Artificial Neural Networks
Topic-01

Inspirations from Human Brain Functions

- *Information Processing in Biological System*
- *The human brain*
- *Structure & Function of Biological Neuron*
- *Artificial Neural Networks: Bio-inspired Computing Paradigm*

Biological Information Systems

- There are two different types of biological information system that exist.
- The most distinguishing characteristics of living things is their ability to store, utilize and pass on information at an intra-cellular level . This information is encoded in DNA (that present within a cell) as a specific sequence of four different nucleotides(without any known exception). So DNA contains functional and structural information about an organism in extraordinary details. Bioinformatics strives to decode what information is biologically important and to interpret how it is used to precisely control the chemical environment within living organism.
- The brain is a highly *complex, nonlinear, and massively parallel information-processing system that occurs at inter-cellular level.*

Human Brain

- The human nervous system can be viewed as a three stage system. Central to the system is the brain represented by biological neural net, which continually receives information from receptors, perceive it and makes appropriate decisions.
- The receptors convert stimuli from human body or the external environment(through different types of receptors that are present in eye nose, skin, ear and tongue) into electrical impulse that covey information to (biological) neural net (brain) by the sensory neurons.
- The effectors converts electrical impulse generated by the neural network sent through the motor neurons into discernible response as system output.
- Human brain weighs approximately 3 pound and the volume is 90 cubic inch. Accordingly, it was estimated to contain 100 billion cells out of which 10% are neurons (the fundamental computing element of the brain). So there are about 10^{10} neurons present in the brain.
- The total number of interconnections in the brain is 10^{14}, this implies that every neuron connected to 10000 other neurons on an average.

Excitable Cells

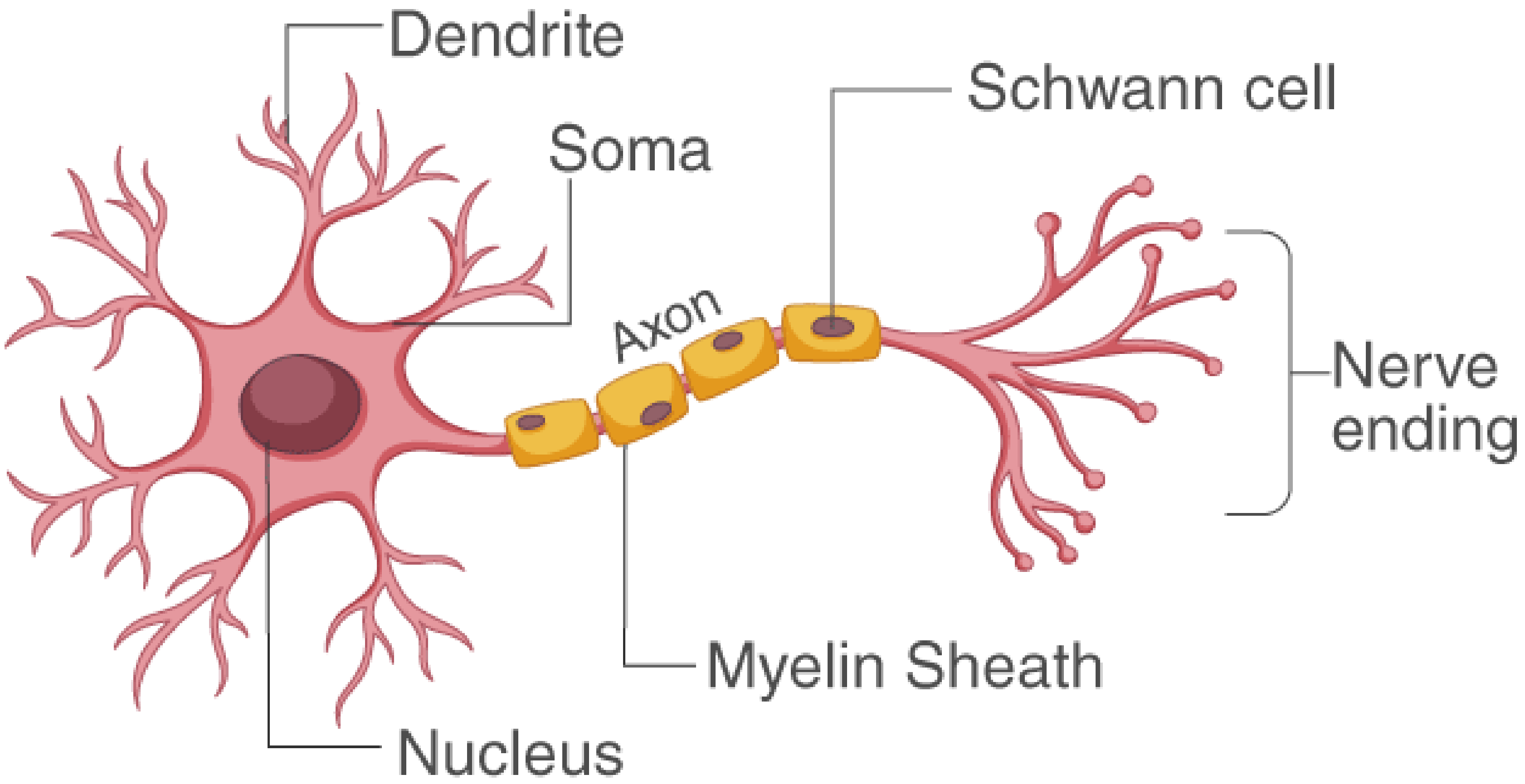
Excitable cells are those cells , which can be stimulated to create tiny electric current

