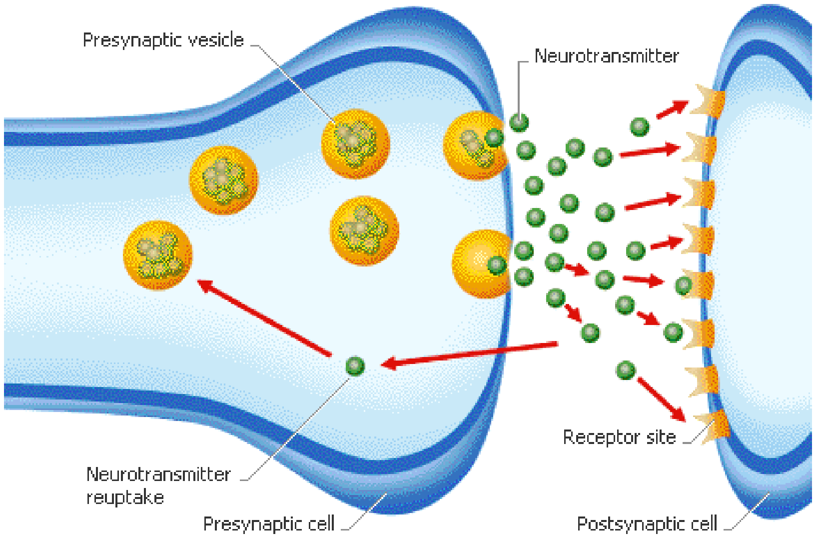
- Neuron: cell body, nucleus, axon, dendrite
- Synapse: connection between neurons
- Axon (pre-) → Synapse → Dendrite (post-)

Synaptic Transmission



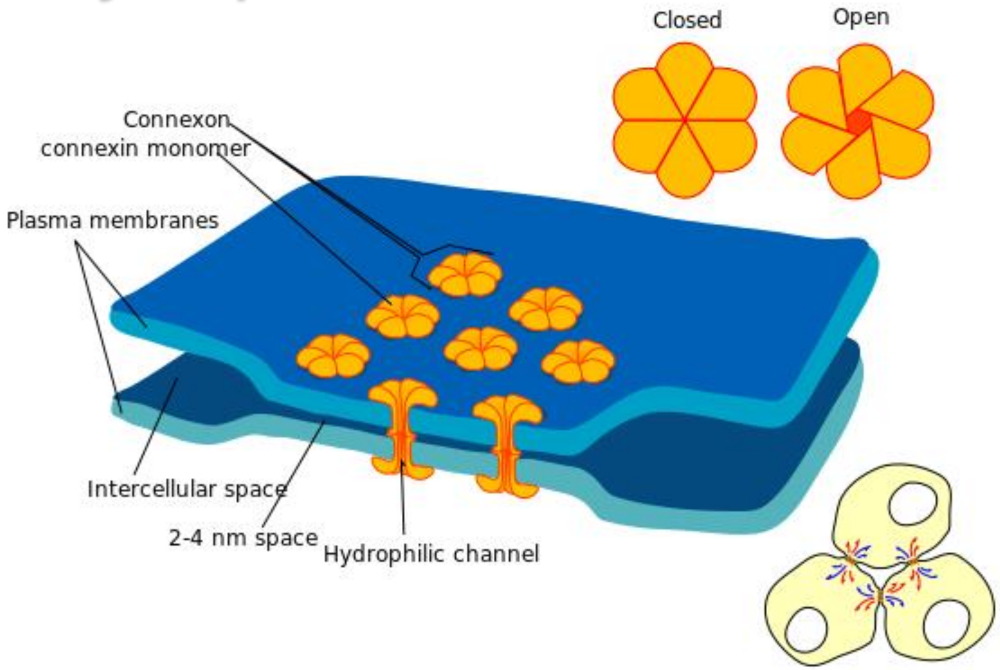
- Neurons are electrically polarized – maintaining a voltage difference across the cell’s membrane → membrane potential
- Resting potential and threshold potential
- Synaptic transmission
  1. Pre-synaptic neuron receives a threshold action potential
  2. Release neurotransmitter across synapse and captured by the receptor
  3. Resulting in short term or long term change in post-synaptic potential

Neurotransmitter in Chemical Synapse



- Neurotransmitters are chemical messengers such as amino acids; over 100 have been identified
- Generated from voltage-gated ion channels in neuron
  - Channels are closed near resting potential;
  - Open if over threshold potential
- Synaptic activities result in Na^+ and Ca^{2+} ion movement in a neuron → changing its membrane potential

