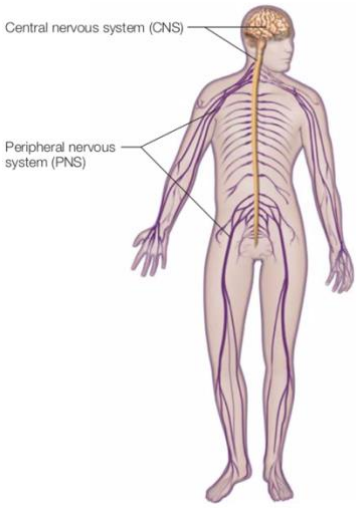
Computational and Cognitive Neuroscience – Summary

Lecture 1 – Structure and function of the Nervous System

I. Nervous System (NS)

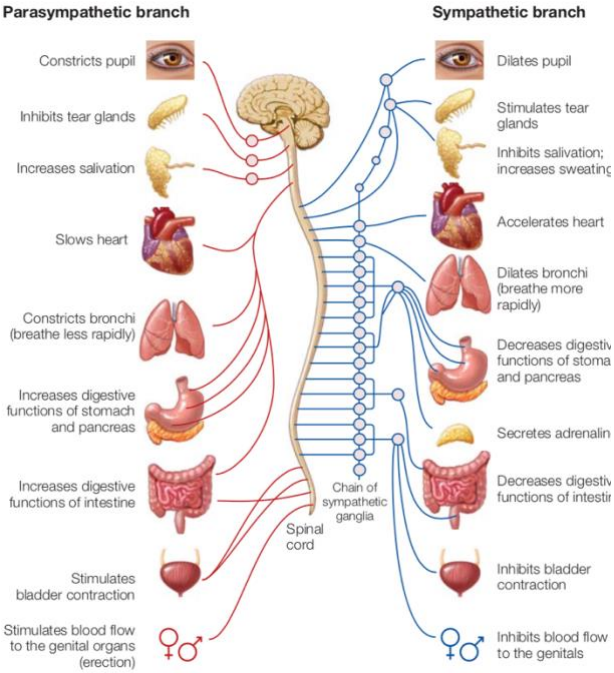


○ Central NS:

- The **CNS** is made up of the delicate brain and spinal cord, each encased in its protective, bony shell and suspended in a sea of cerebrospinal fluid (CSF).
- In the **CNS**, neurons are bunched together in various ways. Two of the most common organizational clusters are in a **nucleus** or in a **layer**. A **nucleus** is a relatively compact arrangement of nerve cell bodies and their connections, ranging from hundreds to millions of neurons, with functionally similar inputs and outputs. They are located throughout both the brain and the spinal cord. The outer layer of the brain, the **cerebral cortex**, on the other hand, has billions of neurons. They are arranged in layers of thin sheets, folded across the surfaces of the cerebral hemispheres.

○ Peripheral NS:

- **Somatic**: system that oversees voluntary control of the skeletomuscular system. This includes bodily movements of the muscles, skin, and bones.
- **Autonomic**: is involved in controlling the involuntary action of smooth muscles, the heart, and various glands. It has two subdivisions: the *sympathetic* and *parasympathetic* branches.



Sympathetic:

This system uses the neurotransmitter norepinephrine.

Parasympathetic:

This system uses acetylcholine as its transmitter.

The two systems frequently operate antagonistically. For example, activation of the sympathetic system increases heart rate, diverts blood from the digestive tract to the somatic musculature, and prepares the body for action (fight or flight) by stimulating the adrenal glands to release adrenaline. In contrast, activation of the parasympathetic system slows heart rate, stimulates digestion, and in general helps the body with functions germane to maintaining the body.