EXCITABLE CELLS

NERVE CELLS(neurons)
Electric current is generated and used to rapidly transmit signals through the animals

MUSCLE CELLS
Electric current is used initiate muscle contraction

STRUCTURE OF NEURON



- Dendrites: These are branch-like structures that receive messages from other neurons and allow the transmission of messages to the cell body.
- Cell Body: Each neuron has a cell body with a nucleus, Golgi body, endoplasmic reticulum, mitochondria and other components.
- Axon: Axon is a tube-like structure that carries electrical impulse from the cell body to the axon terminals that passes the impulse to another neuron.
- Synapse: It is the chemical junction between the terminal of one neuron and dendrites of another neuron.

Neuron Types

Neurons can be classified according to the direction in which they send information.

1. Sensory Neurons: These neurons send information from sensory receptors (present in skin. Eye, nose, tongue, ear etc.) towards the central nervous system.
2. Motor Neurons : These neurons send information away from the central nervous system to muscle or gland.
3. Inter-neurons : these neurons receives information from sensory neurons and convey response through motor neuron

Resting Membrane Potential

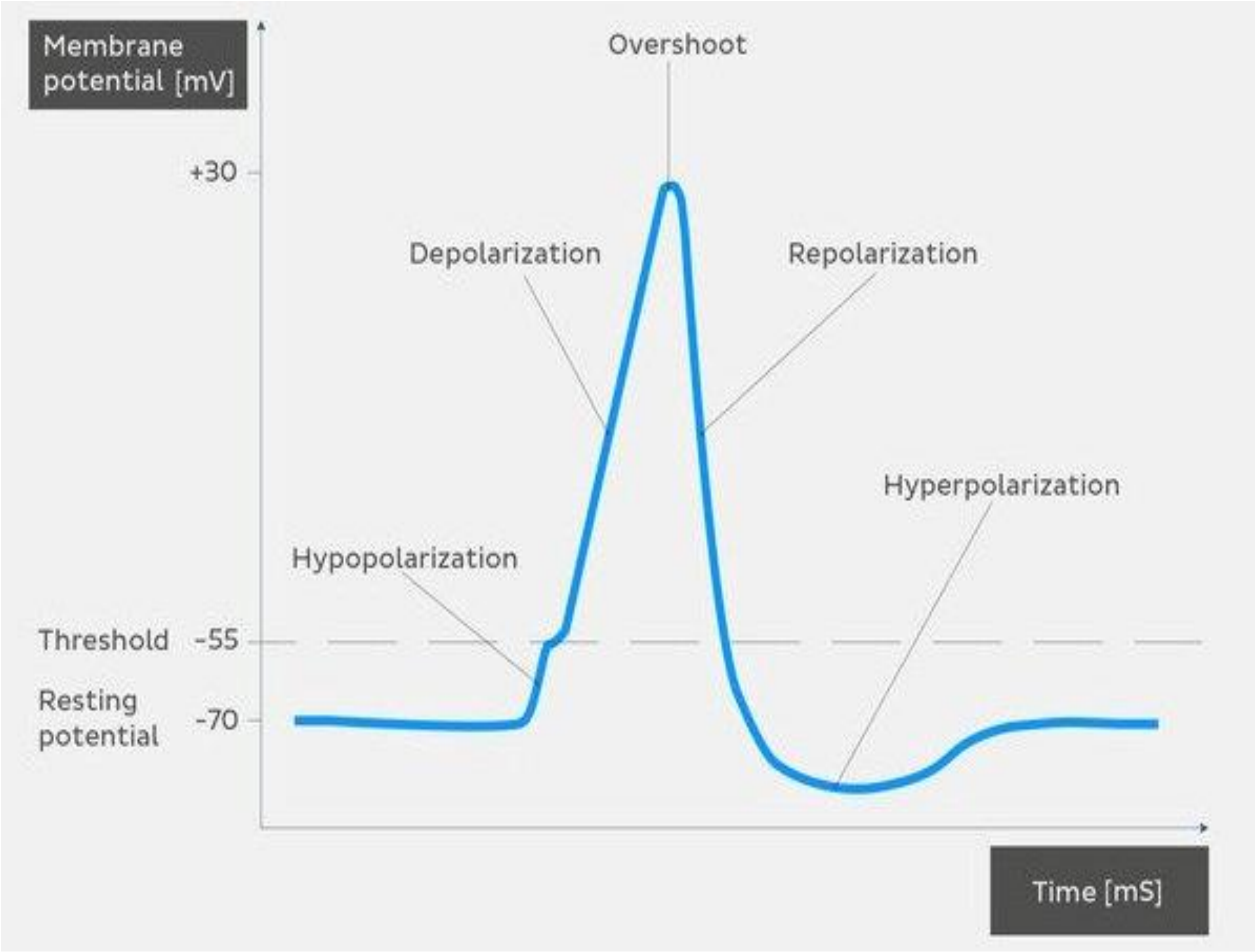
- Resting state of a neuron is the state when it is not transmitting any signal
- At resting state, the inside of the neuron is negative relative to outside extra-cellular fluid. This is because the cell membrane is semi-permeable. It permits only some ion to pass through it and blocks some other ions there by preventing balance of the concentration of different ions on either sides.
- The resting potential arises from two activities:
  1. Na^+K^+ ATPase enzyme located in the cell membrane acts like a pump to push two K^+ ions inside the cell for every three Na^+ ions out of the cell thereby causing net loss of positive charge.
  2. Some potassium channels are leaky which allow diffusion of K^+ ions out of cells
- Thus each resting cell is in a polarized state with an electrical potential across its membrane called Resting Membrane Potential.
- In case of neuron, the resting potential is near about -65mV

