

30. November 2023

A hopfield network has symmetric weights and 0 self-weights

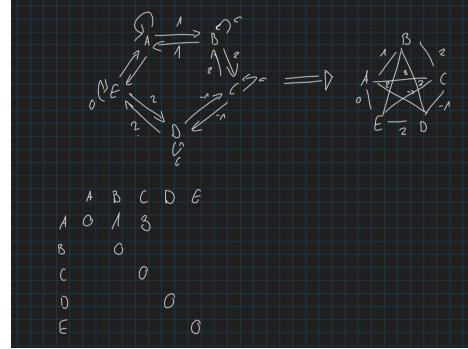


Figure 1: Hopfield network

we update the state by updating a unit's output

A	B	C	D	E
1	1	0	0	0
1	1	0	1	0
1	1	0	1	1

The state doesn't change after this (because every unit stays the same when updated) → the network has *converged*

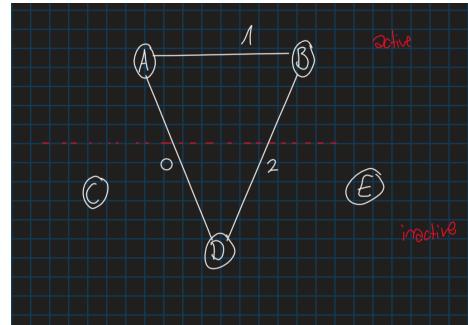


Figure 2: Graph

We move a unit to the top (bottom) if the sum of weights to *upper* units is positive (negative)

Let's consider the sum of all weights between active units. This has to increase at every step. → every time we change the state of a unit.

Biased Graph:

Even considering bias terms and cases where the threshold is reached exactly, the network has to converge to a stable state.

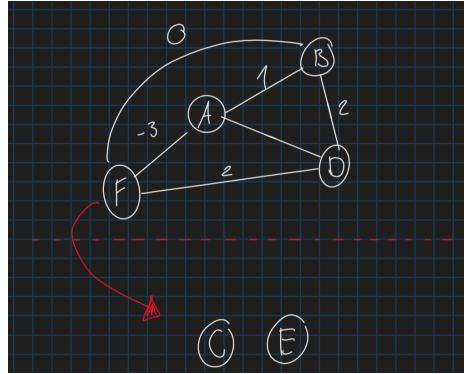


Figure 3: Graph 2

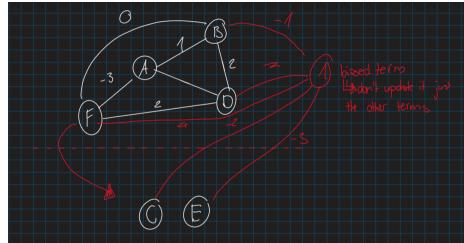


Figure 4: Biased graph

Hopfield Network

A hopfield network is an *associative memory*

An associative memory restores a full memory from a partial or noisy version of the memory.

Representations

We can also use ± 1 as the two states of a unit.

So people don't worry about using one type vs the other - they use whichever they prefer.

Asynchronous updates: Updating units one at a time.

Synchronous updates: Updating all units simultaneously.

We can use our theorem about asynchronous networks to analyze synchronous ones. How?

A	B	C	D	E
1	-1	1	1	-1
-1	1	1	1	-1

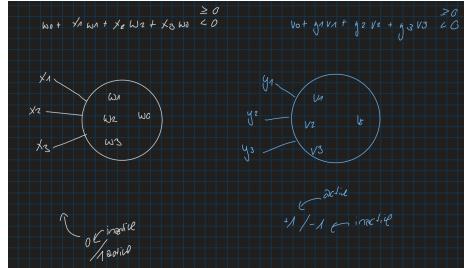


Figure 5: Representation

$x_1 = 1 \Rightarrow y_1 = 1$ $x_1 = 0 \Rightarrow y_1 = 0$ $y_1 = 1$ $y_1 = \frac{w_1}{2} + \frac{w_2}{2}$	Behavior of 0/1 unit written in terms of \vec{w} $w_1 + (\frac{w_2}{2} + \frac{w_3}{2})x_1 + (\frac{w_2}{2} + \frac{w_3}{2})x_2 + (\frac{w_3}{2})x_3$ $(w_1 + \frac{w_2 + w_3}{2}x_1) + y_1 \cdot \frac{w_2}{2} + y_2 \cdot \frac{w_3}{2} + y_3 \cdot \frac{w_3}{2}$ $y_1 = w_1 + \text{other weights}$ $y_1 = \frac{w_1}{2}$ $y_2 = \frac{w_2}{2}$ $y_3 = \frac{w_3}{2}$	The unit has the same behavior as the 0/1 unit
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Figure 6: Representation 2

Lecture

Population Codes

- Neurons work together to encode a value or multiple values
- Each neuron is "tuned" to a particular value of the stimulus
- By looking at the activity of the population, the value is easy to read out.