Electrical Synapses



- Electrical synapses
  - Mechanical and electrically conductive link
  - minority in the nervous systems
  - direct connection between neurons through gap junctions
  - action potential can be transmitted directly via free flow of ions in a non-chemical mediated transmission
  - faster but lacking gain

Synaptic Plasticity

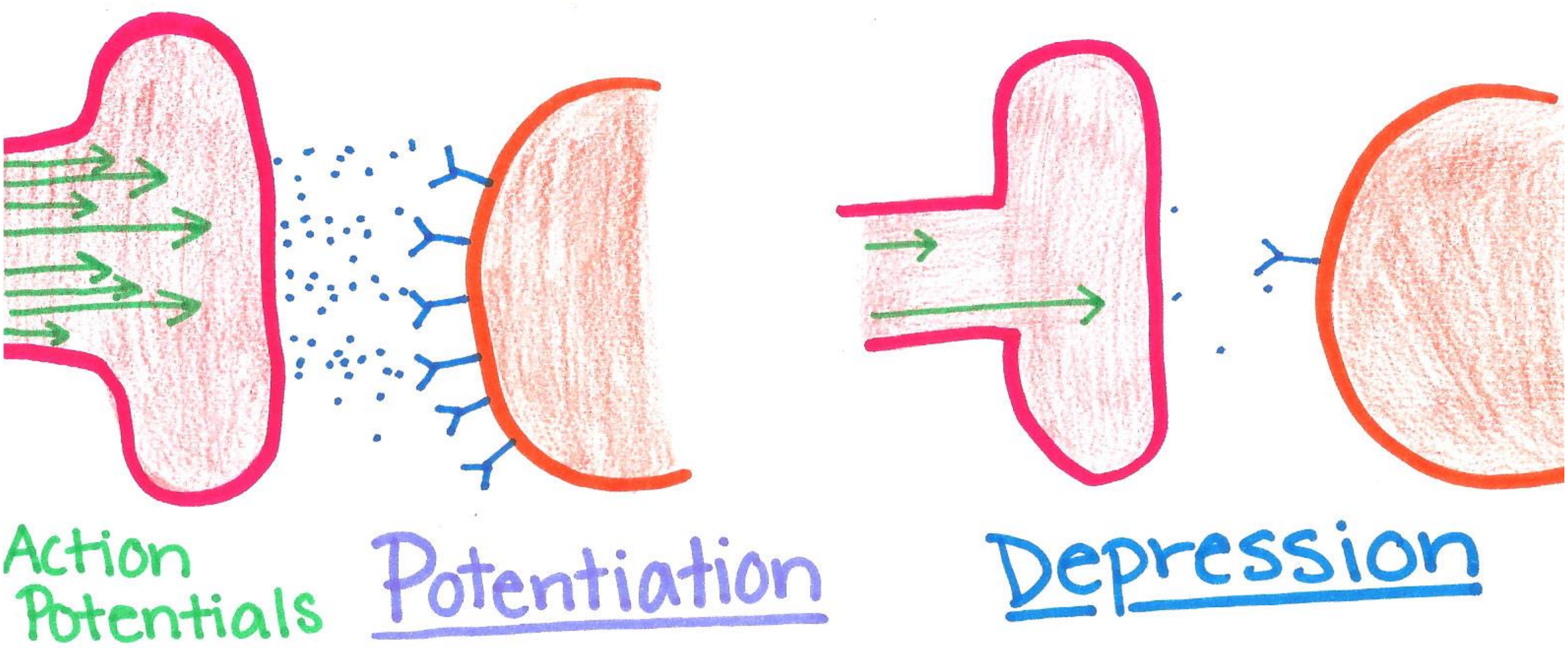
- Electrical synapse are stable
- Chemical synapses possess plasticity

