

CBC SENIOR SIX: TERM 1 TOPIC 6: COORDINATION

Competency: The learner assesses the physiological and behavioural processes during organisms' responses to internal and external stimuli, in order to appreciate the adaptive behaviour of organisms and, therefore, promote their welfare to ensure survival and reproductive success.

COORDINATION IN PLANTS

PLANT HORMONES

If shoots always grow towards light, roots grow downwards, bananas ripen faster near ripe ones, and farmers can make crops flower at the same time ;what hidden signals inside plants could be controlling all these responses?

Plants, unlike animals, do not have a nervous system, but they still respond to changes in their environment. These responses include bending towards light, growing roots downward, flowering at specific times, and ripening of fruits. Such responses are controlled by **plant hormones**, chemical messengers produced in one part of the plant and transported to another, where they influence growth and development.

Plant hormones play a central role in processes such as **tropisms** (directional growth movements), **photoperiodism** (responses to day length), and various **agricultural applications** like fruit ripening, flowering control, weed management, and tissue culture.

Plant hormones include:

- ✓ Auxin
- ✓ Cytokines
- ✓ Ethylene (ethene)
- ✓ Absciscic acid

AUXINS

Role of auxins in elongation growth

Auxins are a group of chemical substances of which indole acetic acid (IAA) is the most common. The transport of auxin is in one direction, away from the tip of shoots and roots where it is produced. Auxin has a number of effects on plant cells, including altering the state of the cell wall so that permanent elongation of the cells can occur. This is only effective on young cell walls before they have developed greater rigidity through secondary thickening.

Auxin acts to promote growth and elongation, and environmental signals can influence the distribution of auxin in the plant. The proposed explanation of how auxin has a role in this elongation growth is called the **acid growth hypothesis** and is outlined below.

- ❖ Auxin binds to receptors, which causes transport proteins (ATPases) in the cell surface membrane to actively transport protons (hydrogen ions) from the cytoplasm into spaces in the cell wall.
- ❖ The protons cause the fluid-filled spaces in the cell wall to become more acidic.
- ❖ The decrease in pH creates the optimum conditions for proteins known as expansins to weaken the cell wall, temporarily disrupting the hydrogen bonding between cellulose microfibrils and between these and other cell wall polysaccharides.
- ❖ This causes a loosening of the cell wall.

- ❖ Water entering the cell by osmosis will cause an increase in turgor pressure and the loosening of the cell wall means that during active cell growth its protoplast can expand, causing elongation of the cell.

TROPISMS

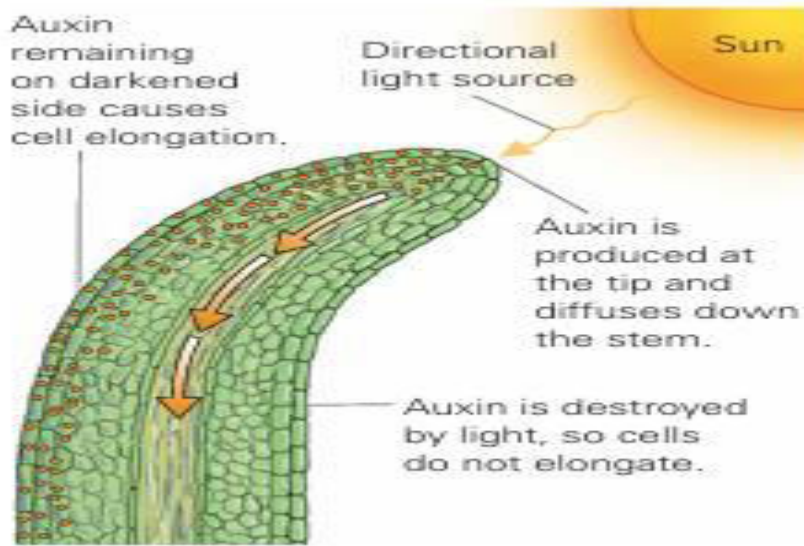
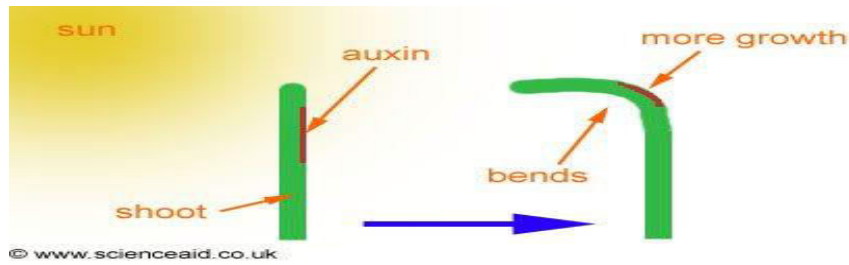
A tropism is a biological phenomenon, indicating growth or turning movement of a biological organism, usually a plant, in response to an environmental stimulus. In tropisms, this response is dependent on the direction of the species. The word tropism comes from the Greek trope (“to turn” or “to change”). Tropisms are usually named for the stimulus involved and may be either positive (towards the stimulus) or negative (away from the stimulus).

PHOTOTROPISM

Phototropism: This is the growth movement of part of the plant in response to unidirectional light. Plant shoots are positively phototropic that is, they grow towards the direction of light while the roots are negatively phototropic (they grow away from the direction of light). The shoot apex detects a light stimulus. When a shoot apex is exposed to a unilateral source of light causes auxins, which are plant growth hormones produced at the shoot apex to migrate to the shaded side. The higher concentration of auxins on the shaded side causes faster growth than on the illuminated side, hence the shoot curves towards the source of light.

IAA's Role in Phototropism

IAA is produced in the meristems of the stem. The auxin diffuses down the shady side of a stem and not the sunny side. As a result, the cells on the shady side elongate more than the sunny side and the stem bends toward the sun.



Importance of phototropism

- ❖ The shoot grows towards light hence the leaves are able to absorb light to carry out photosynthesis.
- ❖ Roots grow away from light into the ground from which water and mineral salts are absorbed and also provide support.

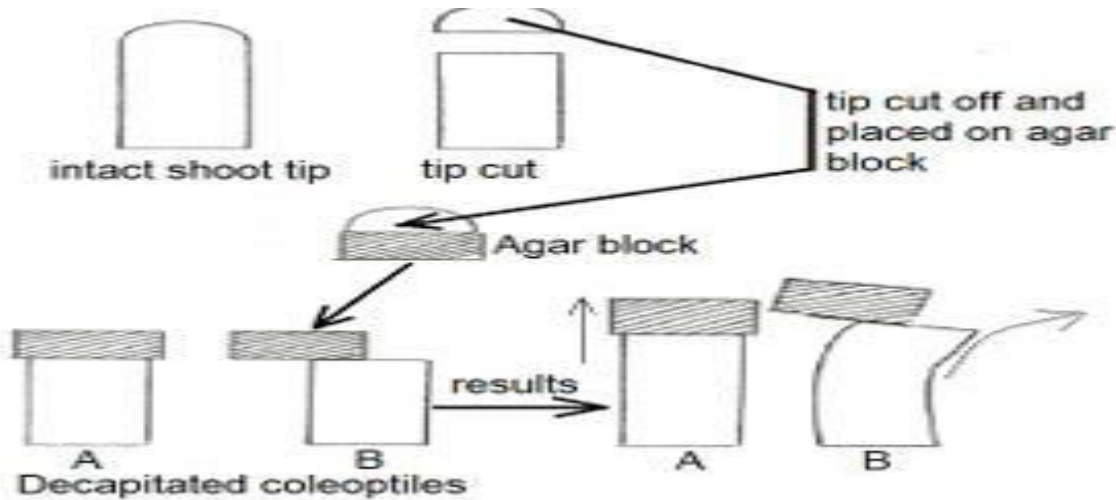
Experiment to show the effect of unequal distribution of auxins and to show that auxins are diffusible

Apparatus/Material:

Maize seedlings with coleoptiles, agar block (gelatinous substance through which auxins diffuse) and razor blade.