Action Potential

- Action potentials are nerve signals. Neurons generate and conduct these signals in order to transmit them to the target tissues. Upon stimulation, they will either be stimulated, inhibited, or modulated in some way .
- An action potential is defined as a sudden, fast, transitory, and propagating change of the resting membrane potential. Only neurons and muscle cells are capable of generating an action potential; that property is called the excitability.
- From an electrical aspect, action potential is caused by a stimulus with certain value expressed in milli-volts Not all stimuli can cause an action potential. Adequate stimulus must have a sufficient electrical value which will reduce the negativity of the nerve cell to the threshold of the action potential.
- There are sub-threshold, threshold, and supra-threshold stimuli.
  - Sub-threshold stimuli cannot cause an action potential.
  - Threshold stimuli are of enough energy or potential to produce an action potential (nerve impulse).
  - Supra-threshold stimuli also produce an action potential, but their strength is higher than the threshold stimuli.

- An action potential is a momentary reversal of membrane potential from -65mV to +40mV, lasting less than 1 ms,, followed by a restoration of its original resting membrane potential.
- Action potential are triggered by any depolarisation of membrane beyond a critical value, called the voltage threshold.
- Action potential are all or none meaning that any stimulation above the voltage threshold results in the action potential response

Action Potential Curve



Different Phases of Action Potential

- An action potential has several phases;
    1. Hypopolarization
    2. Depolarization
    3. Overshoot
    4. Repolarization
    5. Hyperpolarization
- **Hypo-polarization Phase**: It is the initial increase of the membrane potential to the value of the threshold potential.
- **Depolarization Phase**: During this phase the membrane potential exceeds the threshold opens hundreds of voltage-gated sodium channels and around 7000 sodium ions rushes into the cell and consequently the cell becomes more positively charged inside.

