COMP9444
Neural Networks and Deep Learning

1. Neuroanatomy

What is a Neural Network?

- massively parallel distributed processor made up of simple processing units
- knowledge acquired from environment through a learning process
- knowledge stored in the form of synaptic weights

Why Neural Networks?

- biologically inspired
- good learning properties
- continuous, nonlinear
- well adapted to certain tasks
- fault tolerant
- graceful degradation

Sub-Symbolic Processing

Theories about Intelligence

- 380BC Plato (Rationalism - innateness)
- 330BC Aristotle (Empricism - experience)
- 1641 Descartes (mind-body Dualism)
- 1781 Kant (Critique of Pure Reason)
- 1899 Sigmund Freud (Psychology)
- 1953 B.F. Skinner (Behaviourism)

Artificial Intelligence Origins

- 1642 Blaise Pascal (mechanical adding machine)
- 1694 Gottfried Leibniz (mechanical calculator)
- 1769 Wolfgang von Kempelen (Mechanical Turk)
- 1837 Charles Babbage & Ada Lovelace (Difference Engine)
- 1848 George Boole (the Calculus of Logic)
- 1879 Gottlob Frege (Predicate Logic)
- 1950 Turing Test
- 1956 Dartmouth conference

Neural Network Origins

- 1943 McCulloch & Pitts (neuron models)
- 1948 Norbert Wiener (Cybernetics)
- 1948 Alan Turing (B-Type Networks)
- 1955 Oliver Selfridge (Pattern Recognition)
- 1962 Hubel and Wiesel (visual cortex)
- 1962 Frank Rosenblatt (Perceptron)

Serial Symbolic AI

- 1956 Newell & Simon (Logic Theorist)
- 1959 John McCarthy (Lisp)
- 1959 Arther Samuel (Checkers)
- 1965 Joseph Weizenbaum (ELIZA)
- 1967 Edward Feigenbaum (Dendral)

Neural Network "Dark Ages"

- 1969 Minsky & Papert published Perceptrons, emphasizing the limitations of neural models, and lobbied agencies to cease funding neural network research.
- from 1969 to 1985 there was very little work in neural networks or machine learning.
- a few exceptions, e.g. Stephen Grossberg, Teuvo Kohonen (SOM), Paul Werbos.

Knowledge-Based Systems

- 1970s and early 1980s, AI research focused on symbolic processing, Expert Systems
- Some commercial success, but ran into difficulties:
  - combinatorial explosion in search spaces
  - difficulty of formalising everyday knowledge as well as expert knowledge

Neural Network Renaissance

- 1986 Rumelhart, Hinton & Williams (multi-layer, backprop)
- 1989 Dean Pomerleau (ALVINN)
- late 1980's renewed enthusiasm, hype
- 1990s more principled approaches
- 2000's SVM, Bayesian models became more popular
- 2010's deep learning networks, GPU's
- 2020's spiking networks(?)

Applications of Deep Learning

- Image processing
  - classification
  - segmentation
- Language processing
  - translation
  - semantic disambiguation
  - sentiment analysis
- Combining images and tex
  - automatic captioning
- Game playing
  - AlphaGo
  - Deep Q-Learning

History of Deep Learning

Two perspectives on the history of Deep Learning

Viewpoint 1: Focusing on recent work (after 2012)

`https://www.cs.toronto.edu/~hinton/absps/NatureDeepReview.pdf`

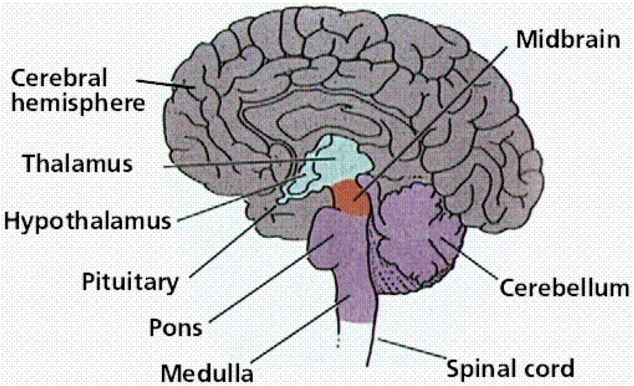
Viewpoint 2: Focusing on earlier work (before 2012)

`http://people.idsia.ch/~juergen/deep-learning-overview.html`

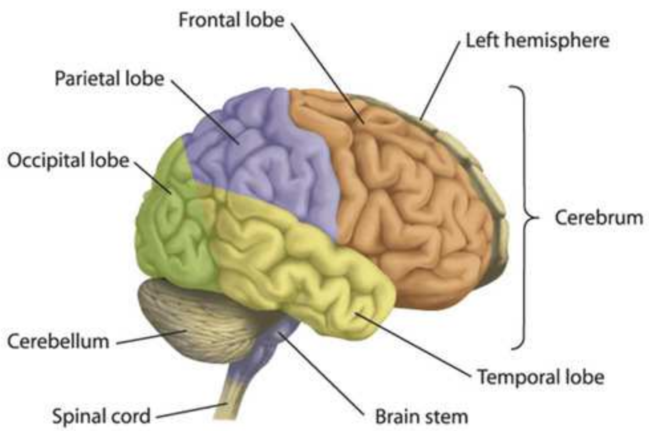
Neuroanatomy

- Central Nervous System
  - Brain
  - Spinal cord
- Peripheral Nervous System
  - Somatic nervous system
  - Autonomic nervous system
  - Enteric nervous system