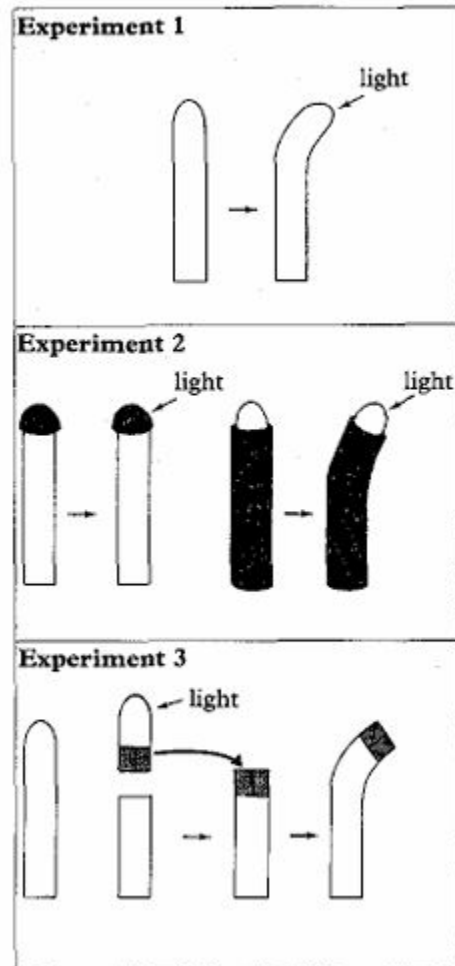
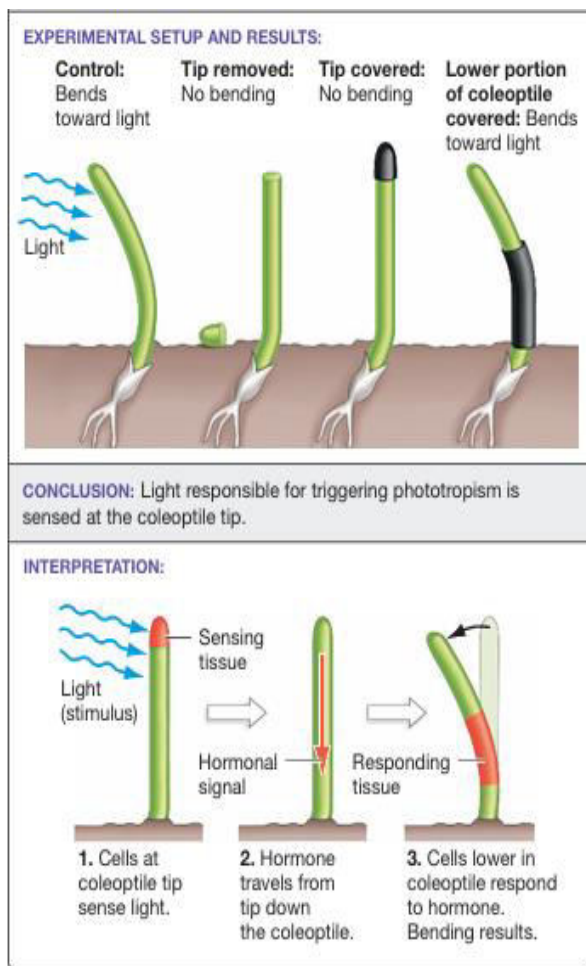
- i. Procedure:**
- ii. Two maize seedlings with coleoptiles at least 2cm long are exposed to light for at least 4 hours.
 - iii. Cut the coleoptiles tips and transfer each on to an agar block and leave them for 24 hours.
 - iv. Remove the coleoptile tips and place the agar blocks on fresh decapitated shoot tips.

Observation



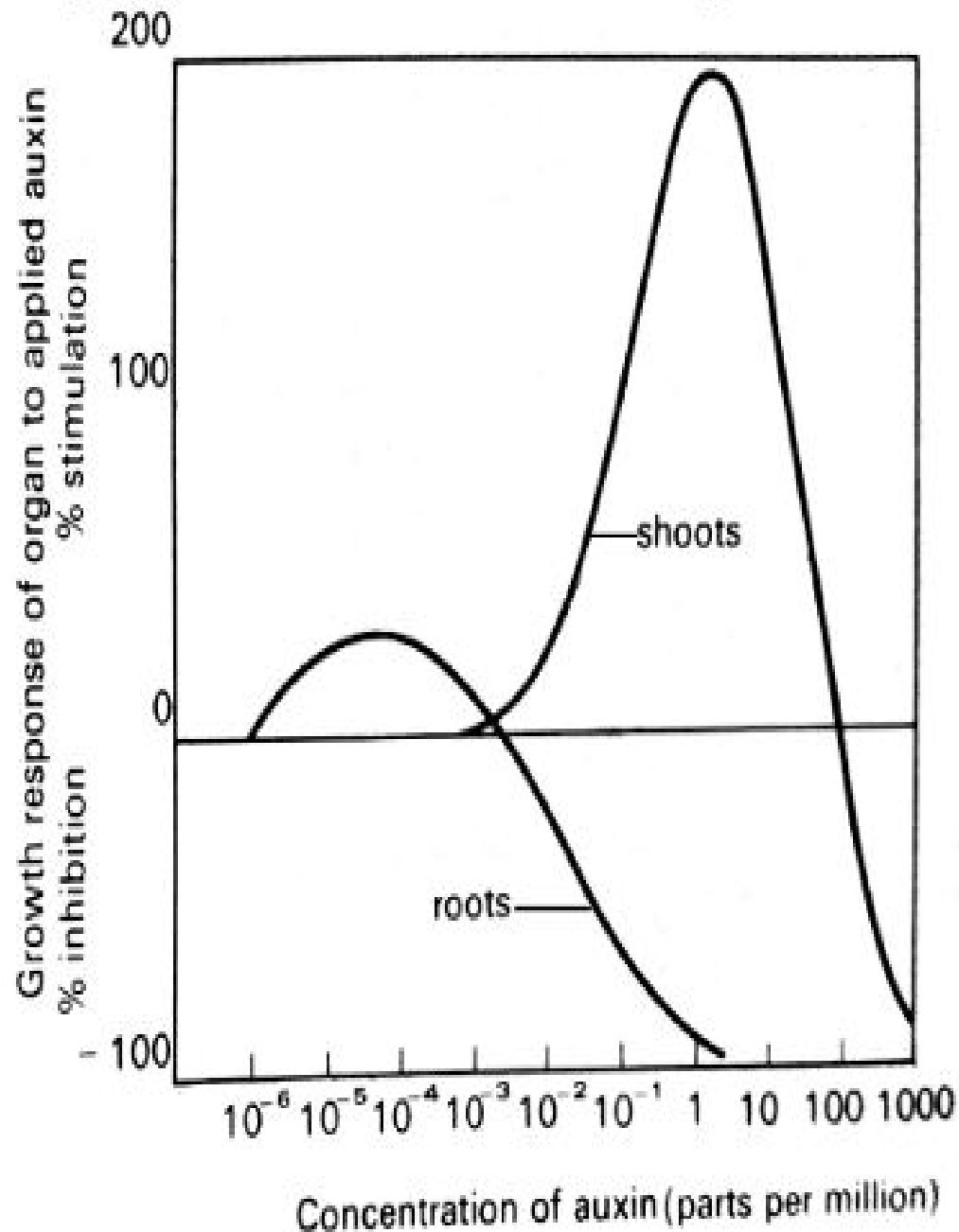
Shoot A grew straight upright while shoot B grew bending away from the side with agar block.

Explanation: Auxins diffused from the coleoptile tips into the agar block. Thus auxins are evenly distributed on the agar block. In shoot A- Auxins diffuse from the agar block into the decapitated shoot. All sides receive same concentrations of auxins. Cell elongation occurred and growth took place evenly with the shoot growing up right. In shoot B- Auxins diffused on one side of the shoot. I.e. the side covered with agar block. There was faster cell elongation and hence faster growth on the side compared to the uncovered side. This resulted to the growth curvature observed.