- Plastic → reshaping or the art of modeling

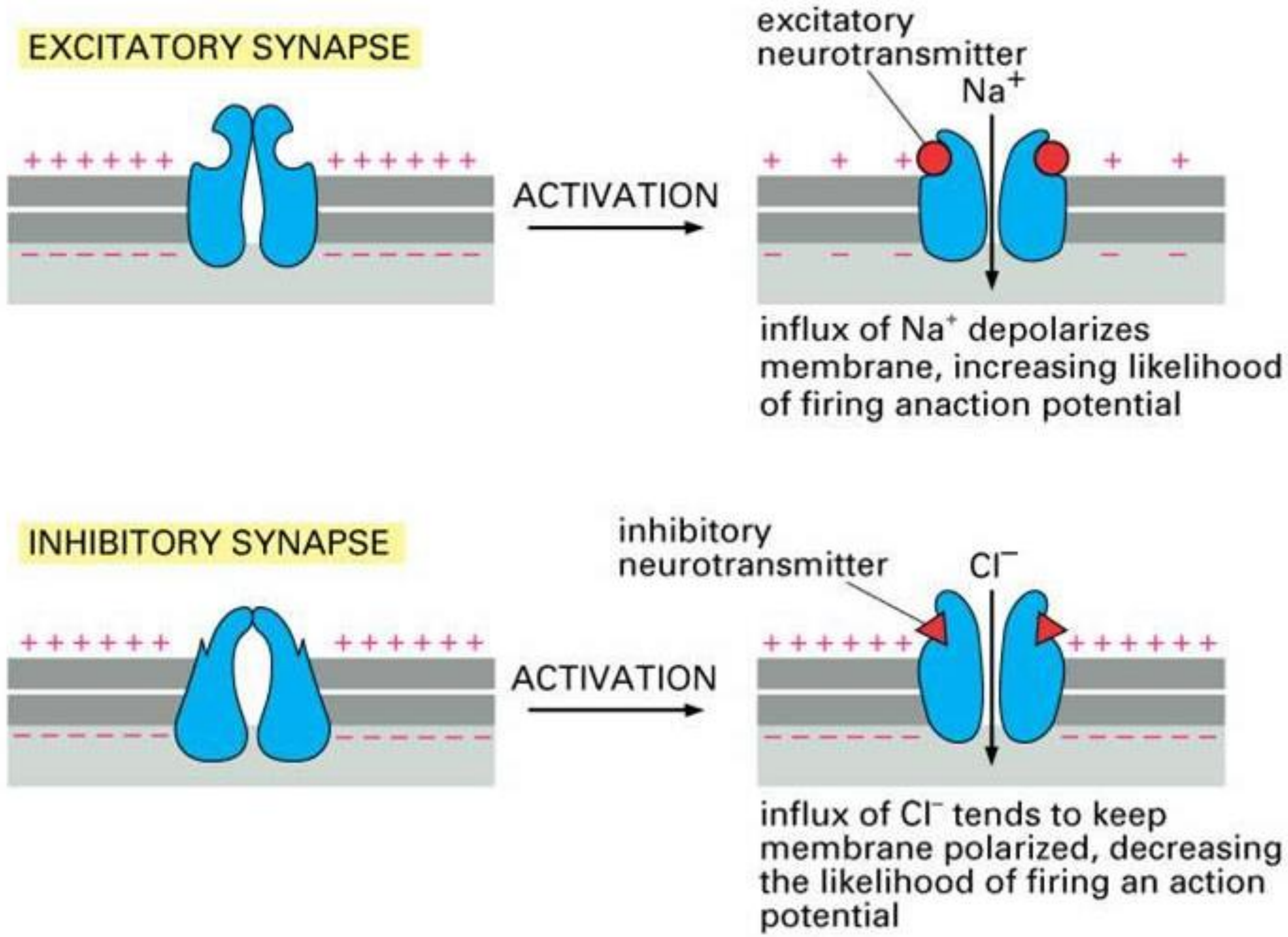
- Plasticity: synapse' ability to strengthen or weaken their connection, in response to increase or decrease neural activities
- Physically: change in the number of neurotransmitter receptors in a synapse; as well as how much neuron responds to neurotransmitters
- Important to memory and learning

Potentiation and Depression

- Potentiation: synapse connection increases in weight or conductance
- Depression: synapse connection decreases in weight or conductance