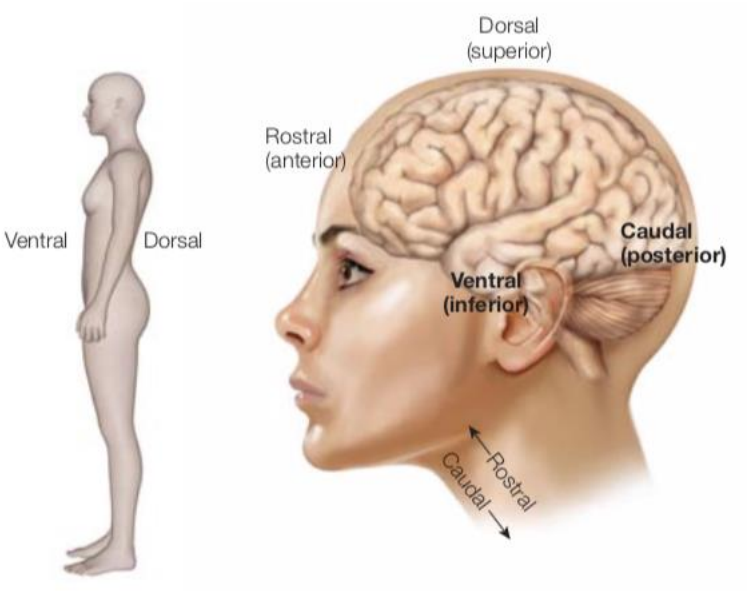
II. Neuroanatomy

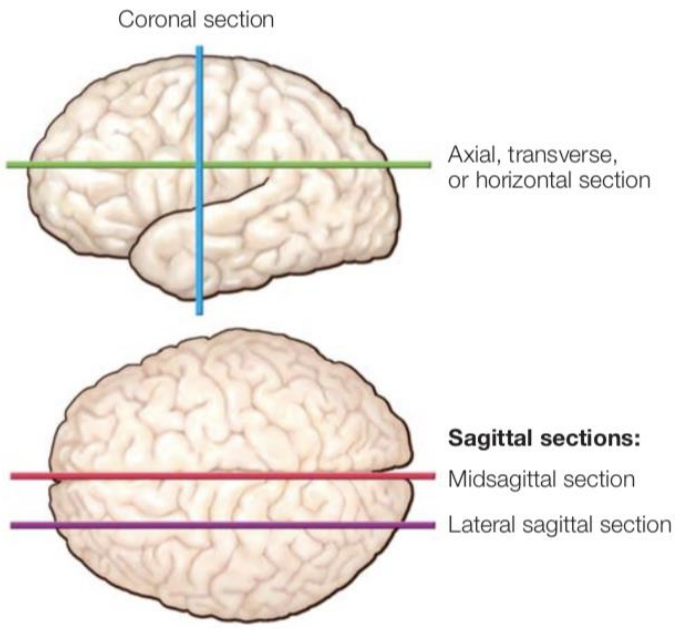
○ Planes:

- **Saggital:** Left/right plane (when facing from front/back)
- **Coronal:** Front/back plane (when facing from front/back)
- **Transverse/Axial/Horizontal:** Bottom/top plane (When facing front/back)

○ Directions: (From the human perspective)

- **Superior/Dorsal:** Top part of the brain.
- **Inferior/Ventral:** Bottom part of the brain.
- **Anterior/Rostral:** Front side of the brain
- **Posterior/Caudal:** Back side of the brain.
- **Medial:** The Medial Line is the line down the middle, from front to back, of the brain.
- **Lateral:** The Lateral side(s) are the sides of the brain (human perspective).





White Matter:

- Made up mostly of **MYELINATED** axons (and other information transmitters) that are the "information highways" of the brain.

Grey Matter:

- Cell bodies and usually **UN-MYELINATED** axons.

Hemispheres:

- There exist two hemispheres of the brain, divided evenly down the ***medial line*** that separate the brain into "Left" and "Right" hemispheres.