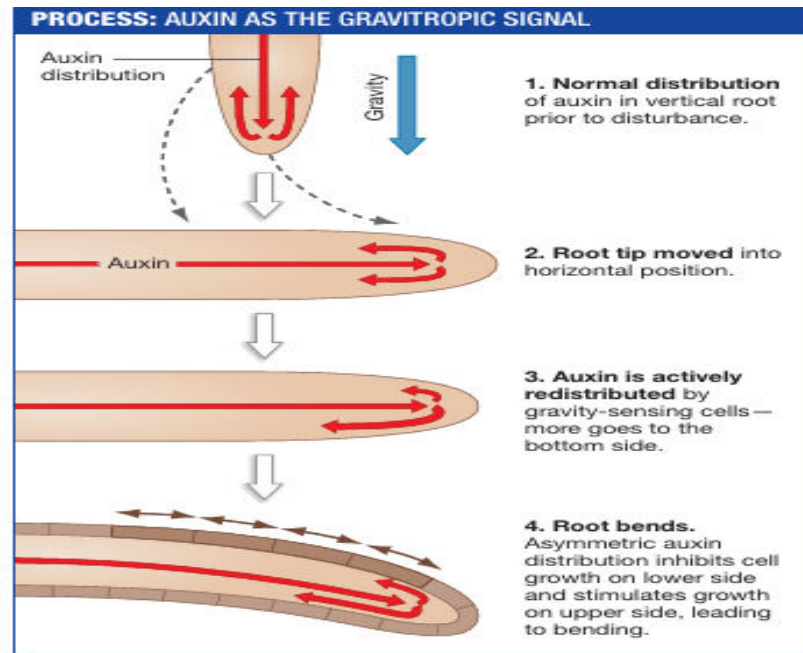
ROOTS AND SHOOTS RESPOND DIFFERENTLY TO AUXINS

Graph showing the effect of auxins concentration on the growth of roots and shoots.



GEOTROPISM

Geotropism, also known as gravitropism, refers to the directional growth response of plants to the stimulus of gravity.



ECOLOGICAL SIGNIFICANCE OF GEOTROPISM

- ❖ Roots display **positive geotropism**, growing downward into the soil. This allows them to anchor the plant firmly and efficiently access water and nutrients. Stems, on the other hand, show **negative geotropism**, growing upward away from gravity to reach sunlight. This coordinated growth ensures the plant is stable and properly oriented to acquire both above-ground and below-ground resources.

MUST DO, Group assignment: In your groups, describe and carry out a scientific experiments to investigate phototropism and geotropism. Make reports for submission.

COMMERCIAL APPLICATIONS OF AUXINS

- ❖ **Herbicides:** synthetic auxins, such as 2,4-D, are used as selective herbicides. At high concentrations, these compounds cause dicot (broadleaf) weeds to grow uncontrollably and die, while leaving monocot (grass) crops like corn and wheat relatively unharmed.
- ❖ **Rooting powders and gels:** auxins are the main active ingredient in rooting hormones used to promote root formation in plant cuttings. This makes it easier to propagate plants vegetatively.
- ❖ **Fruit production:** auxins can be used to prevent the premature dropping of fruits, ensuring a better harvest. They are also used to induce the development of **parthenocarpic** (seedless) fruits, such as some varieties of tomatoes and cucumbers.
- ❖ **Tissue culture:** in plant tissue culture, the balance between auxins and cytokinins is crucial for controlling the development of new plants. The ratio determines whether the cultured cells will form roots or shoots.

CYTOKININS

- ❖ Cytokinins comprise another group of naturally occurring growth hormones in plants.
- ❖ A cytokinin is a plant hormone that, in combination with auxin, stimulates cell division and differentiation. Most cytokinins are produced in the root apical meristems and transported throughout the plant. Developing fruits are also important sites of cytokinin synthesis. Cytokinins promote the growth of lateral buds into branches. Conversely, cytokinins inhibit the formation of lateral roots, whereas auxins promote their formation. As a consequence of these relationships, the balance between cytokinins and auxin largely determines a plant's form.

Commercial applications of cytokinins

- ❖ **Tissue Culture:** In plant tissue culture, a specific ratio of cytokinins to auxins is used to control the development of new shoots and roots. A high cytokinin-to-auxin ratio promotes shoot formation, while a low ratio favors root formation.
- ❖ **Delaying Senescence:** Cytokinins are sprayed on leafy vegetables like lettuce and broccoli to keep them fresh for longer by delaying the yellowing of leaves.

- ❖ **Improving Crop Yield:** They are used to increase branching and flowering in some crops, leading to a bushier plant with a higher yield.

GIBBERELINS

Gibberellins are a large family of hormones primarily known for promoting **stem and internode elongation** and stimulating **seed germination**. GAs cause cell elongation and division, leading to increased plant height. They also play a crucial role in breaking **seed dormancy** by stimulating the synthesis of enzymes (like amylase) that break down stored starch into energy for the embryo. They can also induce **flowering** in some plants and promote the development of **parthenocarpic** (seedless) fruits.

Gibberellins, which are synthesized in the apical portions of stems and roots, have important effects on stem elongation. The elongation effect is enhanced if auxin is also present.

Gibberellins also affect a number of other aspects of plant growth and development.

COMMERCIAL APPLICATIONS OF GIBBERELINS

- ❖ **Fruit enlargement:** Applying GAs to grapes, for example, increases the size of the berries and the length of the fruit stalks, creating more space and preventing mold.
- ❖ **Malting:** In the brewing industry, GAs are used to speed up the malting process of barley, which involves the germination of seeds to produce enzymes needed to convert starch into sugar.
- ❖ **Seed germination:** GAs are used to promote uniform germination in crops like sugar beet and certain cereals.
- ❖ **Ornamentals:** They can induce early flowering in certain ornamental plants, allowing for better scheduling and market timing.

TABLE SHOWING COMPARISON BETWEEN EFFECTS OF AUXINS AND GIBBERELINS

Process affected	Auxins	Gibberellins
Stem growth	Promote cell enlargement in region behind apex. Promote cell division in cambium.	Promote cell enlargement in presence of auxin. Also promote cell division in apical merand apical cambium. Promote 'bolting' of some rosette plants.
Root growth 	Promote at very low concentrations. Inhibitory at higher concentrations, e.g. geotropism.	Usually inactive
Root initiation	Promote growth of roots from cuttings and calluses.	Inhibitory
Bud (shoot) initiation	Promote in some calluses but sometimes antagonistic to cytokinins and inhibitory. Sometimes promote in intact plant if apical dominance broken (see below).	Promote in chrysanthemum callus, Sometimes promote in intact plant if apical dominance broken.
Leaf growth* 	Inactive	Promote
Fruit growth	Promote. Can sometimes induce parthenocarp.	Promote. Can sometimes induce parthenocarp.
Apical dominance	Promote, i.e. inhibit lateral bud growth.	Enhance action of auxins.
Bud dormancy* 	Inactive	Break
Seed dormancy* 	Inactive	Break , e.g. cereals, ash
Flowering*	Usually inactive (promote in pineapple)	Sometimes substitute for red light. Therefore promote in long-day plants, inhibit in short-day plants.
Leaf senescence	Delay in a few species	Delay in a few species
Fruit ripening	– Inhibit. Sometimes promote once abscission starts or	– Inactive

ETHYLENE

- ❖ Ethylene plays a major role in fruit development. At first, auxin, which is produced in significant amounts in pollinated flowers and developing fruits, stimulates ethylene production; this in turn hastens fruit ripening. Complex carbohydrates are broken down into simple sugars, chlorophylls are broken down, cell walls become soft, and the volatile compounds associated with flavor and scent in ripe fruits are produced.
- ❖ When auxin is transported downward from shoot apical meristem, it stimulates the production of ethylene in the tissues around the lateral buds and thus prevents their growth. Ethylene also suppresses stem and root elongation. Carbon dioxide gas as an opposite effect to ethylene thus it arrests fruit ripening.