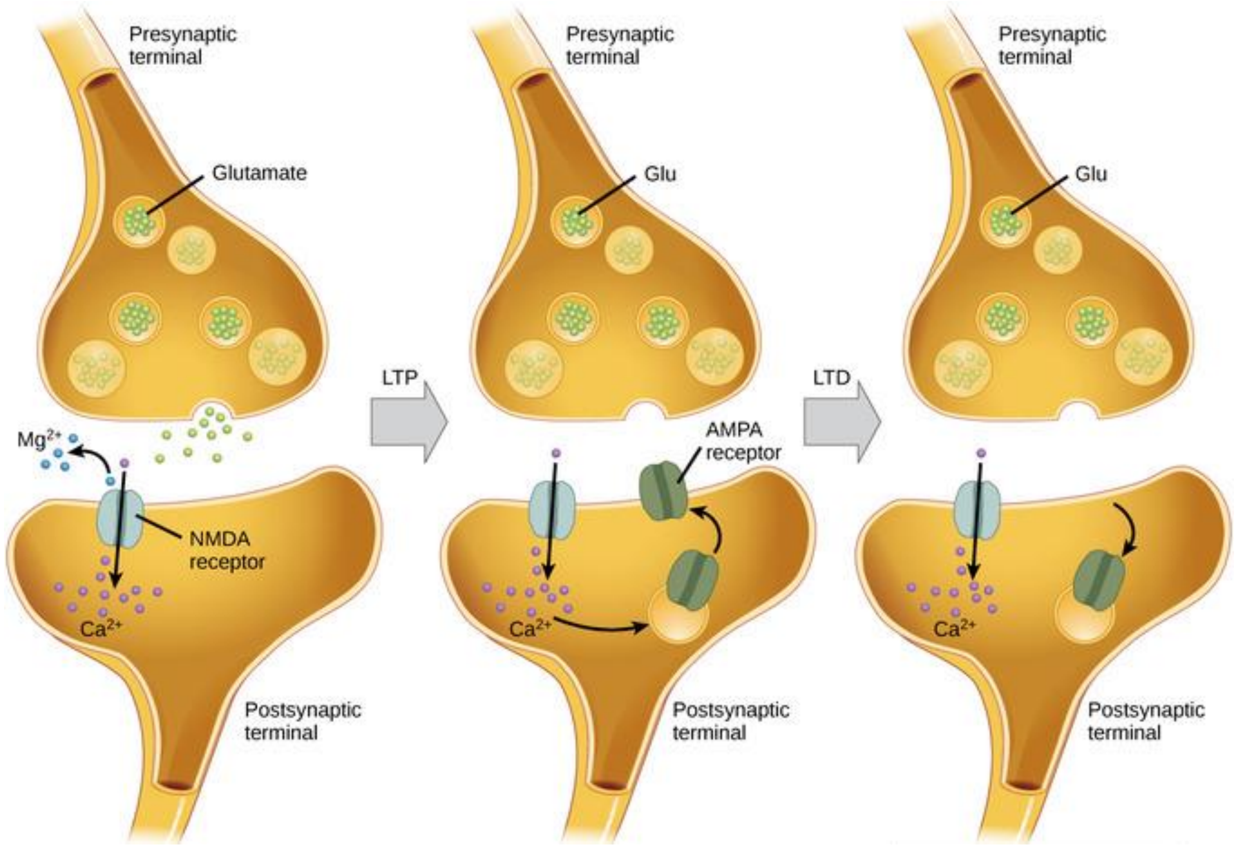
Excitatory and Inhibitory Synapse



- Excitatory synapse: potentiates upon pre-synaptic signal
- Inhibitory synapse: depresses upon pre-synaptic signal

Long Term Potentiation and Depression

- Long term plasticity: durable and persistent
- LTP: long term potentiation
- LTD: long term depression

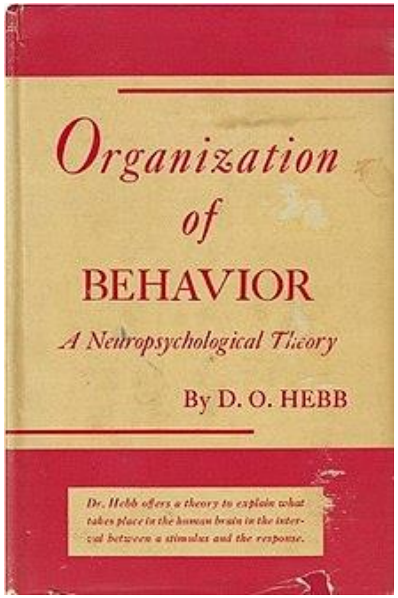


Hebbian Learning

- Neurons that fire together, wire together!
- First introduced by Donald Hebb in 1949 in his book “The Organization of Behavior”

Donald Hebb
Canadian Psychologist

- Principle: any two cells or systems of cells that are repeatedly active around the same time tend to become associated, so that activity in one facilitates activity in the other



Spike Timing Dependent Plasticity (STDP)

- Hebbian learning: connection strength between neurons are modified based on neural activities during learning
- STDP
  - spike timing dependent plasticity
  - focus on **temporal order** of spikes in cellular learning
  - plasticity depends on relative timing of pre- and post-synaptic spikes