Ventricles:

- Ventricles produce Cerebrospinal Fluid (CSF) which acts as a cushion, or buffer, between the Cerebral Cortex and the inside of the skull. CSF also plays a large roll in blood flow throughout the brain, and cerebral autoregulation.

Brain Stem:

- Provides the main motor and sensory input to the face and neck. Additionally, all the motor and sensory nerves from the brain pass through the brain stem to the rest of the body. The brain stem regulates the Central Nervous System.
- **Hindbrain:** Supports vital bodily processes.
    - **Medulla:** Basic functions (IE respiration, heart rate)
    - **Cerebellum:** Motor and cognitive functions
    - **Pons:** Basic functions (IE digestion, sleeping)
- **Midbrain:** The midbrain controls many autonomous and manual functions, such as the sleep/wake cycle, vision, hearing, motor control, alertness, and temperature regulation.
- **Diencephalon (Part of the Forebrain)**
    - **Thalamus:** Relay station of the brain. Processes input, and distributes it to the relevant centers in the brain.
    - **Hypothalamus:** Hormone and autonomic control, Nervous System control. Regulates hunger, hormones, temperature, sleep, and other cycles.

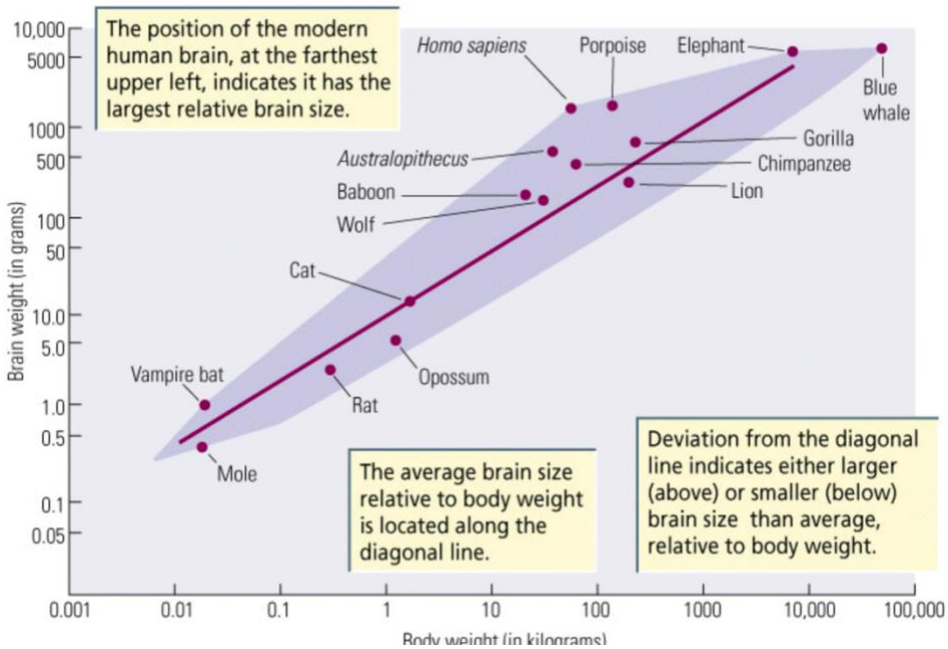
Telencephalon:

- **Limbic System:** Memory and Emotions
- **Basal Ganglia:** Group of structures in the Thalamus overseeing motor control and motor learning processes.
- **Cerebral Cortex:** The Cerebral Cortex is the outermost layer of matter on the brain, made up of **neural tissue,** that plays the role in **MEMORY, ATTENTION, PERCEPTION, AWARENESS, THOUGHT, LANGUAGE, AND CONSCIOUSNESS.** The human CC is 2-4mm thick.
    - **Gyri:** "**Bumps" on the brain surface.**
    - **Sulci: "Grooves" on the brain surface.**
    - **Cortical Layers:** There exist 6 layers of the cerebral cortex, where each layer has a different cell density, along with separate functions for each.
    - **Brodmann's Areas:** Histological classifications.
- **Lobes and their functions:** Each lobe of the Cerebral Cortex plays a different role in the overall function.
    - **Frontal Lobe:** Motor function, planning, language production, personality.
    - **Temporal Lobe:** "What" pathway, auditory cortex, language perception, memory.
    - **Occipital Lobe:** Exclusively reserved for visual processing.
    - **Parietal Lobe:** Attention, High-Order vision, Somatosensory Cortex.
        - **Sensorimotor:** Control, body position, and voluntary movements.
        - **Somatosensory Cortex:** Sensory cortex that responds to changes of internal state within the body.