Example

Neurons tuned to possible angles of a line at a certain location in the visual field

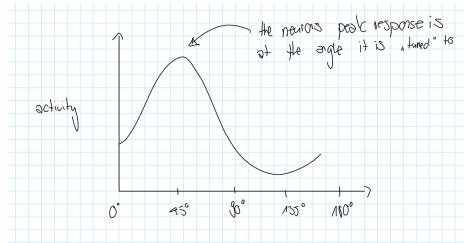


Figure 7: Neuron activity

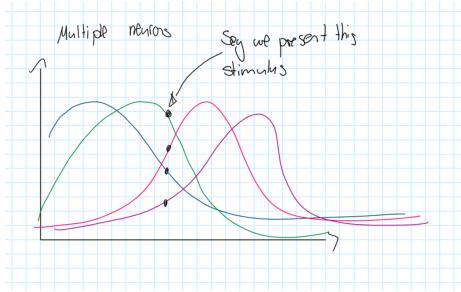


Figure 8: Multiple neuron activity

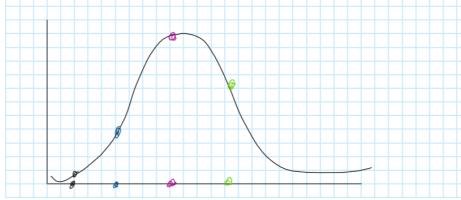


Figure 9: Tuned neuron activity

To read out a value, we look at the activities in the population
 We plot each neuron at the position it is tuned to. The green neuron activity
 is always shown positioned at 170° because that is the angle it is tuned to.
 Why are curves of a similar shape? Think of a 3D picture

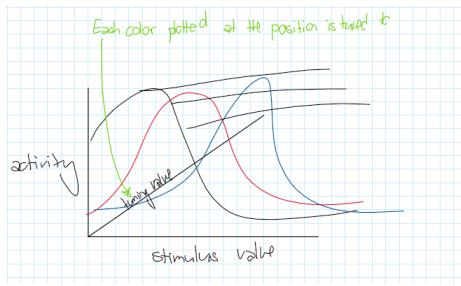


Figure 10: 3D representation

Other neurons can reliably and accurately read out the value. Some neurons are tuned to values, with high firing rates at those values. Some neurons have a threshold, and as the stimulus passes, the threshold, the rate goes up.
 Again, easy for other neurons to read out robustly and accurately
 Is it easy to convert between these formats?
 How can we compute something with this sort of data encoding? We'll use tuning-based units because threshold-based units only "work well" with scalars.

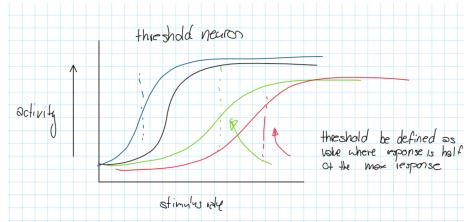


Figure 11: Graph conversion

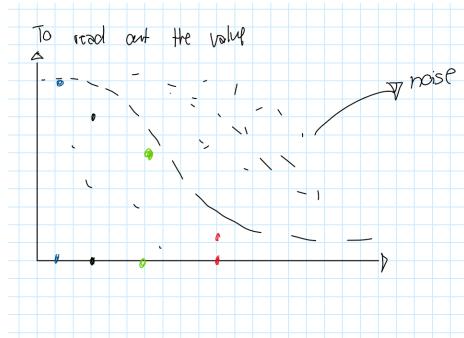


Figure 12: Graph conversion 2

In one dimension, the relationship is simple: $H = E + R$

Lecture 1, Brain

Brain

- Average human brain: 1.5kg, 1.1-1.2l volume

Why do we have a brain, input output art, we need to interact with our environment

Encoding

1. Stimuli in the environment
2. Encoding
3. Neuronal Representation Perception Sensory Integration, Memory / maintenance
4. Decoding
5. Movement, Actions Decisions Behavior

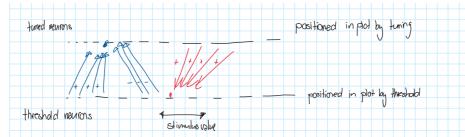


Figure 13: Image

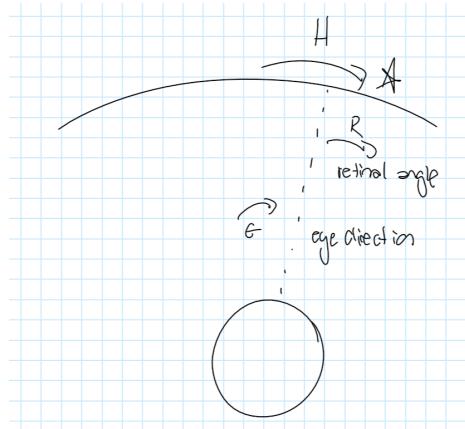


Figure 14: Image 1

6. Stimuli in the Environment

The cells (neurons) that make up brains are very similar between species

- usually cell body
- axon

Brain, Computer similarity, differences

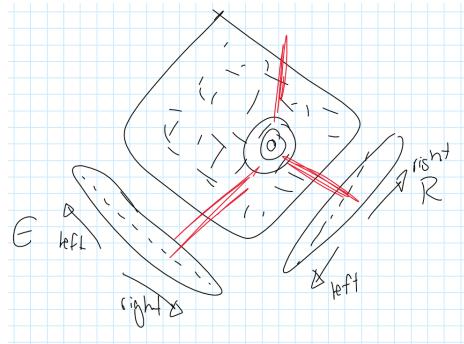


Figure 15: Computational model

Similar	Different
Process information	Massive parallelism
Logical operations	Separation of memory and processing
Memory	Constantly adapting
Use electrical(digital) signaling	Chemical signaling
Can learn from inputs	Unreliable units
Consume energy	Analog computation
	Robust to damage
	Very energy efficient