Brain Regions



Cerebral Cortex



Cerebral Cortex

- “cortex” from Latin word for “bark” (of tree)
- cortex is a sheet of tissue making up outer layers of brain, 2-6cm thick
- right and left sides connected by corpus callosum
- functions: thought, voluntary movement, language, reasoning, perception

Brain Stem

- general term for area of brain between the thalamus and spinal cord
- includes medulla, pons, tectum, reticular formation and tegmentum
- functions: breathing, heart rate, blood pressure, and others

Cerebellum

- from Latin word for “little brain”
- functions: movement, balance, posture

Midbrain

- functions: vision, audition, eye movement, body movement

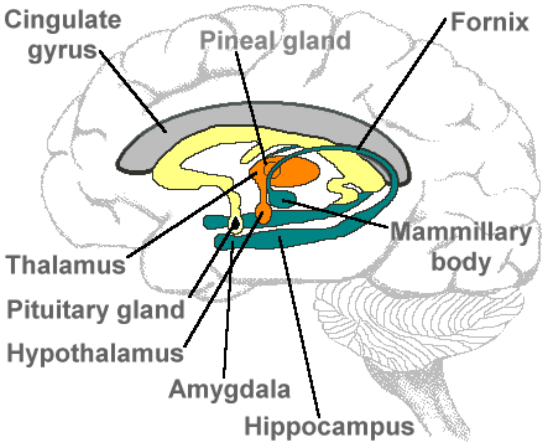
Thalamus

- receives sensory information and relays it to the cerebral cortex
- also relays information from the cerebral cortex to other areas of the brain, and the spinal cord
- functions: sensory integration, motor integration

Hypothalamus

- composed of several different areas at the base of the brain
- the size of a pea (about 1/300 of the total brain weight)
- functions: body temperature, emotions, hunger, thirst, circadian rhythms

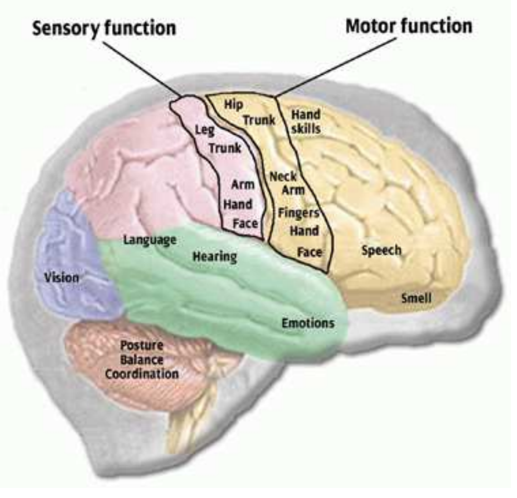
Limbic System



Limbic System

- group of structures including amygdala, hippocampus, mammillary bodies and cingulate gyrus
- important for controlling the emotional response to a given situation
- hippocampus also important for memory
- functions: emotional behaviour

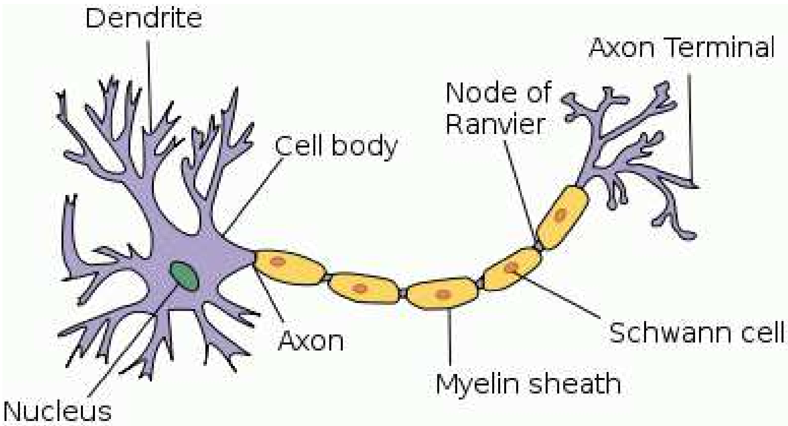
Brain Functions



Neurons as Body Cells

- The body is made up of billions of cells. Cells of the nervous system, called neurons, are specialized to carry "messages" through an electrochemical process.
- The human brain has about 100 billion neurons, and a similar number of support cells called "glia".
- Neurons are similar to other cells in the body in some ways, such as:
  - neurons are surrounded by a cell membrane
  - neurons have a nucleus that contains genes (DNA)
  - neurons carry out basic cellular processes like protein synthesis and energy production