COMMERCIAL APPLICATIONS OF ETHYLENE

- ❖ **Controlled ripening:** Ethylene is widely used in the agricultural industry to ripen fruits on demand. Fruits like bananas and tomatoes are often harvested unripe and transported to their destination, where they are then exposed to ethylene gas in ripening rooms.

- ❖ **Fruit degreening:** Ethylene is used to break down chlorophyll and enhance the yellow or orange color in citrus fruits, making them more visually appealing to consumers.
- ❖ **Synchronizing flowering:** In some crops like pineapples, a controlled application of ethylene can be used to synchronize flowering, leading to a more uniform harvest.
- ❖ **Post-Harvest management:** Ethylene absorbers are used in packaging to delay the ripening and decay of fresh produce, extending its shelf life.

ABSCISIC ACID

- ❖ Absciscic acid (ABA) appears to be synthesized mainly in mature green leaves, fruits, and root caps. The hormone earned its name because applications of it appear to stimulate fruit dropping (abscission) in cotton, but there is little evidence that it plays an important role in this process. Ethylene is actually the hormone that promotes senescence and abscission.
- ❖ ABA plays a role in seed dormancy and is antagonistic to gibberellins during germination. ABA levels rise during embryogenesis. As maize embryos develop in the kernels on the cob, ABA is necessary to induce dormancy and prevent premature germination, called vivipary. It is also important in controlling the opening and closing of stomata.

COMMERCIAL APPLICATIONS OF ABSCISIC ACID

- ❖ **Improving stress tolerance:** while not as widely used as other hormones for growth, synthetic aba analogs are being developed to help agricultural crops withstand drought and other stresses, improving their survival and yield.

TABLE COMPARING EFFECTS OF CYTOKININS AND ABSCISIC ACID

Process affected	Cytokinins	Abscasic acid
Stem growth	Promote cell enlargement in region behind apex. Promote cell division in cambium.	Promote cell enlargement in presence of auxin. Also promote cell division in apical meristematic and apical cambium. Promote 'bolting' of some rosette plants.
Root growth 	Promote at very low concentrations. Inhibitory at higher concentrations. e.g. geotropism.	Usually inactive
Root initiation	Promote growth of roots from cuttings and calluses.	Inhibitory
Bud (shoot) initiation	Promote in some calluses but sometimes antagonistic to cytokinins and inhibitory. Sometimes promote in intact plant if apical dominance broken (see below).	Promote in chrysanthemum promote in intact plum?
Leaf growth* 	Inactive	Promote
Fruit growth	Promote. Can sometimes induce parthenocarpy.	Promote. Can sometimes
Apical dominance	Promote, i.e. inhibit lateral bud growth.	Enhance action of auxins.
Bud dormancy* 	Inactive	Break
Seed dormancy* 	Inactive	Break, e.g. cereals, ash
Flowering*	Usually inactive (promote in pineapple)	Sometimes substitute for red light. Therefore promote in long-day plants, inhibit in short-day plants.
Leaf senescence	Delay in a few species	Delay in a few species
Fruit ripening	—	—
Abscission	—	—

SUMMARY FOR PLANT HORMONES

Plant hormones.		
Hormone Type	Effects	Commercial Applications
Auxin	Promotes cell expansion, apical dominance, tropic responses, differentiation of vascular tissue; promotes roots on plant cuttings; inhibits fruit and leaf abscission; stimulates fruit development; stimulates ethylene production (in high doses)	Rooting powder for plant cuttings; prevents fruit and flower drop; promotes seedless fruit production; used as weed killer by triggering too-rapid growth
Gibberellin	Stimulates leaf and stem cell elongation and division; hastens seed germination, breaks seed dormancy; stimulates fruit development	Used to cause uniform germination of barley used in brewing; prevents flower initiation; promotes seedless fruit production
Cytokinin	Promotes cell division; triggers lateral bud growth even in presence of auxin; with auxin, regulates root and shoot production; delays leaf aging	Used to trigger growth of whole plants from genetically engineered plant cells
Ethylene	Inhibits cell expansion; promotes fruit ripening; promotes abscission	Hastens ripening of tomatoes, walnuts, and grapes after harvest; used as fruit-thinning agent in commercial orchards; used to defoliate plants
Absciscic acid	Prevents seed germination; promotes dormancy	Inhibits growth and promotes flowering of potted plants for florists

PHOTOPERIODISM

All plants have a biological clock which enables them to anticipate certain events, rather than to be controlled by them.

The relative length of day and night varies with the time of year and is called the photoperiod. The response of a plant to changes in day length or night length is called photoperiodism. One of the most studied examples is flowering.

Photoperiodism is the response of an organism to the relative lengths of day and night. This phenomenon influences a wide range of activities in both plants and animals. While it's most well-known effect is on flowering, it also controls other functions, such as seed germination and the dormancy of buds in plants, as well as migration and reproduction in animals.

Types of Flowering Plants and Their Response to Light

Flowering plants can be divided into three groups based on their differing responses to light and dark:

❖ Long-Day Plants

These plants require a light period that is **longer than a certain critical length** in each 24-hour cycle to flower. For these plants, a light treatment induces early flowering, whereas a dark treatment delays it. An important point is that the flowering of long-day plants is actually triggered by a night that is **shorter than a critical length**. By carefully adjusting the photoperiod, plant breeders can make early and late varieties of such plants flower simultaneously, enabling them to be cross-bred. Examples include **petunias, spinach, radishes, and lettuce**.

Characteristics of long day plants

- ❖ Short nights are more essential than the length of the day. Thus they are commonly known as short night plants.

- ❖ They flower during summer when the days are longer than the night, like wheat.
- ❖ They flower even when the short night is interrupted by flashes of light and do not need an interrupted short night. They also show flowering even when the long day is interrupted by short dark periods.
- ❖ They flower only when the light period exceeds the critical length of the day (12 hours).
- ❖ They require long days and short nights to flower.

❖ **Short-Day Plants**

These plants flower only when the light period is **shorter than a critical length** in each 24-hour cycle. The key factor for their flowering is a **long, uninterrupted dark period**. The influence of the photoperiod on short-day plants can be demonstrated by exposing them to a **brief flash of light in the middle of the night**. This intervention, if continued for a sufficient number of days, will delay flowering. This knowledge is used by horticulturists to guarantee a supply of plants like **chrysanthemums** and **poinsettias** at specific times, such as Christmas. To make these plants flower early, they are given extra darkness. In some cases, just one long night is enough to induce flowering. Other examples include **cocklebur**.

Characteristics of short day plants

- ❖ They require short days and long nights for them to flower.
- ❖ They flower only when day length become shorter than the critical day length.
- ❖ They do not flower if given short days and long nights interrupted by flashes of light. On the contrary, if the short days are interrupted by intervals of darkness but left with an interrupted long night they flower.

❖ **Day-Neutral Plants**

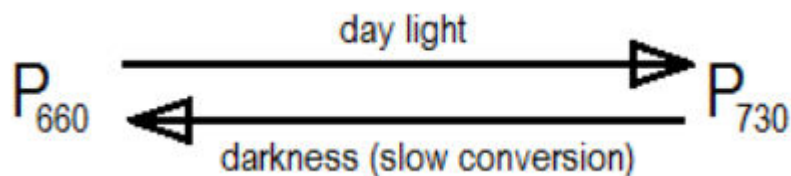
These plants are **indifferent to day-length**. Their flowering is not regulated by the duration of the light or dark periods. Instead, they flower once they have reached a certain stage of maturity. Examples of day-neutral plants are **tomato** and **cotton**.