Lecture 2, Brain

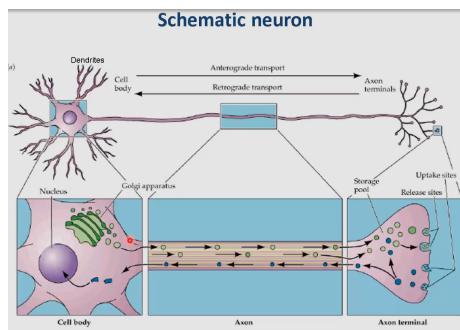


Figure 16: Schematic neuron

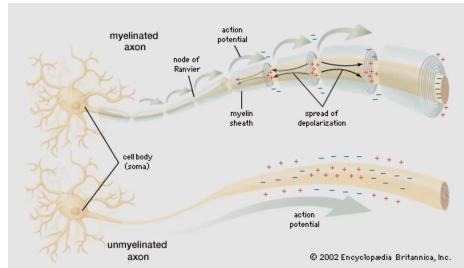


Figure 17: Axon

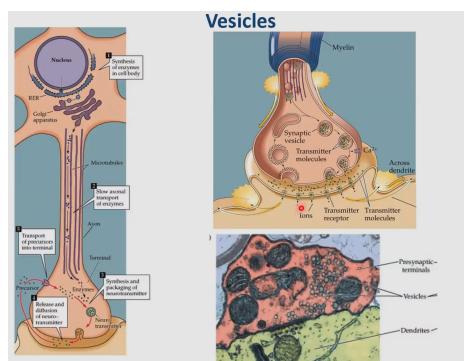


Figure 18: Vesicles

Sequence of events

1. Neurotransmitter release
2. Receptor binding
3. Ion channels open or close
4. Conductance change causes current flow
5. Postsynaptic potential changes
6. Postsynaptic cells
7. Summation determines whether not an action potential occurs

Gross Anatomy

Directions of Orientation in the CNS:

- Anterior: Toward the front.
- Posterior: Toward the back.

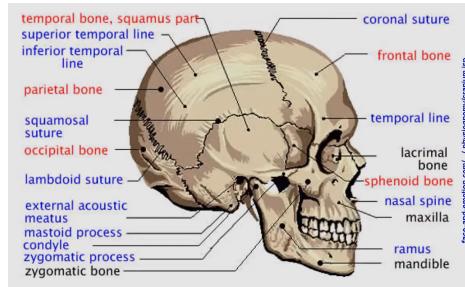


Figure 19: Gross anatomy

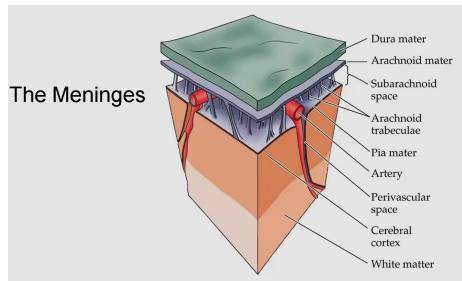


Figure 20: Gross anatomy 2

- Inferior: Toward the bottom.
- Superior: Toward the top of the head/body.
- Medial: Toward the middle/midline.
- Lateral: Away from the middle/midline.
- Rostral: Toward the nose.
- Caudal: Toward the tail/rear.
- Proximal: Near the trunk/center.
- Distal: Away from the center.
- Dorsal: Toward the back.
- Ventral: Toward the belly.
- Ipsilateral: On the same side.
- Contralateral: On the opposite side.
- Bilateral: On both sides.
- Unilateral: On one side.

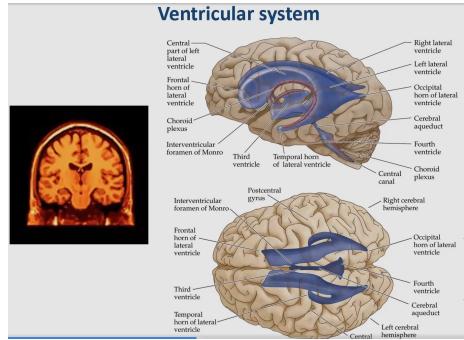


Figure 21: Ventricular system

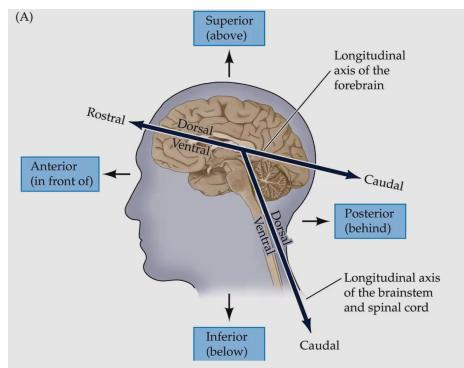


Figure 22: Central nervous system

Hypothalamus

Upper Brain Stem: Diencephalon

- Hypothalamus
 - Structure
 - * Very small
 - * Contains an important collection of nuclei
 - Function
 - * Controls autonomic mechanisms
 - * Link to endocrine system