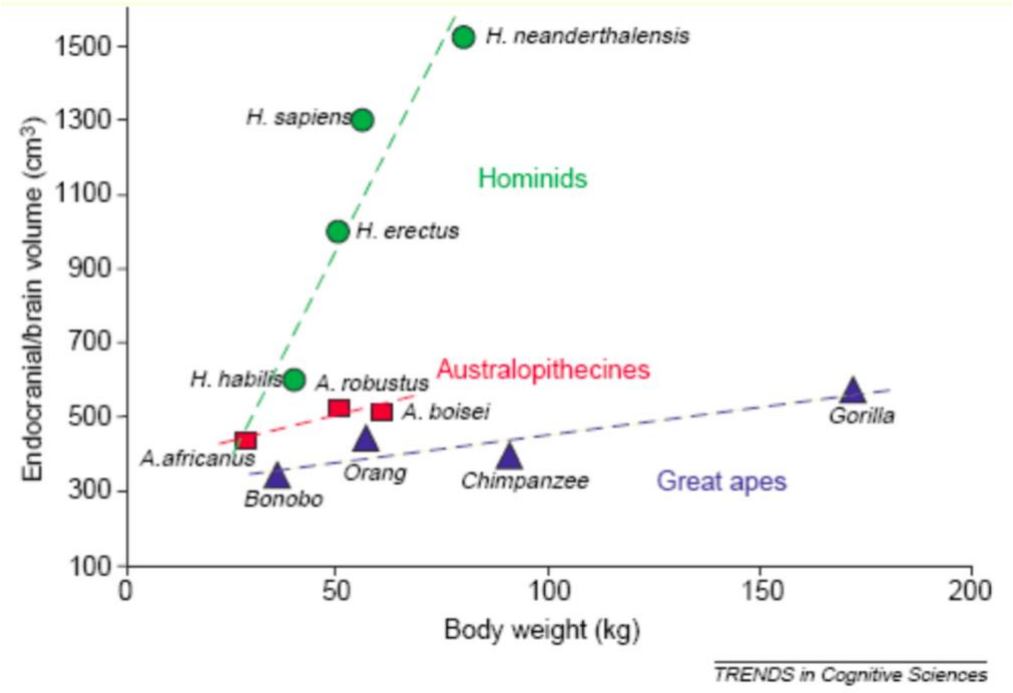
Lecture 2 - Evolution and development

I. Brain evolution

- **Brain size to body size ratio:**



- **Brain size increase in hominids:**

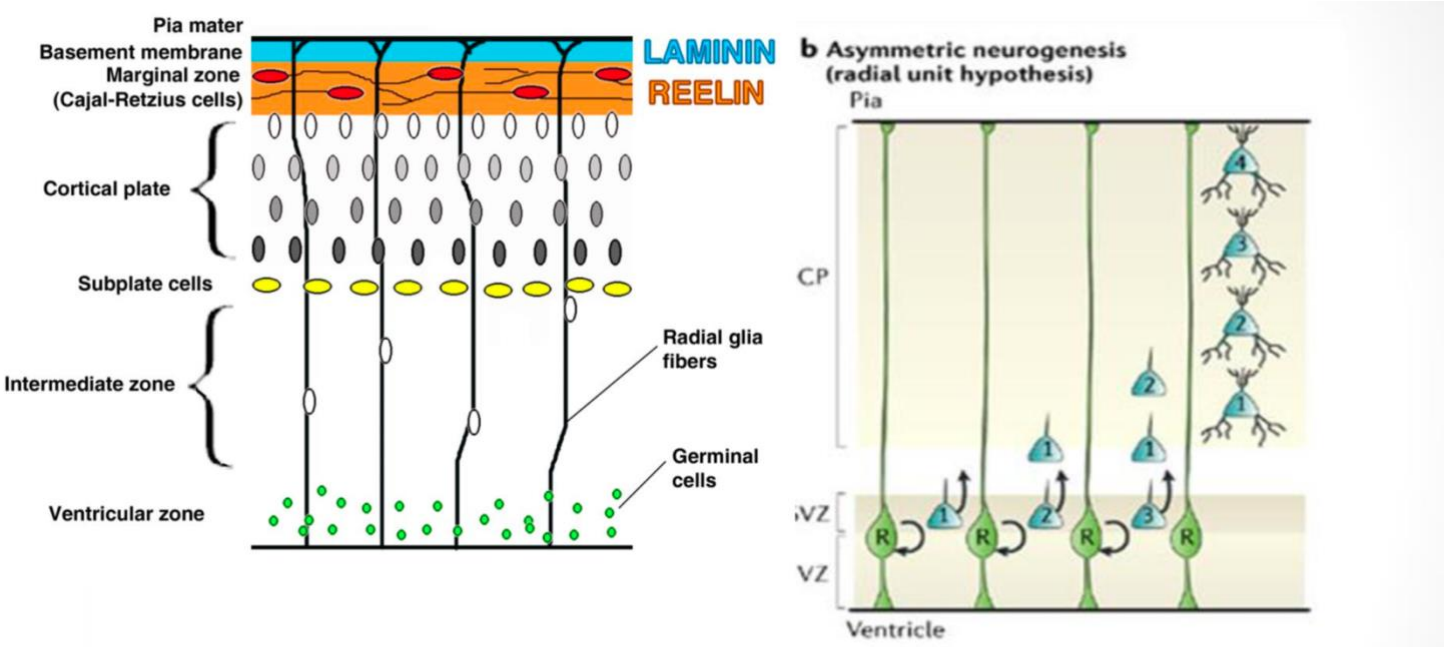


- **Bigger brains:**