PHYTOCHROME AND THE DETECTION OF NIGHT LENGTH

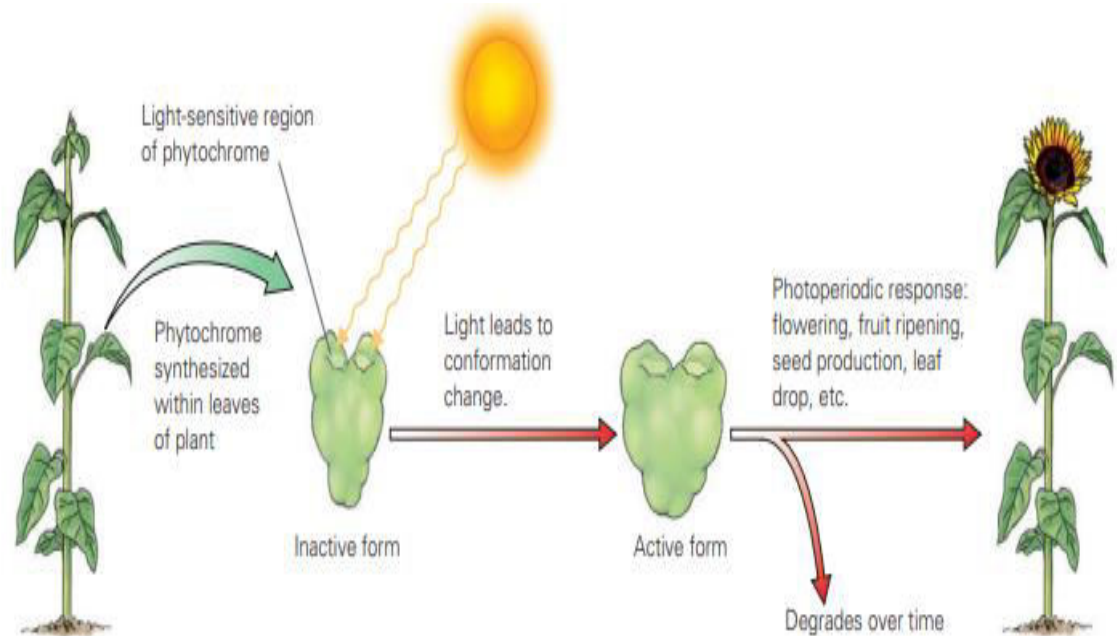
- ❖ Photoperiodism requires a mechanism for detecting the length of darkness. The best-known candidate for this job is a pale-blue light-sensitive protein called phytochrome. It exists in two interconvertible forms: P_{660} , which absorbs red light (light with a wavelength of 660 nm), and P_{730} , which absorbs far-red light (light with a wavelength of 730 nm). Phytochrome far-red is the biologically active form and it serves to stimulate flowering in long-day plants to delay it in short-day plants.



- ❖ Phytochrome is synthesized in its P_r form. Experiments with specific wavelengths of light show that P_r is converted into P_{fr} when exposed to red light, and that P_{fr} is converted back into P_r when exposed to far-red light or when in darkness. During the day, there is more P_{fr} than P_r because sunlight has a higher proportion of red light than far-red light. During the darkness of night, P_{fr} is gradually converted back to P_r .

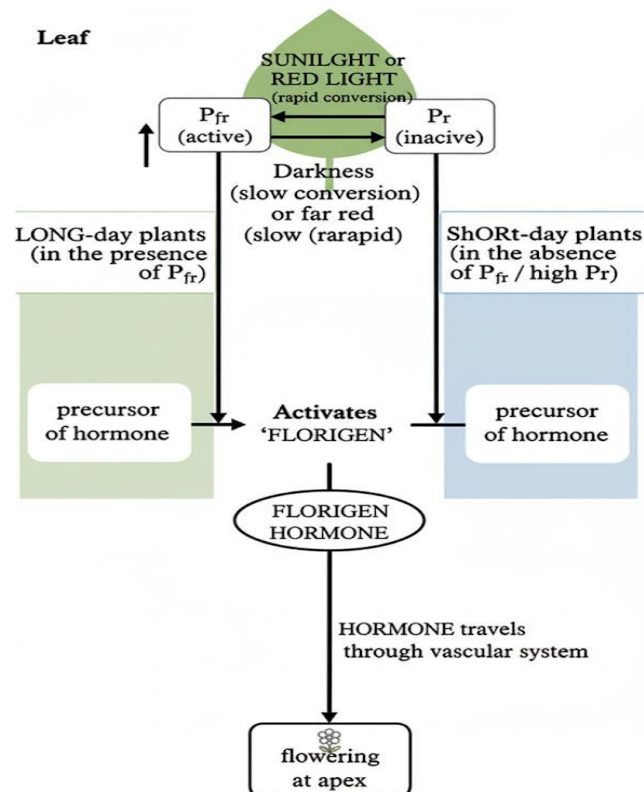


- ❖ Thus the relative amounts of the two forms of phytochrome could indicate day length. It is thought that the balance between the two forms of phytochrome control flowering in short-day and long-day plants. A build-up of P_{fr} could stimulate flowering in long-day plants, whereas in short-day plants, P_{fr} could inhibit flowering.



- ❖ If phytochromes are involved, their detection of the photoperiod takes place in the leaves. If only one leaf of a short-day or long-day plant is exposed to normal daily routines of light and darkness and the rest of the plant including all the flower buds is kept in constant darkness, the plant will still flower normally. As the flowering response takes place in the flower buds the plant must have some means of transmitting information from leaves to flower buds. A chemical messenger called florigen has been suggested. If florigen exists, it might be secreted in response to the relative amounts of the two forms of phytochrome in the leaves, and then carried in the vascular system to the flower buds. In long-day plants, high levels of Pfr or low levels of Pr may stimulates florigen secretion, whereas in short-day plants, florigen may be secreted when Pfr levels are low or when Pr levels are high.

SUMMARY ILLUSTRATION SHOWING THE INTERACTION OF PHYTOCHROMES AND FLORIGEN HORMONE TO BRING ABOUT FLOWERING



COORDINATION ON ANIMALS

All living organisms must be able to detect changes in their environment and respond appropriately. Changes in the environment are called stimuli (singular: stimulus).

A stimulus may be in either the external environment (outside the organism) or the internal environment (inside the organism). Sensitivity, the ability to respond appropriately to stimuli, is one of the characteristic features of life. Each organism has its own specific type of sensitivity that improves its chances of survival.

This process of detecting and responding to stimuli relies on two primary systems: the nervous system, which transmits rapid electrical impulses via neurons for immediate responses like reflexes or voluntary movements, and the endocrine system, which releases hormones into the bloodstream for slower, sustained regulation of processes such as growth, metabolism, and stress responses.

THE NERVOUS SYSTEM

As animal species became more complex and the number of receptors and effectors increased, it became more efficient to link each receptor and effector to a central control Centre. This is the **central nervous system**, consisting of the brain and spinal cord. The inter-relationships of all these various components are shown in Figure 1.