Limbic System

- Structure
 - Structures on medial and basal surfaces of cerebral hemispheres

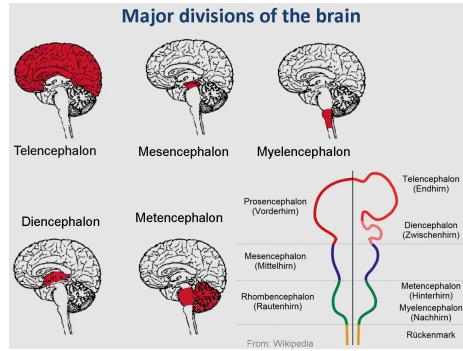


Figure 23: Brain division

- Cingulate gyrus + parahippocampal gyrus + ...
- Anatomic circuits include basolateral circuit and the Papez circuit
- Function
 - Emotional expression
 - Memory acquisition
 - Fear conditioning
 - Violence and aggression
- Basal Ganglia
 - Structure
 - Collection of nuclei embedded deep within cortex
 - Partially surround the thalamus
 - Sensory projections to cerebrum
 - Efferents to other nervous system structures
 - Function
 - Regulate voluntary movement
 - Integrative or just a relay station?
 - Pathology
 - Movement disorders (Parkinson's)

Lecture 6, Synapsis

Soup vs Spark

- is synaptic transmission mediated chemically or by direct electrical transfer of charge
- NMJ accepted that it was chemical → certain aspects too fast to be mediated chemically

Frog experiment

- to support neurotransmitter hypothesis
- first frogs heartbeat slowed, second frog inhibitory effect of vagus transferred
- building connection of synapsis not rebuilding brain

Lecture 7

Electrical vs. Chemical Synapse

Electrical Synapse	Chemical Synapse
simple primitive system	highly developed structure
often symmetrical, bidirectional	polarized, structurally and functionally
gap junction (connexins)	pre: active zone post: postsynaptic density
very fast, no synaptic delay	slower, synaptic delay (~ 0.5 ms)
Ca ²⁺ -independent	transmitter release requires Ca ²⁺ influx
temperature-insensitive	temperature-sensitive
large synapse	thousands of small synapses
limited functions, usually excitatory	versatile: excitatory and Inhibitory
synchronized activity	specificity: point to point communication

Figure 24: Synapse

Brain Structure

Telencephalon Regions

The cerebral cortex (neocortex) is anatomically divided into 4 lobes separated from the frontal lobe by the **central sulcus**. Primary lobe for somatosensory processing (afferent inputs from receptors in the skin). Additionally, subserves other sensori-motor functions. Separated from the frontal and parietal lobe by the **lateral fissure (Sylvian fissure)**. Involved in auditory processing and language comprehension (**Wernicke's area**). Additionally, responsible for visual object recognition. The

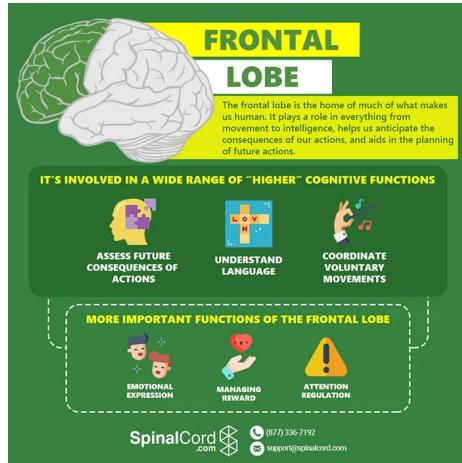


Figure 25: Frontal lobe

medial portion of the temporal lobe includes a **portion of the hippocampal formation which is involved in formation of new memories**

sub-cortical structure significantly involved in motor learning and control. Degeneration of a subset of dopaminergic neurons in the basal ganglia results in Parkinson's disease.

centre for emotional processing and is strongly linked to the olfactory senses (sense of smell).

composed of several nuclei which act as relay stations to transmit information to and from neocortex.

The brain and spinal cord are protected by three layers collectively known as meninges:

- dura-mater: A thick leather-like inelastic layer present directly below the bone.
- arachnoid-mater: A thin, delicate, middle layer present directly below the dura-mater. Has spider web like filamentous extensions into the subarachnoid space which reach the pia-mater
- pia-mater: A thin, delicate, translucent layer that directly lines the gyri/sulci of the brain, and the spinal cord. Rich in blood-vessels that supply oxygen and nutrients to the brain. Functionally, it forms the blood brain barrier (BBB).

Diencephalon Regions

Thalamus: composed of several nuclei which act as relay stations to transmit information to and from neocortex.

Hypothalamus: required for regulation of autonomic bodily functions

Pituitary Gland: regulation of the endocrine (hormonal) system

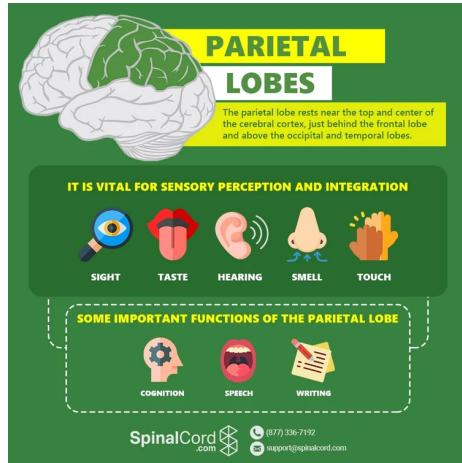


Figure 26: Parietal lobe

Forebrain (Prosencephalon) which can be further sub-divided into:

- Telencephalon: develops into the cerebral cortex, basal ganglia, hippocampal formation, amygdala
- Diencephalon: gives rise to structures like the thalamus, hypothalamus and the pituitary gland.