- Overshoot Phase. Inside of the cell becomes more and more electropositive during the depolarization phase, until the potential gets closer the electrochemical equilibrium for sodium of +61 mV. The phase of extreme positivity is the overshoot phase. During this phase the sodium ion influx slows down.
- Repolarization Phase: After the overshoot, the sodium permeability suddenly decreases due to the closing of its channels. The overshoot value of the cell potential opens voltage-gated potassium channels, which causes a large potassium efflux, decreasing the cell's electro-positivity. The purpose of this phase is to restore the resting membrane potential
- Hyperpolarization Phase: Repolarization always first leads to hyperpolarization state in which the membrane potential becomes more negative than the resting potential and this period is known as refractory period. But soon after that, the membrane establishes again the values of the resting potential.

Refractory Period

- During the refractory period, the excitable cell cannot produce another action potential. There are two sub-phases of this period, absolute and relative refractoriness.
- Absolute Refractoriness: This overlaps the depolarization and around 2/3 of repolarization phase. A new action potential cannot be generated during this period because all the voltage-gated sodium channels are already opened or being opened at their maximum speed. During early repolarization, a new action potential is impossible since the sodium channels are inactive and need the resting potential to be in a closed state, from which they can be in an open state once again. Absolute refractoriness ends when enough sodium channels recover from their inactive state.
- Relative Refractoriness: During this period the generation of a new action potential is possible, but only upon a suprathreshold stimulus. This period overlaps the final 1/3 of repolarization phase.

Propagation of Action Potential

- An action potential is generated in the body of the neuron and propagated through its axon. Propagation doesn't decrease or affect the quality of the action potential in any way, so that the target tissue gets the same impulse no matter how far they are from the neuronal body.
- The action potential generated at one spot of the cell membrane. It propagates along the membrane with every next part of the membrane being sequentially depolarized. This means that the action potential *doesn't move* but rather causes a new action potential of the adjacent segment of the neuronal membrane.
- The action potential always propagates forward, never backwards. This is due to the refractoriness of the parts of the membrane that were already depolarized, so that the only possible direction of propagation is forward. Because of this, an action potential always propagates from the neuronal body, through the axon to the target tissue.