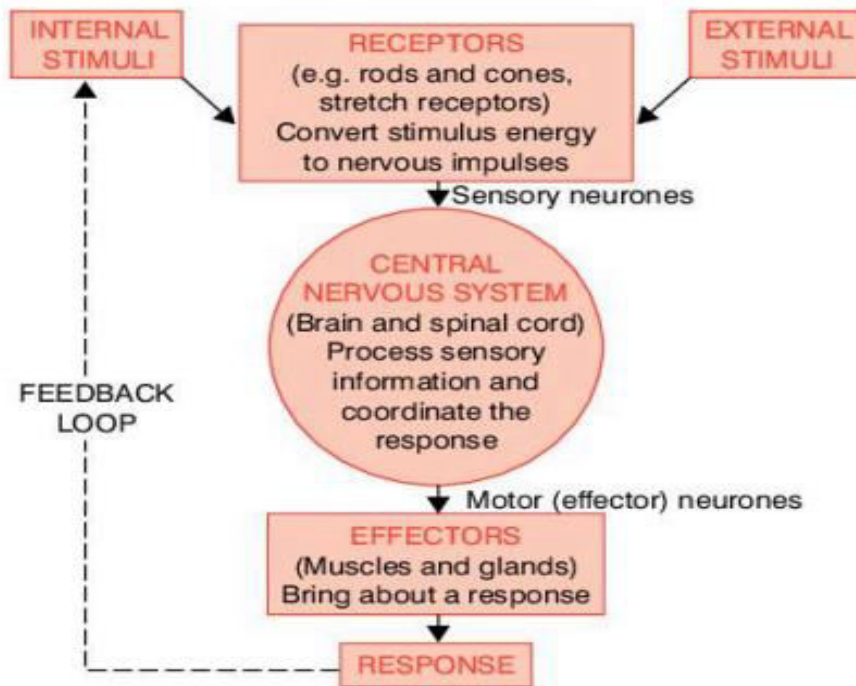
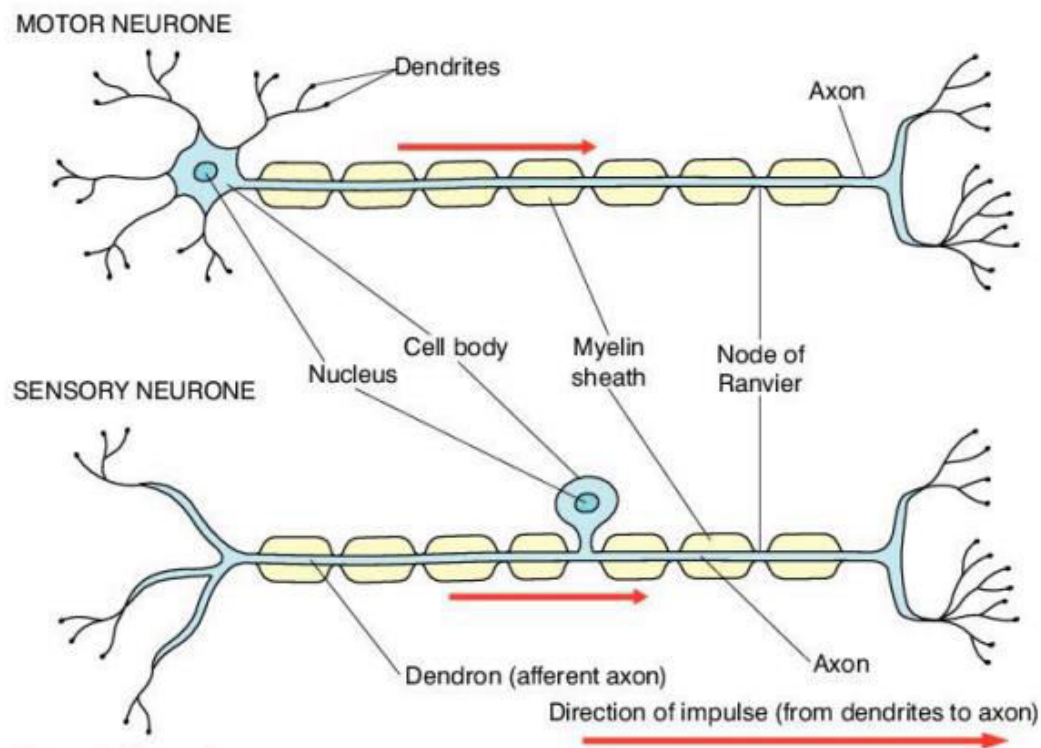


Figure 1 Inter-relationships of components of the nervous system

The basic functional unit of the nervous system is the neuron.

Structure of a motor and sensory neuron



ADAPTATIONS OF THE PARTS OF A NEURON TO THEIR FUNCTIONS

- ❖ **Long axon:** The long, fine axon allows nerve impulses to be transmitted over **long distances** throughout the body, from the central nervous system to distant parts like muscles or sensory organs, without losing signal strength.
- ❖ **Numerous dendrites:** The highly branched, tree-like structure of dendrites provides a **large surface area** to receive signals from a multitude of other neurons, allowing for complex information processing.
- ❖ **Myelin sheath:** Many axons are covered by a fatty, insulating layer called the **myelin sheath**. This sheath acts as an electrical insulator, preventing the impulse from dissipating. It also causes the impulse to "**jump**" from one gap in the sheath (called a **node of Ranvier**) to the next, a process known as saltatory conduction, which dramatically increases the speed of signal transmission. The myelin sheath is secreted by the Schwann cells.
- ❖ **Mitochondria:** Neurons have a high concentration of mitochondria, particularly in the axon terminals. This is an adaptation to provide the large amount of **energy (ATP)** needed for active processes like pumping ions to maintain the resting potential and synthesizing and releasing neurotransmitters across the synapse.
- ❖ **Specialized junctions:** The axon terminals contain **synaptic knobs** with vesicles that store neurotransmitters, ensuring that chemical signals are ready to be released when an electrical impulse arrives, allowing for communication with other cells.
- ❖ **Numerous Nissl's granule:** These are for protein synthesis to produce proteins required for impulse transmission for example enzymes.

TYPES OF NEURONS

- ❖ **Sensory neurones** transmit nerve impulses from a receptor to a relay or motor neurone. They have one afferent dendron that brings the impulse towards the cell body and one axon that carries it away from the cell body.
- ❖ **Relay neurones** (intermediate neurones) transmit impulses between neurones, e.g. from sensory to motor neurones. They have numerous short processes (extensions).
- ❖ **Motor neurones** (effector neurones) transmit nerve impulses from a relay or sensory neurone to an effector such as a gland or a muscle. They have a long axon and many short dendrites.

IMPULSE TRANSMISSION

A nerve impulse may be defined as a self-propagating wave of electrical disturbance that travels along the surface of the axon membrane. It is not, however, an electrical current, but a temporary reversal of the electrical potential difference across the axon membrane. This reversal is between a state called the **resting potential** and another called the **action potential**.

RESTING POTENTIAL

A resting neuron is so called because it does not convey a nerve impulse, not because it is inactive. On the contrary, a resting neuron expends much energy in maintaining a potential difference across its membrane. This is called the resting potential and measures about -70 millivolts.

During the resting potential, the inside of the neuron is negative relative to the outside because of an unequal distribution of charged ions. On the outside, sodium ions (Na^+), chloride ions (Cl^-), and calcium ions (Ca^{2+}) are present in higher concentrations than inside the cell. By contrast, the inside of the cell has a higher concentration of potassium ions (K^+) and organic anions (negative ions).

This unequal distribution of ions results from a combination of active transport and diffusion of sodium and potassium ions across the cell membrane, and the inability of large organic anions to pass out of the cell.

The movement of sodium ions (Na^+) and potassium ions (K^+) across the axon membrane is controlled in a number of ways:

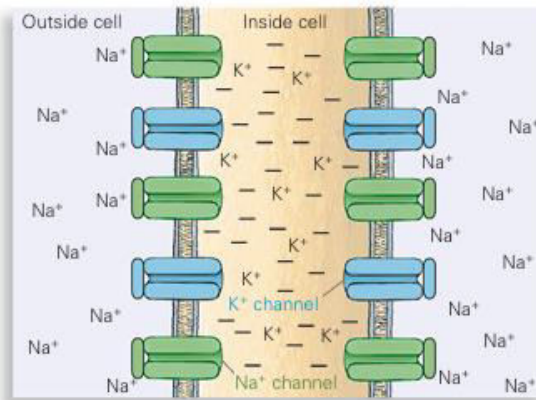
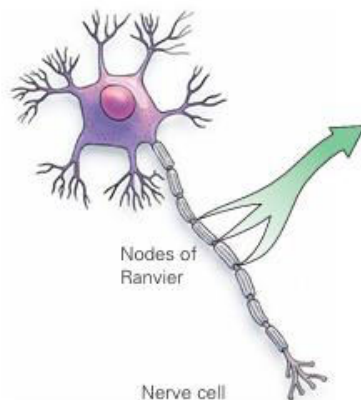
- ❖ The **phospholipid** bilayer of the axon cell surface membrane is impermeable to sodium ions (Na^+) and potassium ions (K^+).
- ❖ The channels are specific for either sodium or potassium ions. One type of channel, termed a voltage-gated channel, can be opened to allow the specific ion across or closed to prevent movement of that ion. A different type of channel remains open and allows diffusion of the ion across. There are more of these channels, sometimes termed 'leak' channels, for potassium ions than for sodium ions.
- ❖ Some intrinsic proteins **actively transport** potassium ions into the axon and sodium ions out of it. This is called the **sodium–potassium pump (cation pump)**.