Midbrain (Mesencephalon) tectum and tegmentum, which exist in all vertebrate brains. The tectum in the mammalian brain consists of the superior colliculus and the inferior colliculus.

Hindbrain (Rhombencephalon) consists of the Metencephalon (develops into the pons, cerebellum) and the Myelencephalon (develops into the medulla oblongata)

Neurons are hyperpolarized which means they have a resting potential of -70 mV within and 0 mV outside of them. Hyperpolarization refers to an increase in membrane potential whereas depolarization refers to a decrease in membrane potential

Action potentials are all or nothing operations which have four components which take place over the course of 1-2 ms: Depolarization: Depolarization is when a change occurs inside a cell that causes the distribution of electric charges to alter, leaving the cell with a less negative charge than the outside. Numerous cell functions, cell-cell communication, and the general physiology of an organism all depend on depolarization

Exam Questions

1. **Grid Cells:** Grid cells are types of neurons found in the brains of many animals, including humans, that allow for spatial navigation and are thought

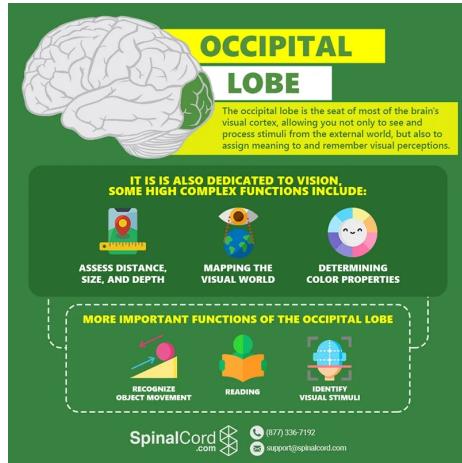


Figure 27: Occipital lobe

to form part of the brain's positioning system. These cells are located in the entorhinal cortex and exhibit a unique pattern of activity that corresponds to multiple, evenly spaced locations in an environment, forming a grid-like structure. This pattern helps in self-positioning and navigation by providing a metric for spatial coding. Understanding grid cells involves knowing how their firing patterns contribute to the neural code for representing space in the brain.

2. **Brain Size Scaling with Species Size:** The relationship between brain size and the size of a species, also known as allometric scaling, is an important area of study in comparative neuroscience. Generally, brain size increases with body size, but not in a simple linear way; instead, it follows a power law where the exponent is less than one, indicating that larger animals have larger brains but not proportionally to their body size. This is sometimes expressed as the encephalization quotient (EQ), which measures brain mass relative to an expected value for a given body mass.
3. **Perceptrons and XOR Function:** A perceptron is a simple linear classifier that can only solve linearly separable problems. The XOR function is not linearly separable, which means a single perceptron cannot compute an XOR function. However, a multi-layer network with at least one hidden layer (also known as a multi-layer perceptron) can solve the XOR problem by creating a non-linear decision boundary.
4. **Convergence in Hopfield Networks:** A given state in a Hopfield network will converge to a stable state if it's close to one of the stored patterns (memories) or local minima of the energy function. To determine which of the four states will converge to a stable state, you would analyze the

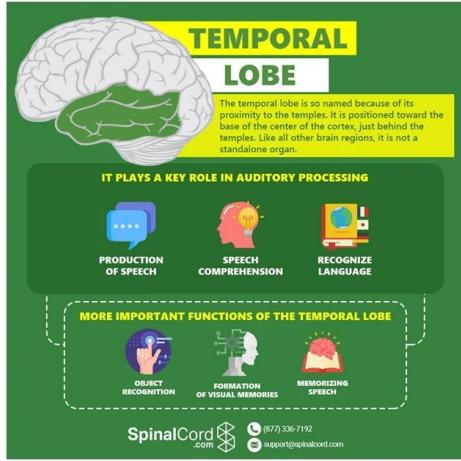


Figure 28: Temporal lobe

energy function of the Hopfield network and determine which states are local minima.

5. **Output from an Integrate-and-Fire Circuit:** An integrate-and-fire neuron model is a simplified representation of a neuron that accumulates input signals until it reaches a threshold, at which point it 'fires' (generates an action potential) and then resets. The output of such a circuit is typically a series of spikes or action potentials over time.
6. **Short-Term Plasticity vs Long-Term Potentiation:** Short-term plasticity refers to transient changes in synaptic strength that occur over a short period, such as facilitation or depression due to recent activity. Long-term potentiation (LTP), on the other hand, is a long-lasting increase in synaptic strength following high-frequency stimulation, which is a mechanism underlying learning and memory.
7. **Tuning Curves (Population Codes):** A tuning curve represents the response of a neuron to a range of stimuli, showing how the firing rate of the neuron changes with different stimulus values. It's an essential concept in understanding population coding, where the combined activity of multiple neurons with different tuning properties can encode complex information, such as sensory inputs.
8. **Activation Levels from a 2D Stimuli Input:** The question likely refers to interpreting a heatmap or graph showing how a neuron's activation level varies with two-dimensional stimulus input. Areas of highest activation would correspond to the preferred stimulus of the neuron, while areas of lowest activation would correspond to non-preferred stimuli.

