**Neural Networks for Signal Processing – I**

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Lecture – 01

The Human Brain

Let us begin with a brief introduction to how the brain functions and how we can draw inspiration from it to design neural networks. The brain is a complex organ, and one of its critical regions is the cerebrum. The cerebrum comprises many functional areas responsible for voluntary movement, memory, and other essential functions.

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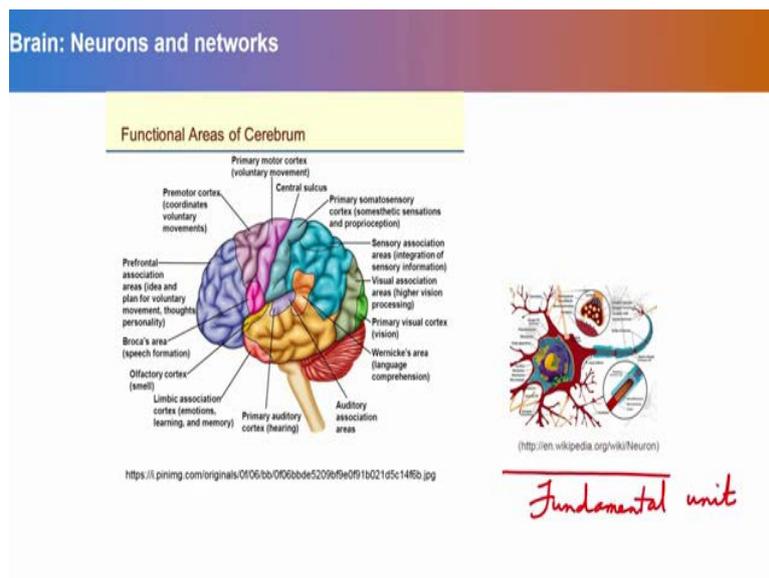
Functional Areas of the Cerebrum:

i. **Voluntary Movement**: The pink shaded area controls voluntary movement.

ii. **Sensory Association**: This region is responsible for the integration of sensory information.

iii. **Visual Association**: The light green shaded area handles vision processing.

iv. **Primary Visual Cortex and Language Comprehension**: This region is involved in processing visual information and understanding language.

v. **Auditory Association Areas**: These areas are responsible for processing sounds.

vi. **Emotions, Learning, and Memory**: The red shaded region is involved in emotional responses, learning, and memory.

vii. **Olfactory Cortex and Speech Formation**: These areas are involved in the sense of smell and the formation of speech.

The brain controls various functions, from motor control to thoughts, emotions, and behavior, through a complex process of chemical and electrical message exchange. This makes the brain a crucial information processing engine for the human body, facilitating communication, computation, and control.

Neurons: The Fundamental Units of the Brain

- **Structure**: Neurons consist of an axon, a nucleus, and dendrites. The axon terminals contain synaptic vesicles that release chemical messengers. These messengers pass through synaptic junctions to the next neuron.

- **Importance**: Neurons are vital because they enable us to develop biophysical models or plausible mathematical models that can be used to create networks.

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Brain Functions: Communication, Computation, and Control

- **Massive Parallel Distributed Information Processing**: The human brain, and mammalian brains in general, operate as massive parallel distributed information processing engines.

- **Analogy with Silicon Systems**: The human brain contains about 100 billion neurons and approximately 100 trillion synapses. An adult human brain weighs between 1.5 to 2 kilograms. The conduction speed of a nerve impulse ranges from 0.6 meters per second to 120 meters per second. The brain consumes 20% of the body's power, and it operates at about 10^{-16} Joules per operation per second.

- **Electrochemical Process**: Information transport in the brain occurs through an electrochemical process, involving cycles of ion exchange and electrical signal conduction through neurons. The brain operates at a temperature of 37 ± 2 degrees Celsius. It is an impressive fault-tolerant system with built-in error correction. Neuron firing is asynchronous, and as we know from circuits and systems, asynchronous systems lack an inbuilt clock, which results in power reduction. This is one of the many inspirations we can draw from biology. Furthermore, we need 7.5 to 8 hours of sleep to function optimally.

Neuron Schematic

- **Soma**: The soma is the bulbous cell body containing the nucleus.

- **Dendrites**: These are long, filament-like branching structures attached to the cell body. Dendrites receive sensory inputs.

- **Axon**: The axon is a single, long transmission line, about 1000 times the size of the neuron in terms of length. Each axon terminal has many small vesicles or sacs. These vesicles release neurotransmitters that bind to chemical receptors on the receiving neuron.

In the following discussions, we will delve deeper into synapses and other aspects of neurons, laying the foundation for understanding and designing artificial neural networks inspired by the human brain.

Information Processing in the Brain

How do we process information in the brain? This involves several stages, with the first being information transmission. This process relies on a combination of chemical messaging and electrical signals during memory encoding and recall. This is fundamental because whenever we store or recall patterns, encoding takes place, leading to information transmission.