- **Number of neurons:** 100 billion (10^{11})
- **Number of synapses:** 10^{15} synapses = 10.000 / neuron

II. Radial Unit Hypothesis

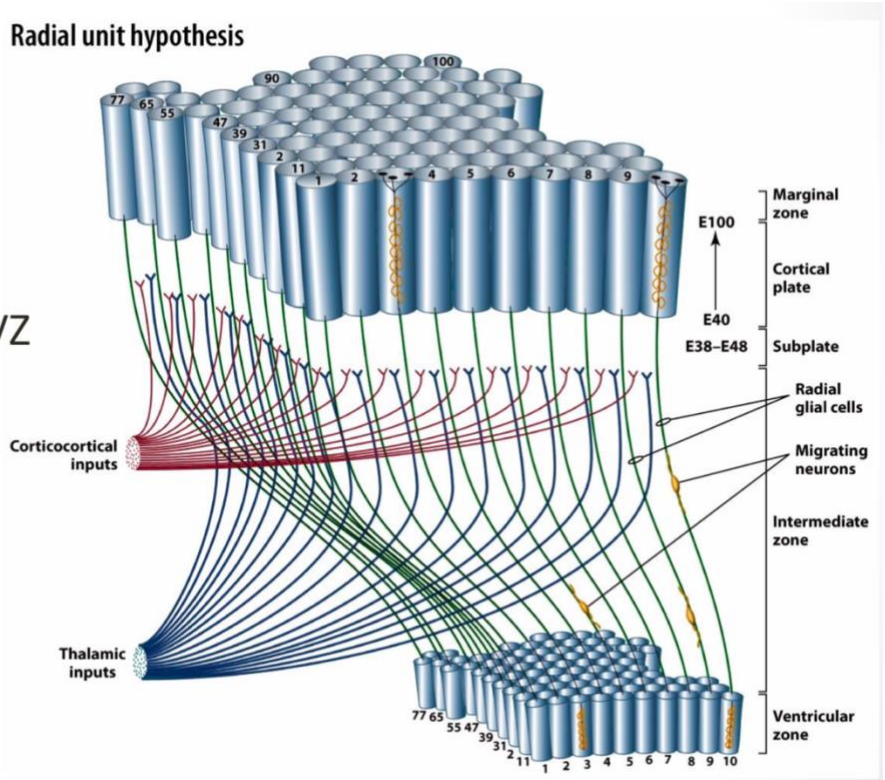
- **Symmetrical & asymmetrical division:**



