COMP9444 Neural Networks

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

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 successes, but many difficulties:
  - combinatorial explosion in search spaces
  - limited computer capabilities to do anything useful
  - difficulty of formalising everyday knowledge as well as expert knowledge
  - Moravec’s paradox: hard problems are easy, easy problems are hard. eg chess vs vision
- Alternative approaches, Connectionism and Embodied cognition, systems that connect perception to action without symbolic reasoning. 1991 Rodney Brooks (Elephants Don’t Play Chess)

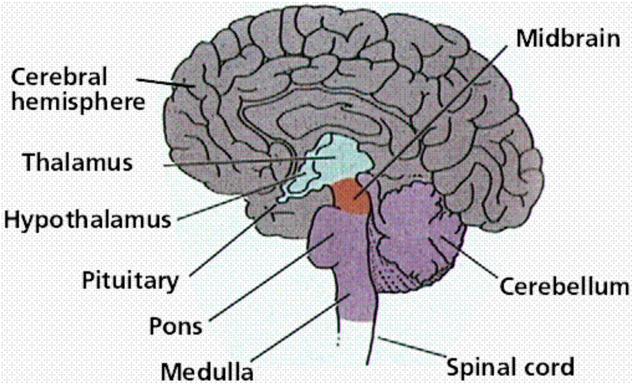
Neural Network Renaissance

- 1986 Rumelhart, Hinton & Williams (multi-layer perceptrons, backprop)
- 1989 Dean Pomerleau (ALVINN)
- late 1980’s renewed enthusiasm, hype
- 1990s more principled approaches
- 2000’s SVM, boosting Bayesian models
- 2010’s Neural network rennaissance, deep learning networks. Convolutional neural networks, deep Restricted Boltzmann Machines