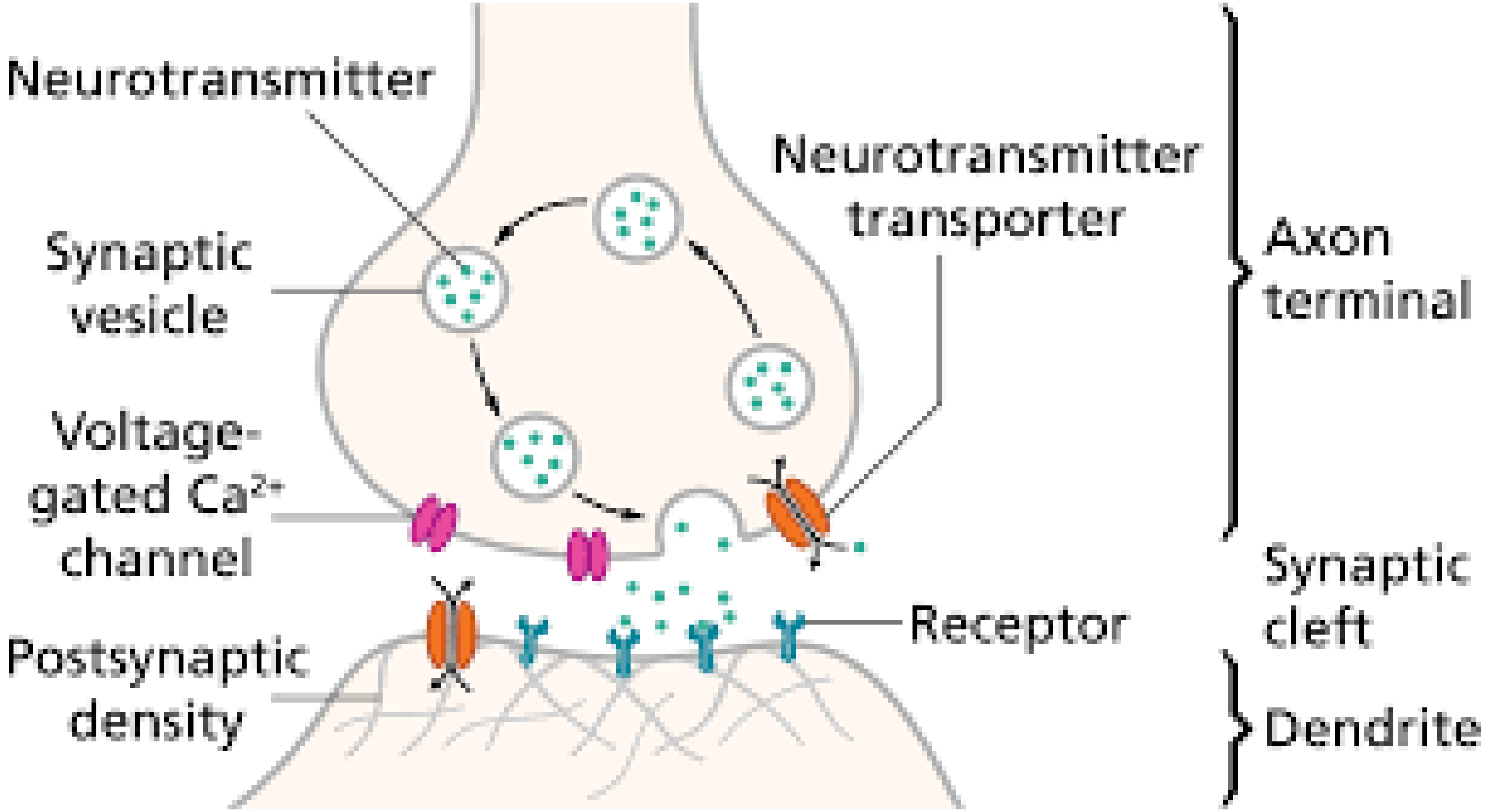
- In non-myelinated axon the action potential are conducted continuously.
- In Myelinated axon the action potential is conducted saltatory(jumping).
    - Sheath of Schwann cells which envelop the axon called myelin sheath. It act as a biological electrical insulator creating a region of high electrical resistance.
    - Nodes of Ranvier separate each Schwann cell from the next. Ion channels are located in the nodes of Ranvier only. Schwann cells prevent continuous conduction
    - Action potential jumps as an electrical current from one node to the next.
    - When the current reaches a node, opens sodium ion channels such that it generate PD large enough to create the current to reach the next node to pass on.
    - It is a very fast form of conduction(130m/s)

SYNAPSE

- The end of an axon can be associated with several dendrires or an axon or soma of other nerve cells or with the site of either muscle or secretory cells: these associations are termed as synapses (highly specialized contacts between nerve cells that transmit signals from the presynaptic neuron to the postsynaptic cell.).
- Depending on the type of target tissue, there are central and peripheral synapses.
  - Central synapses are between two neurons in the central nervous system
  - Peripheral synapses occur between a neuron and muscle fiber, peripheral nerve, or gland.
- Each synapse consists of the:
  1. Pre-synaptic membrane – membrane of the terminal button of the nerve fiber
  2. Post-synaptic membrane – membrane of the target cell
  3. Synaptic cleft – a gap between the presynaptic and postsynaptic membranes
- There are two types of synapses
  1. Electrical synapse
  2. Chemical Synapse

- Electrical Synapse
  - These are specialized for rapid signal transmission
  - The cell are separated by a gap,
  - the synaptic cleft of only 0.2nm, so that an action potential arriving the pre-synaptic side of the cleft sufficiently depolarize postsynaptic membrane to directly trigger its action potential.
- Chemical Synapse
  - These are the common most type of synapse, consists of a bulbous expansion of nerve terminal called synaptic Knob. Synaptic knob contains numerous tiny round structure called synaptic vesicles, each vesicle consists 10,000 molecules of neurotransmitters. The cell are separated by a gap , the synaptic cleft of 20nm.
  - When a wave of depolarization reaches the presynaptic membrane, voltage gated calcium channels open. Outside concentration of calcium ion is so large , so they diffuse inside which stimulate synaptic vesicle to move to terminal membrane to fuse with it. Then ruptures to release the neuro-transmitter chemicals in the cleft.