- First cells divide symmetrically in the Ventricular Zone (**VZ**): keep the same function
- After this they divide asymmetrically: one cell gets a different function (ie. neuron) and the differentiated cell migrates to the Cortical Plate (**CP**)
- The cortex is formed from an inside-out manner
  - From the ventricular zone (VZ) to the cortical plate (CP), deeper layers first

- **Radial glia cells & radical migration:**

- Neuron migration happens along radial glial cells
- Radial glial cells form radial units from the VZ through the intermediate zone to the CP
- These maintain their topography (relative locations)



III. Synaptogenesis

- **Synaptogenesis** is the formation of synapses between neurons in the nervous system

IV. Myelination

Myelin is a fatty substance that insulates the **AXON.** Signals propagated by myelinated axons travel faster and further than those without the myelin sheath.

- **Differential timing in human development:**

- Myelination of axons extends further into life than other developmental processes
- Axons in different cortical areas myelinate at different times
  - Sensory and motor areas first
  - Frontal and parietal areas last
- Myelination of frontal cortex continues way into adulthood
  - Some estimates say up until age 25-30
- So, you don't just "use it or lose it" …
  - **But use it now (in your 20s) or never get it!**

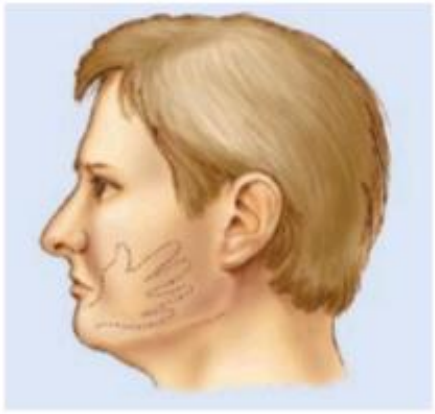
V. Ontogenesis = phylogenesis

- Or, the development of the brain mirrors the evolution of the brain
- On cellular level:
  - Enormous growth in amount of cells = symmetric division of cells
- On brain system level:
  - "early" and "lower" in areas = early in evolution

VI. Brain plasticity

- The brain also displays enormous potential for plasticity after complete development
- Your brain constantly changes: after this lecture, I will have permanently altered your brain
  - Learning
  - Mostly connectivity: synaptic changes
  - More on this when we talk about memory
- The brain can also repair or reorganize after an accident

- More in this when we talk about brain damage
  - The brain can even recruit other areas that are / were used for something else
  - The amputee can feel his hand on his face
  - Other, amputees report feeling their amputated limb
  - This is known as phantom-limb experience
  - Areas from the somatosensory cortex that are not used anymore are recruited by other parts
  - This is also the reason why blind people can hear and feel better
  - It all comes down to: use it or lose it!