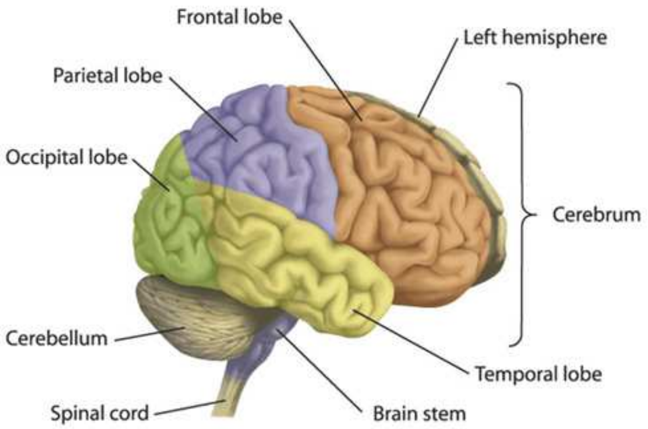
Neuroanatomy

- 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

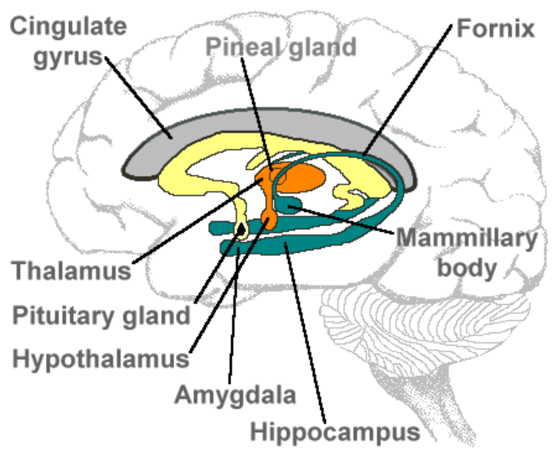
Thalamus

- 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



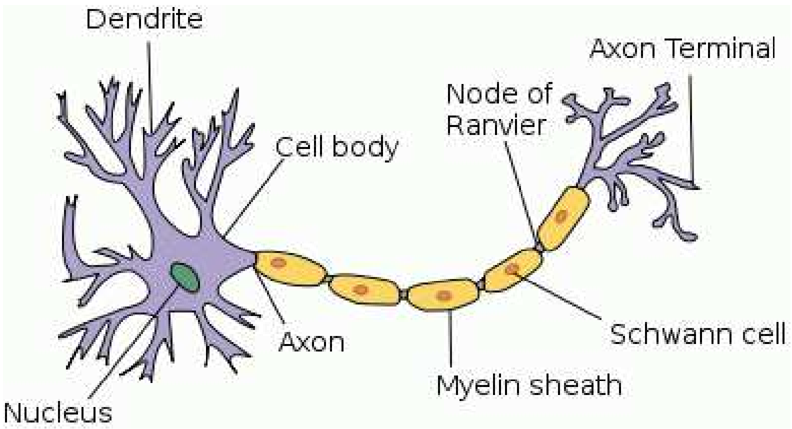
Limbic System

- 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

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

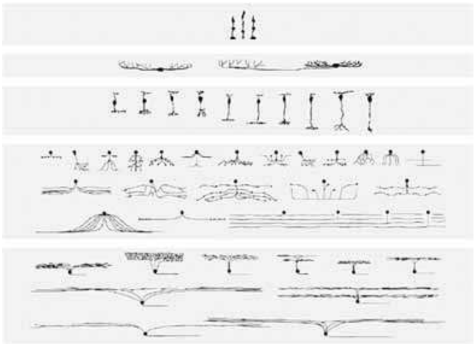
Structure of a Typical Neuron



Neurons versus Body Cells

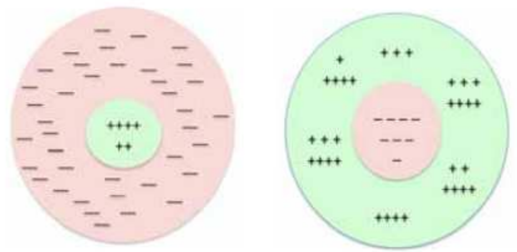
- Neurons have specialized extensions called dendrites and axons Dendrites bring information to the cell body, while axons take information away from the cell body.
- The axon of one neuron can connect to the dendrite of another neuron through an electrochemical junction called a synapse.
- Most neurons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

Variety of Neuron Types



- Top to bottom: photoreceptors, horizontal cells, bipolar cells, amacrine cells, ganglion cells. Connective properties influence behaviour.

Cell Responses



- These ganglion cells in the visual cortex provide responses based on activations in the central and outer regions. This allows the cells to capture contrast, and different size receptive fields will respond to different spatial frequencies.

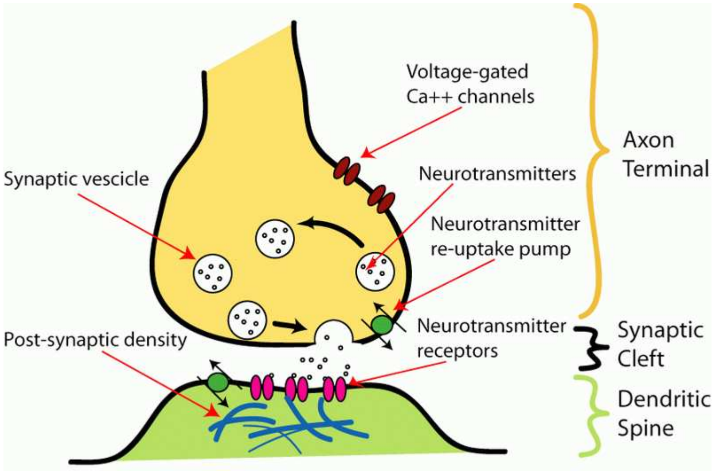
Receptive fields in vision

- Various cells provide tiled and overlapping responses to visual information

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

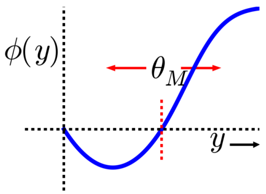


Synapses and Ion Channels

- 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)

Learning

- Hebbian learning- Cells that are repeatedly active at the same time will tend to become ‘associated’, so activity in one facilitates activity in the other. (Hebb 1949)
- Basic model: $\Delta w_i = \eta x_i y$
- More detailed description, BCM rule. Weak post-synaptic activation weakens the connection (LTD), and strong activation strengthens it (LTP).



Neural Coding

- How is information captured in neuron structure and behaviour?
- In synapses between neurons
  - Sparse coding- features are captured in a small set of neurons, or “grandmother cell”
  - Population coding- a distributed representation over a group of neurons
- Spike trains
  - Rate coding- based on the rate in which neurons fire
  - Temporal coding- the timing of firings is significant, such as correlations between neurons

The Big Picture

- Human brain has 100 billion neurons with an average of $10,000$ synapses each
- Latency is about 3-6 milliseconds
- At most a few hundred "steps" in any mental computation, but massively parallel
- Artificial Neural Networks are simplified models of learning related to neuron behaviour
- In terms of weights, the largest, most modern artificial neural nets are at most a millionth of the size of one small brain region. (eg. Stanford / Google Convolutional Neural Networks running on 16,000 cpus)