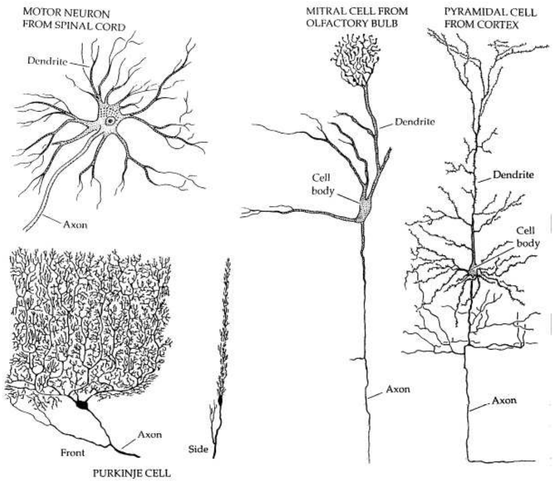
Structure of a Typical Neuron



Neurons versus Body Cells

- Neurons have specialized extensions called dendrites and axons. Dendrites bring information to the cell body, while axons take information away from the cell body.
- The axon of one neuron can connect to the dendrite of another neuron through an electrochemical junction called a synapse.
- Most neurons have only one axon, but the number of dendrites can vary widely:
  - Unipolar and Bipolar neurons have only one dendrite
  - Purkinje neurons can have up to 100,000 dendrites

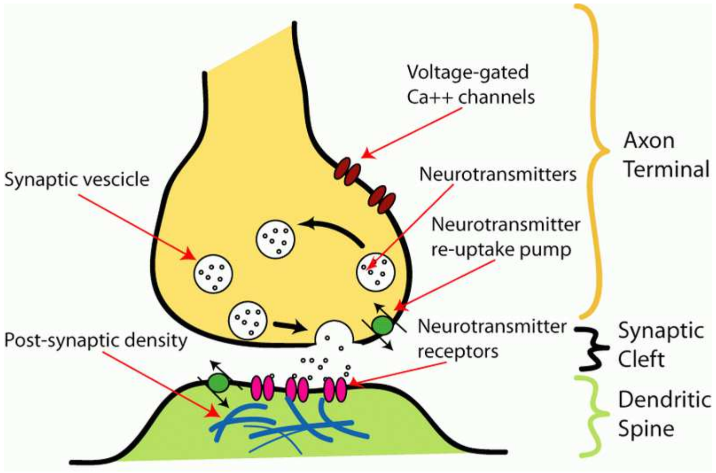
Variety of Neuron Types



Axons and Dendrites

- Dendrites are typically less than a millimetre in length
- Axons can vary in length from less than a millimetre to more than a metre (motor neurons)
- Long axons are sometimes surrounded by a myelinated sheath, which prevents the electrical signal from dispersing, and allows it to travel faster (up to 100 m/s).

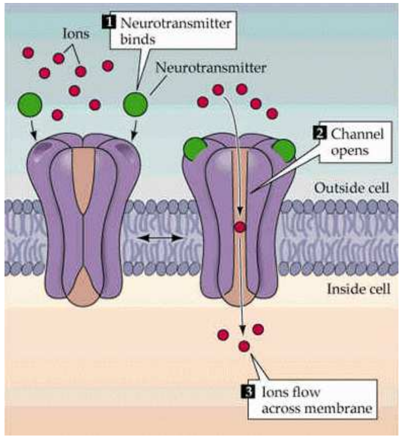
Synapse



Synapses and Ion Channels

- electrical pulse reaches the endbulb and causes the release of neurotransmitter molecules from little packets (vesicles) through the synaptic membrane
- transmitter then diffuses through the synaptic cleft to the other side
- when the neurotransmitter reaches the post-synaptic membrane, it causes a change in polarisation of the membrane
- the change in potential can be excitatory (moving the potential towards the threshold) or inhibitory (moving it away from the threshold)

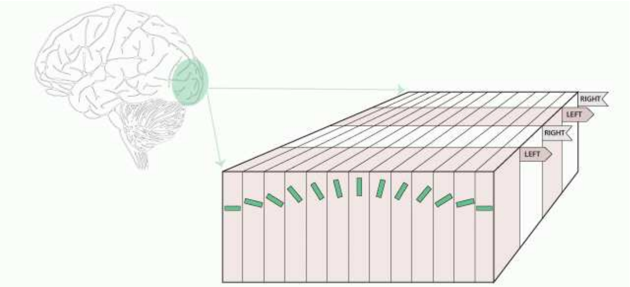
Ion Channel



The Big Picture

- human brain has 100 billion neurons with an average of $10,000$ synapses each
- latency is about 3-6 milliseconds
- therefore, at most a few hundred "steps" in any mental computation, but massively parallel

Hubel and Weisel – Visual Cortex



- cells in the visual cortex respond to lines at different angles
- cells in V2 respond to more sophisticated visual features
- Convolutional Neural Networks are inspired by this neuroanatomy
- CNN's can now be simulated with massive parallelism, using GPU's

Spiking Neurons

- biological neurons spike in different patterns (quiescent, persistent, sporadic)
- spike timing might carry important information
- most NN models ignore timing information, but some work has been done on spiking network models
- in the future, special hardware might lead to a revolution for spiking networks, similar to what GPU's provided for CNN's