Chemical Synapse



- These neuro-transmitter molecules rapidly pass to the other side of the gap to combine with specific receptor molecules on the post-synaptic cell to create electric current which is passed further in this cell.
- At the end of the signal, synaptic knob reabsorb some neurotransmitters and enzymes in the synapse, and neutralize others.

- In humans, synapses are chemical. If a neurotransmitter stimulates the target cell to an action, then it is an excitatory neurotransmitter. On the other hand, if it inhibits the target cell, it is an inhibitory neurotransmitter The postsynaptic membrane contains receptors for the neurotransmitters. Once the neurotransmitter binds to the receptor, the ligand-gated channels of the postsynaptic membrane either open or close. Depending on whether the neurotransmitter is excitatory or inhibitory, this will result with different responses.

Postsynaptic Potential

- Postsynaptic potentials are the changes in the membrane potential of the postsynaptic terminal of a chemical synapse
- Postsynaptic potential should not be confused with action potential although their function is to either initiate or inhibit action potential depending up on the type of neurotransmitters released by terminal button of the presynaptic neuron 's axon into the synaptic cleft.
- Postsynaptic potential begin to be terminated when the neurotransmitter detaches from the receptors. The receptor is then free to return to its previous structural state.
- Ion channel that had been opened by the receptor when the neurotransmitter was bound to it will now close. Once the channels are closed, the membrane is returned to its equilibrium potential.

Web links for Video Lecture on Action Potential and Synapse

- Action potential in neuron https://youtu.be/oa6rvUJlg7o
- How a synapse works https://youtu.be/OvVl8rOEncE

The function mechanism of a single neuron is known and the networks of neuron still be unknown(remains to be discovered)

Artificial Neural Networks

A Bio-inspired Computing Paradigm

- The artificial neural networks, commonly referred to as "neural networks," has been motivated by the way the human brain computes which is entirely different from the conventional digital computer.
- The brain has the capability to organize its structural constituents, known as *neurons, so as to* perform certain computations (like pattern recognition, perception, and motor control) many times faster than the fastest digital computer in existence today.
- The brain intelligence is due to its inbuilt structure and has the ability to build up its own rules of behavior through experience(learning). which is built up over time. The major development (i.e., hardwiring) of the human brain taking place during the first two years from birth, but the development continues well beyond that stage.

- This development of nervous system is synonymous with a plastic brain: Plasticity permits the developing nervous system to adapt to its surrounding environment. Just as plasticity appears to be essential to the functioning of neurons as information-processing units in the human brain(biological Neural Networks), so it is with (artificial)neural networks made up of artificial neurons.
- A neural network is a massively parallel distributed processor made up of simple processing units that has a natural propensity for storing experiential knowledge and making it available for use. It resembles the brain in two respects:
    1. Knowledge is acquired by the network from its environment through a learning process.
    2. Interneuron connection strengths, known as synaptic weights, are used to store the acquired knowledge.

Salient Features of Artificial Neural Networks

- *Generalization Ability:* it refers to the ability of the neural network to produce the reasonable outputs for the inputs which are not encountered during the training (learning).
- *Graceful Performance Degradation (Fault Tolerance):* A neural network, inherently fault tolerant, or capable of robust computation, in the sense that its performance degrades gracefully when a neuron or its connecting links are damaged or recall of a stored pattern is impaired in quality.
- *Nonlinearity:* An artificial neuron can be linear or nonlinear. A neural network, made up of an interconnection of nonlinear neurons, is itself nonlinear. Moreover, the nonlinearity is distributed throughout the network. Nonlinearity is a highly important property, particularly if the underlying physical mechanism responsible for generation of the input signal (e.g., speech signal) is inherently nonlinear

Learning Through Input–Output Mapping

- The learning with a teacher, or supervised learning, involves modification of the synaptic weights of a neural network by applying a set of labeled training examples.
- Each training example consists of a unique input signal and a corresponding desired (target) response.
- The network is presented with an example picked at random from the training set, and the synaptic weights (free parameters) of the network are modified so as to minimize the difference between the desired response and the actual response produced by the network for the input signal.
- The training of the network is repeated for many examples in the training set, until the network reaches a steady state where there are no further significant changes in the synaptic weights. The previously applied training examples may be reapplied during the training session, but in a different order.
- Thus the network learns from the examples by constructing an input–output mapping for the problem at hand.