HOW RESTING POTENTIAL IS MAINTAINED

As a result of these various controls, the inside of an axon is negatively charged relative to the outside. This is known as the **resting potential** and is in the range 50–90 millivolts (mV), but is usually 65mV. In this condition the axon is said to be **polarized**. To achieve this potential difference the following events occur:

- 1) Sodium ions are actively transported **out of** the axon by sodium–potassium pumps (specialized carrier proteins).
- 2) Potassium ions are actively transported **into** the axon by sodium–potassium pumps.
- 3) The active transport of sodium ions is faster than that of potassium ions, so that three sodium ions move out for every two potassium ions that move in.
- 4) Although both sodium and potassium ions are positively charged, the outward movement of sodium ions is greater than the inward movement of potassium ions. As a result, there are more sodium ions in the tissue fluid surrounding the axon than in the cytoplasm, and more potassium ions in the cytoplasm than in the tissue fluid. For each ion, this creates a chemical gradient.
- 5) The sodium ions begin to diffuse back naturally into the axon while the potassium ions begin to diffuse back out of the axon.
- 6) As there are more of the leak channel proteins for potassium ions, the result is that the axon membrane is **100 times more permeable to potassium ions**, which therefore diffuse back out of the axon faster than the sodium ones diffuse back in. This further increases the potential difference between the negative inside and the positive outside of the axon.
- 7) Apart from the chemical gradient that causes the movement of the potassium and sodium ions, there is also an electrical gradient. As more and more potassium ions diffuse out of the axon, so the outside becomes more and more positive. Further outward movement of potassium ions is therefore made difficult because, being positively charged, they are attracted back into the axon by its overall negative state and repelled from moving outwards by the overall positive state of the surrounding tissue fluid.
- 8) The presence of large, negatively charged proteins within the cytoplasm of the axon contributes to this overall negative state. Thus the inside of the axon membrane is negatively charged relative to the outside.

(a) Resting nerve cell and polarization



THE ACTION POTENTIAL

Another name for a nerve impulse is an action potential. An action potential transmits a signal along the length of a neuron. *An action potential is a brief reversal of the electrical charge across the membrane of a nerve cell.* The action potential is propagated as a wave of electrical current down the length of the neuron.

The action potential results from the changes in the permeability of cell membranes to ions. At rest, the membrane permeability of a nerve fibre is thought to depend on ion channels through which specific ions can move. An ion channel consists of a protein molecule spanning the membrane, with a pore through the centre. Sodium ions move through one type of channel and potassium ions through another. There are many more of these ion channels for potassium than for sodium, therefore at rest the membrane permeability to potassium ions is much greater than that to sodium ions.

During an action potential, special ion channels control ion movements across the membrane, these channels are believed to have voltage-sensitive gates that open and close in response to voltage changes, and are therefore called **voltage-gated ion channels**

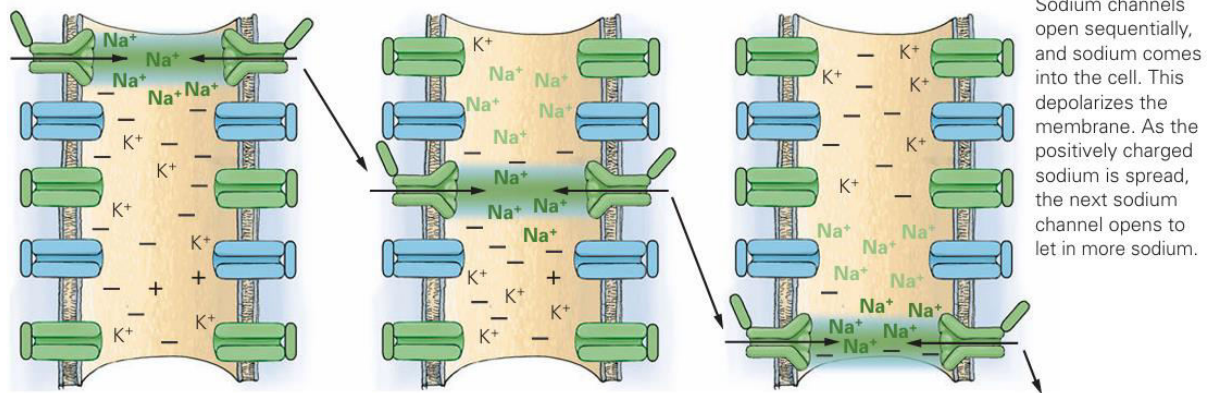
The energy conversion that occurs when a stimulus is received by a receptor leads to a temporary reversal of the charges on the axon membrane. As a result, the negative charge of -65 mV inside the membrane becomes a positive charge of around +40 mV. This is known as **the action potential**, and in this condition the membrane is said to be **depolarized**. This depolarization involves the voltage-gated channels.

THE SEQUENCE OF EVENTS INVOLVED IN THE DEPOLARIZATION AND REPOLARIZATION OF NEURON

1. At resting potential some potassium ion channels (leak channels) are **open** but the potassium voltage-gated and sodium voltage-gated channels are **closed**.

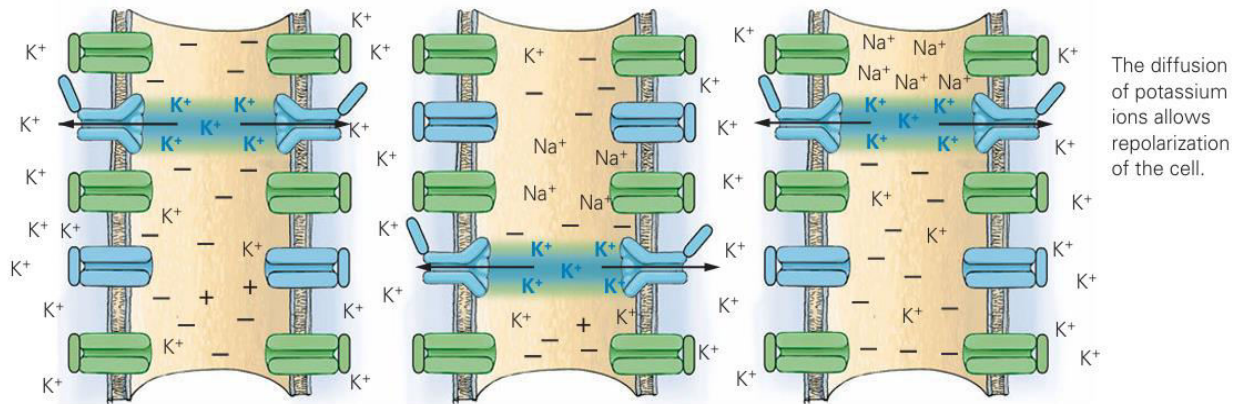
2. As a result of the stimulus some voltage-gated sodium channels in the axon membrane **open** and therefore sodium ions diffuse in through the channels along their electrochemical gradient. Being positively charged, they begin the reversal in the potential difference across the membrane and the membrane depolarizes. Voltage-gated potassium channels remain closed.
3. As sodium ions enter, so more voltage-gated sodium channels open, causing an even greater influx of sodium ions. This is an example of positive feedback. An action potential will only occur if the membrane depolarizes enough to allow the remaining voltage-gated sodium channels to open. This is known as the **threshold potential** (approximately -5 to -15 mV less negative than the resting potential).
4. Once the action potential of around +40 mV has been established (depolarization has occurred), the voltage gates on sodium channels close (so further influx of sodium is prevented) and the voltage gates on the potassium channels begin to open.