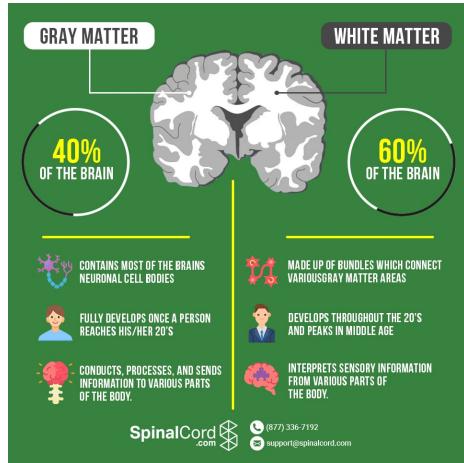


Figure 29: Brain matter

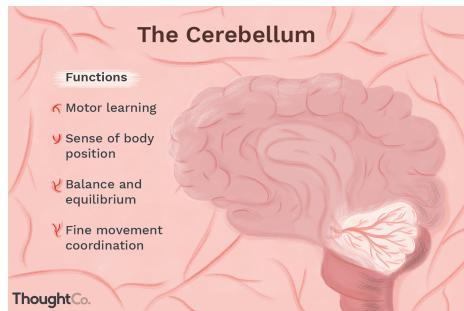


Figure 30: Cerebellum

9. **Action Potential Annihilation Due to Refractory Period:** The refractory period is the time immediately following an action potential during which a neuron is unable to fire another action potential. This refractory period prevents the backward propagation of the action potential and ensures unidirectional travel along an axon.
 10. **Cable Equation and EPSP Potential:** The cable equation describes how electrical signals decay as they travel through the dendrites and axons of neurons. An excitatory postsynaptic potential (EPSP) is a temporary increase in postsynaptic membrane potential due to the flow of positively charged ions into the cell. The potential is highest at the site of the synapse and decreases with distance from the point of synaptic contact due to the cable properties of the neuron.
- **Graph of LTP Changes:** Long-term potentiation (LTP) is typically visualized by plotting the post-synaptic response strength over time. A normal

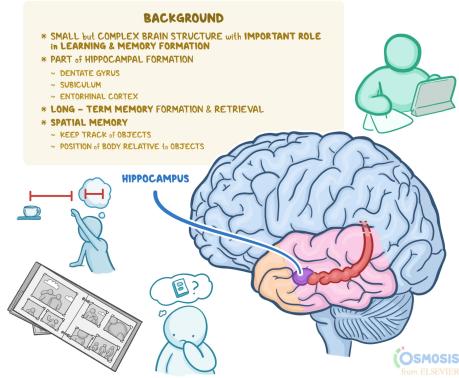


Figure 31: Hippocampus

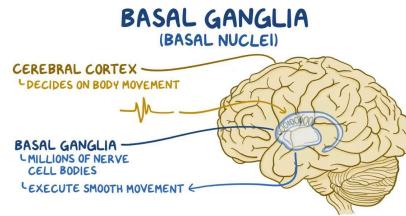


Figure 32: Basal Ganglia

graph of LTP would show a stable baseline of synaptic response followed by a sudden and sustained increase in response following a high-frequency stimulus. A modified graph might show a diminished LTP response, possibly due to pharmacological intervention, genetic modification, or pathology. Analyzing such graphs would involve noting differences in the magnitude, onset, and duration of LTP.

- Injecting Two Currents at Both Ends: When injecting two currents into the ends of a neuron, the interaction of the currents will depend on the neuron's properties, such as membrane resistance and capacitance. The currents will spread passively inside the neuron and decay over distance. The actual effect also depends on whether the currents are excitatory or inhibitory and their relative strengths and timings.

- Reversal Potential of a Single Ion: The reversal potential (also known as equilibrium potential) for a single ion can be calculated using the Nernst equation:

$$E_{\text{ion}} = \frac{RT}{zF} \ln \left(\frac{[\text{ion}]_{\text{outside}}}{[\text{ion}]_{\text{inside}}} \right)$$

where R is the gas constant, T is the temperature in Kelvin, z is the valence of

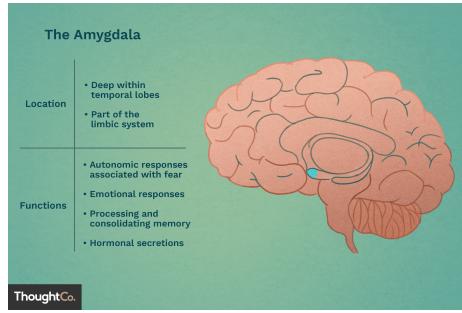


Figure 33: Amygdala

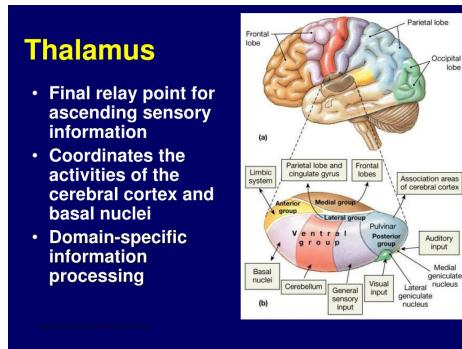


Figure 34: Thalamus

the ion, F is the Faraday constant, and $[ion]_{\text{outside}}$ and $[ion]_{\text{inside}}$ are the external and internal concentrations of the ion, respectively.