VII. Basic genetics

- A **chromosome** is a DNA molecule with part or all of the genetic material (genome) of an organism.
- A **gene** is a sequence of DNA or RNA that codes for a molecule that has a function. During gene expression, the DNA is first copied into RNA. The RNA can be directly functional or be the intermediate template for a protein that performs a function.
- **DNA** (Deoxyribonucleic acid) is a molecule composed of two chains (made of nucleotides) that coil around each other to form a double helix carrying the genetic instructions used in the growth, development, functioning and reproduction of all known living organisms and many viruses.
- The **genotype** is the part of the genetic makeup of a cell, and therefore of any individual, which determines one of its characteristics (phenotype).
- A **phenotype** is the composite of an organism's observable characteristics or traits, such as its morphology, development, biochemical or physiological properties, behavior, and products of behavior.
- Chromosomal **cross-over** is the exchange of genetic material between two chromosomes that results in recombinant chromosomes during sexual reproduction. It is one of the final phases of genetic recombination.
- The **mutation** is the permanent alteration of the nucleotide sequence of the genome of an organism, virus, or extrachromosomal DNA or other genetic elements.

VIII. Genetic algorithms

- **Genotype strings and individuals** (0010110101 – for example):

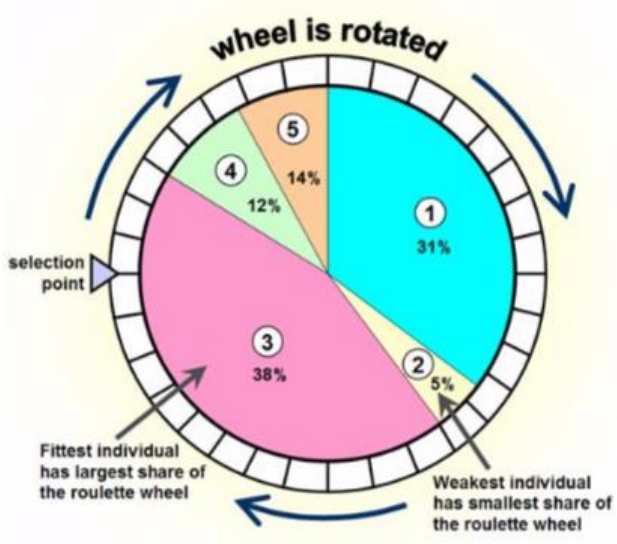
- This represents strands of our DNA
- A genetic algorithm has a large number of strings/genotypes
- Each genotype is called “an individual”
- A collection of individuals is called a “population”
- Each string/genotype/individual is assigned a **fitness value** according to phenotype
- This fitness value can be normalized to a range between 0 and 1
- You can use anything you like to calculate your fitness value

○ Reproduction:

- **Cross-over** in GA's:
  - You have various forms of cross-over
  - The simplest form is single-point cross-over (00110110 x 11001101 = 11000110 x 00111101)
  - It is also possible to have multiple cross-over 2 (00110110 x 11001101 = 00101110 x 11010101)
- **Mutation:**
  - There are various types of mutation, depending on your representation
  - Binary Mutation (001100 = 001110)

○ Selection strategies:

- **Elitist selection:**
  - Order individuals by fitness
  - Select top 10, 20, etc.
  - Advantages:
    - Very straightforward to implement
  - Disadvantages
    - Each generation loses a lot of genetic information
    - "genetic degeneration"
- **Roulette Wheel selection:**
  - Much more random
  - Advantages:
    - Better than elitist selection
- **Tournament selection:**
  - Select at random *k* individuals (*k* = tournament size)
  - From this selection: select the best individual
  - Advantages:
    - Very straightforward
    - Does not have problems of roulette wheel selection
  - Disadvantages:
    - A large *k* boils down to random selection



○ Genetic Algorithms - Pros and Cons:

- Genetic algorithms are very basic, of course the human genome is extremely complex and without a thorough understanding of an organism's genes, it is very difficult to accurately mimic the biological genetic development process.