Action Potential: Each neuron maintains a potential gradient across its membrane due to varying ionic concentrations of sodium, potassium, chlorine, and calcium ions within the cell, resulting from various metabolic activities such as anabolism and catabolism. These varying ionic concentrations lead to potential differences across the neuron's membrane. When the voltage changes significantly, an electrochemical pulse known as an action potential is generated, which can be measured as a brain wave with a rhythmic pattern. Projects like the Connectome Project and the Human Brain Project provide biophysical models of these neurons. Interested readers are encouraged to explore these projects to learn more about biophysical models and understand how to mathematically abstract a biological neuron as accurately as possible.

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Synapse: The next key term is synapse. The electrical pulse travels rapidly along the axon, which functions like a transmission line. This electrical pulse is transferred to a dendrite of a connecting neuron through a synapse. A synapse is a complex membrane gap about 20 nanometers wide, used to transmit signals between neurons. This transfer, also known as a

synaptic connection, typically occurs between an axon and a dendrite, although dendrite-to-dendrite connections also exist, making the process more complex. However, the most common form is the axon-dendrite connection. A typical neuron fires 5 to 50 times per second, which is a significant aspect of neuronal function.

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Biological and Artificial Neural Networks

Neurons are of great interest when it comes to forming neural networks in artificial settings. From a biological perspective, each neuron can establish thousands of connections with other neurons, resulting in approximately 100 trillion synapses that create neural networks. These are known as biological neural networks. Inspired by this evidence, we aim to develop artificial neural networks based on similar principles.

Dynamic Connections: In the biological realm, the connections between neurons are dynamic, which is crucial. These connections strengthen with each memory experience. For instance, the first time I see a red color, it registers in my memory. However, I might forget it over time. Repeated exposure to the same red color reinforces the memory, eventually making it permanent.

Moreover, the connections are not static; some links can break, and new ones can form. This dynamism can inspire the design of artificial neural networks. Can we develop neural networks that are dynamic? Can we form new connections as we process data and reinforce experiences? Can we eliminate redundant neurons and read them out? These are essential considerations in neural network design.

Ion Exchange Channels: Each axon terminal contains thousands of membrane-bound sacs filled with neurotransmitters, which are chemical messengers that relay, amplify, and modulate signals between neurons and other cells. This process differs from the silicon counterpart, which relies on electron-hole transportation due to the presence of transistors. In neurons, the process involves chemical messaging.

When an electrical pulse excites a neuron, various neurotransmitters are released. These neurotransmitters diffuse across the cell membrane into the synaptic gap between neurons, binding to chemical receptors on the dendrites of the receiving neuron. This process alters the cell's permeability to specific ions, which is critical because it determines whether conduction channels open or close for specific ions. This can be thought of as a communication channel with chemical messaging, leading to ion-specific channels.

The potential in the receiving neuron is altered, resulting in a new electrical signal. This entire process occurs in less than 1 to 2 milliseconds. Thus, a message in the brain undergoes cycles of electrical and chemical messaging, involving communication, computation, and control, driven by external stimuli. This illustrates a sophisticated information communication technology embedded in a biological system. Although it may appear slow, this massively parallel and distributed system achieves very high throughput, unlike silicon systems.

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Artificial Neural Networks: Goals and Inspirations
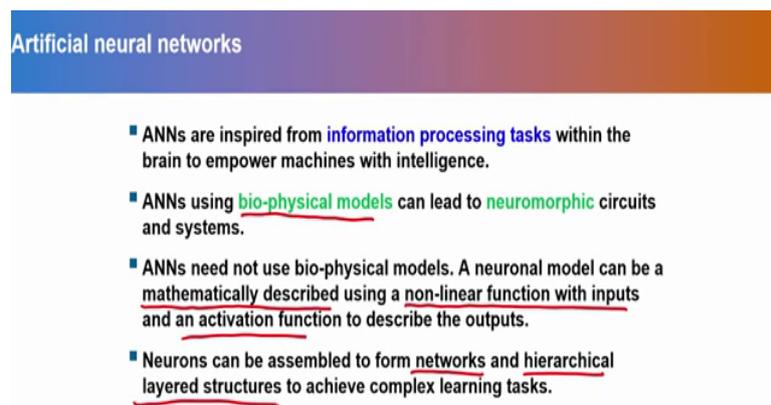
Our primary goal in this course is to explore artificial neural networks (ANNs). ANNs are inspired by the information processing tasks within the brain, aiming to empower machines with human-like intelligence. ANNs can be categorized into two types: those inspired by biophysical models and those that incorporate biophysical models, leading to neuromorphic circuits and systems. This is an active area of research.

For instance, if we aim to develop a robot with human-like vision, speech, or even the ability to sing, we need to understand biophysical processes and integrate these models into our designs.

However, ANNs do not necessarily have to use biophysical models. A neuron model can be mathematically abstracted using a nonlinear function with inputs and an activation function that describes the outputs. By using such a function and activation mechanism, we can create a model of the neuron. Whether it is a biophysical model or a mathematically abstracted one, these neurons can be assembled into networks, forming what we call neural networks. These networks can be structured into hierarchical, layered architectures to accomplish complex learning tasks.

Inspired by the workings of the brain, our journey in this course begins with formulating networks and systems to tackle various learning tasks.