- **Property About Brains:** Humans do not have the largest brains in absolute size—that distinction goes to larger animals like whales or elephants. However, humans do have a high encephalization quotient (EQ), which is a measure of brain size relative to what would be expected for an animal of our body size. Humans also do not have the most neurons; for instance, some species of whales have more neurons due to their larger brains. Brain size generally scales with body size, but not in a simple linear relationship.

- **Resting Potential and Reversal Potential:** The resting potential of a cell is closest to the reversal potential of the ion that has the highest permeability across the cell membrane, which is typically potassium (K^+). This is due to the fact that the resting membrane is most permeable to K^+ , and the movement of K^+ ions out of the cell has the most significant effect on the resting potential.

- **Ion Flow During Resting/Polarization/Depolarization:** During the resting state, K^+ ions flow out of the cell, and Na^+ ions flow into the cell, but the K^+ flow is dominant, keeping the membrane potential close to the K^+ reversal potential. During depolarization, Na^+ ions flow rapidly into the cell,

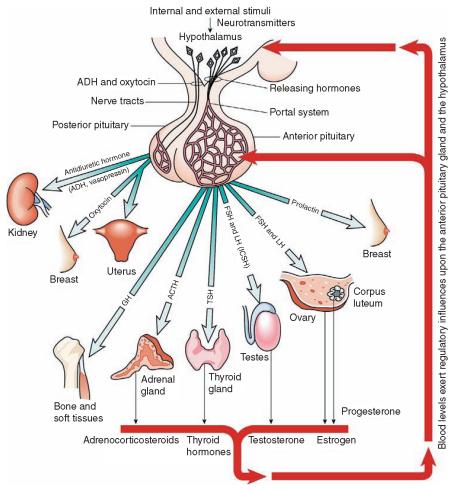


Fig C: Hormones secreted by Pituitary Gland

Figure 35: Pituitary gland

making the inside more positive. During repolarization, K⁺ ions flow out of the cell, restoring the negative internal environment.

- Electrical Synapses vs. Chemical Synapses: Electrical synapses are direct connections between cells that allow for the rapid transfer of electrical signals via gap junctions. They are bidirectional and can synchronize the activity of connected neurons. Chemical synapses, on the other hand, use neurotransmitters to transfer signals from one neuron to another, are unidirectional, and have a synaptic delay. They are also modifiable, meaning they can be strengthened or weakened over time, which is the basis for learning and memory.

- Loewi's Experiment: Otto Loewi demonstrated chemical transmission by showing that stimulating one frog's heart could release a substance (later identified as acetylcholine) that, when transferred to another frog's heart, slowed its rate. This experiment provided evidence that nerve impulses could affect heart rate through chemical means.

- Properties of the PLA (Perceptron Learning Algorithm): The PLA is an algorithm used to train perceptrons. It iteratively adjusts the weights and bias of the perceptron based on its output errors, moving the decision boundary towards the optimal position that separates the classes in linearly separable data sets.

- Hopfield Networks: Hopfield networks have discrete-time dynamics with binary threshold units, are fully connected, and have symmetric weight matrices. They serve as associative memories by converging to stable states, which represent the memorized patterns.

- Perceptrons vs. Logic Gates: Perceptrons are a simple model of a neuron that can learn to make decisions by adjusting its weights in response

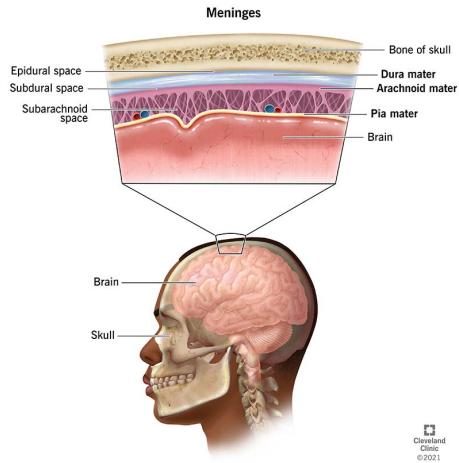


Figure 36: Meninges

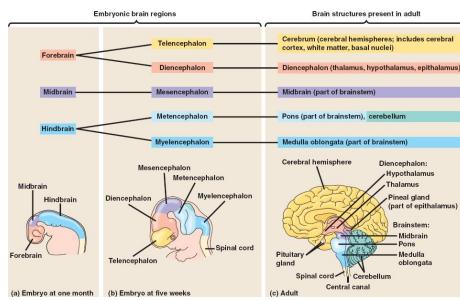


Figure 37: Brain development

to training data. Logic gates, however, are fixed-function devices that perform basic logical operations like AND, OR, and NOT without the ability to learn. Perceptrons can implement certain logic gates (like AND and OR for linearly separable patterns) but not others

Since this is a linear system, which of the following will always be true?

1. The weighting coefficients always lie on a straight line
 - False
2. If you scale the input by a constant, the output will be scaled by the same constant
 - True

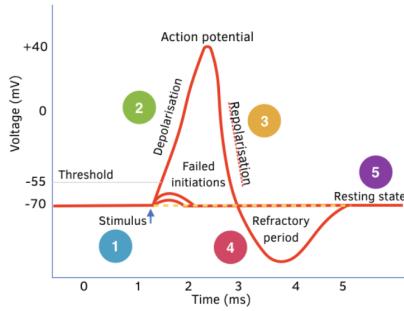


Figure 38: Neuron polarization

3. The output of a sum of different inputs is equal to the sum of the outputs of each of the individual inputs
 - True
4. The filter is a linear function of the input
 - False

Which of the following inputs might cause a linear system with a positive filter to predict a negative rate?

1. An input that slowly varies between a large positive value and a large negative value
 - true
2. A positive input that decays to zero over time
3. A positive input with a discontinuity
4. None of these

Chemical transmission

- Contrary to electrical transmission multiple steps are required to release transmitter chemicals and for them to act on postsynaptic receptors, resulting in a time delay
- Directional, select localization of release machinery to presynaptic terminals and receptors to postsynaptic specializations
- can change sign by release of inhibitory transmitter

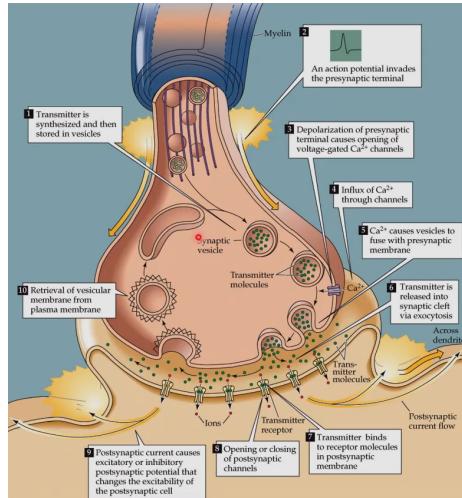


Figure 39: Chemical synapses

- highly modulatable as it has many steps presynaptic terminal and at the postsynaptic sites

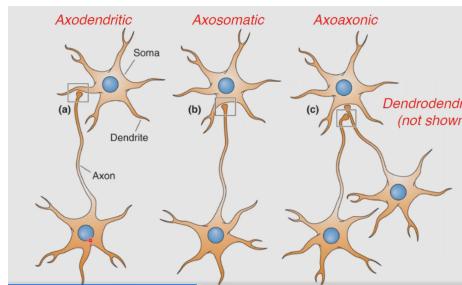


Figure 40: Types of synapses

Steps to chemical synaptic transmission

- First need to bring the presynaptic neuron to threshold at axon hillock
- Conduction down axon length $R * C$ dependent
- Opening of voltage gated Ca channels
- Diffusion and action of Ca at release machinery
- Exocytosis and diffusion of transmitter in cleft
- Activation of postsynaptic receptors

Criteria that define a neurotransmitter

1. must be present at presynaptic terminal
2. must be released by depolarization, Ca^{++} -dependent
3. specific receptors must be present

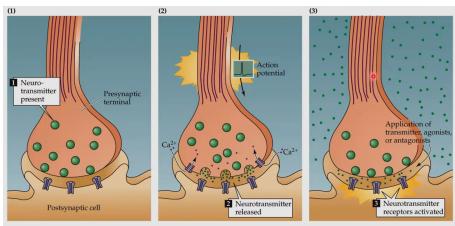


Figure 41: Neurotransmitter

Standard Katz (Quantal) Model of Synaptic Transmission

- One packet of neurotransmitter = 1 quantum
- AP transiently increases in the probability of releasing NX quanta
- Several quanta are available to be released
- Each quantum gives approximately the same postsynaptic response called the Quantal Amplitude
- The average number of quanta released, $m = np$
 - where n = number of quanta available for release
 - p = their average release probability

CNS synapses and quanta

- at CNS synapses with only a single release site, changing the probability of release (i.e. changing calcium concentration) does not effect the amplitude of the response (as only zero or one vesicle is released in theory)
- at CNS synapses with multiple release sites, changing release probability can change the postsynaptic response amplitude as more transmitter is released (graded quantal levels)
- at the NMJ a single nerve can elicit a postsynaptic AP given multiquantal release, while at the CNS synapse (with low number of release sites) multiple synapses must cooperate, forces a network

Docked Synaptic Vesicles

Define the number of readily releasable vesicles a synapse has available. A consequence of having of limited number is depletion at high stimulus frequency, CNS synapses may have only a small number of docked vesicles on the order of 5-10 vesicles for a hippocampal CA1 synapse

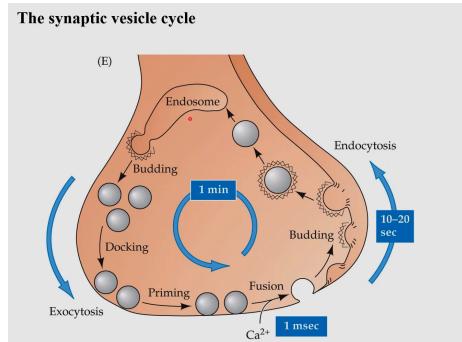


Figure 42: Synaptic vesicle cycle