(b) Propagation of an action potential, or nerve impulse, for depolarization

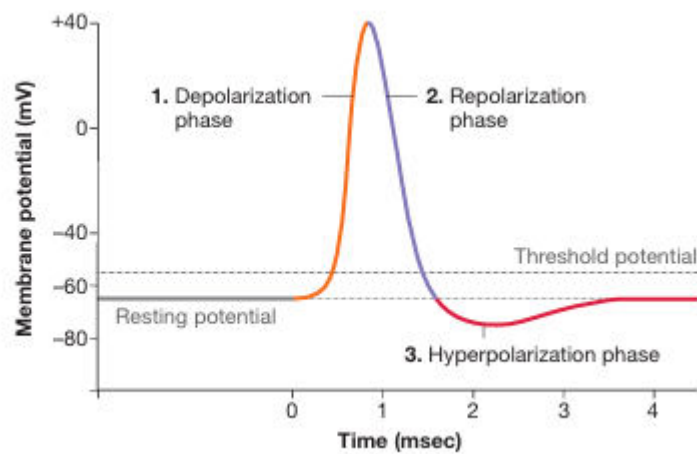


5. With some voltage-gated potassium channels now open this causes the other voltage-gated channels to open and more potassium ions diffuse out, causing repolarization of the axon membrane.
6. The outward movement of these potassium ions and the slight delay in the closing of the gates causes the temporary overshoot of the electrical gradient, with the inside of the axon being more negative (relative to the outside) than usual. This is called **hyperpolarization**. The gates on the potassium channels now close and the activities of the sodium-potassium (cation) pumps cause sodium ions to be pumped out and potassium ions in, once again. The axon membrane returns to a resting potential and the axon is said to be **repolarized**.

(c) Decline of an action potential, or nerve impulse, for repolarization



The action potential has three distinct phases



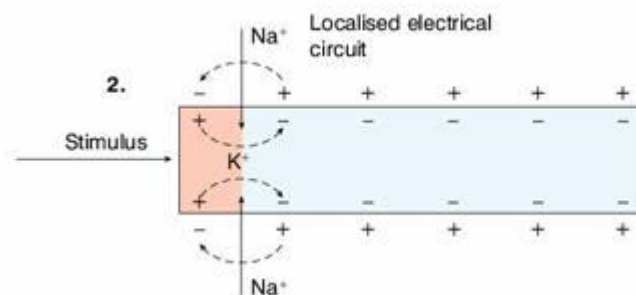
- 1) Depolarization of the membrane. In its resting state, a membrane is said to be polarized because the charges on the two sides are different. Depolarization means that the membrane becomes less polarized than before. During the depolarization phase, the membrane potential changes from highly negative, crosses zero, and then is briefly positive.
- 2) A rapid repolarization, which changes the membrane potential back to negative.
- 3) A hyperpolarization phase, when the membrane potential is slightly more negative than the resting potential.

PROPAGATION OF AN ACTION POTENTIAL ALONG AN UNMYELINATED NEURON.

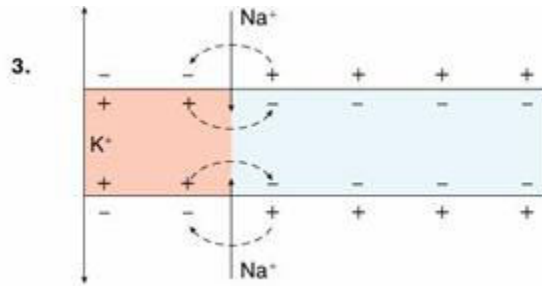
- 1) At resting potential the concentration of sodium ions outside the axon membrane is high relative to the inside, whereas that of the potassium ions is high inside the membrane relative to the outside. The overall concentration of positive ions is, however, greater on the outside, making this positive compared with the inside. The axon membrane is polarized. In our Mexican wave analogy, this is equivalent to all the people in the whole stadium being seated, i.e. at rest.



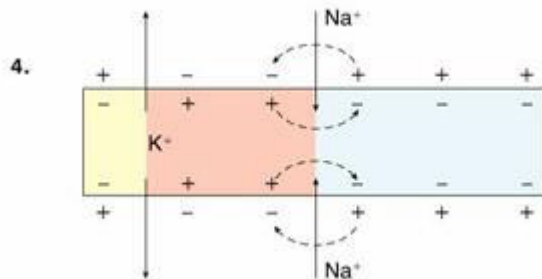
- 2) A stimulus causes the sodium voltage-gated channels to open leading to a sudden influx of sodium ions and hence a reversal of charge on the axon membrane making the inside positive. This is the action potential and the membrane is depolarized. In our analogy, a vertical line of people are stimulated into action and stand up and wave their arms.



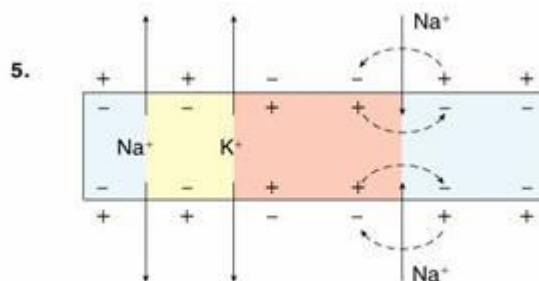
- 3) The localized electrical circuits set up by the influx of sodium ions cause the opening of sodium voltage-gated channels a little further along the axon. The resulting influx of sodium ions in this region causes depolarization. Behind this new region of depolarization, the sodium voltage-gated channels close and the potassium ones open. Potassium ions begin to leave the axon along their electrochemical gradient. The sight of the person next to them standing and waving stimulates the person in the adjacent seat to stand and wave. A new vertical line of people stands and waves, while the original line of people begin to sit down again.



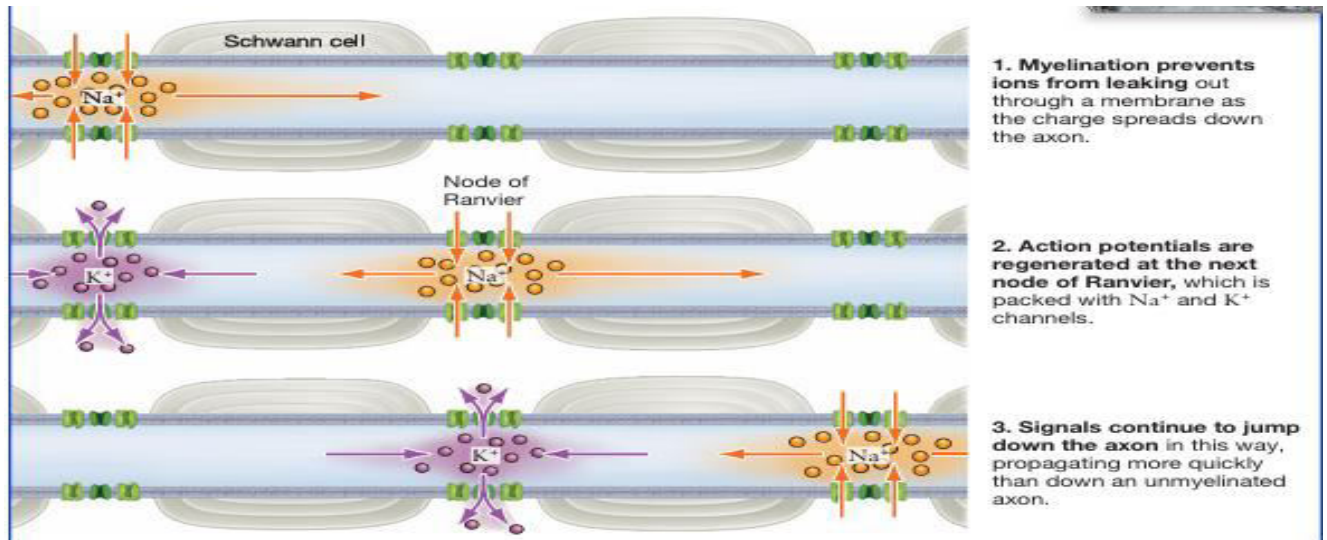
- 4) The action potential (depolarization) is propagated in the same way further along the axon. The outward movement of the potassium ions has continued to the extent that the axon membrane behind the action potential has returned to its original charged state (positive outside, negative inside), i.e. it has been repolarized. The second line of people standing and waving stimulates the third line of people to do the same. Meanwhile, the first line have now returned to their original positions as they are now sitting down.



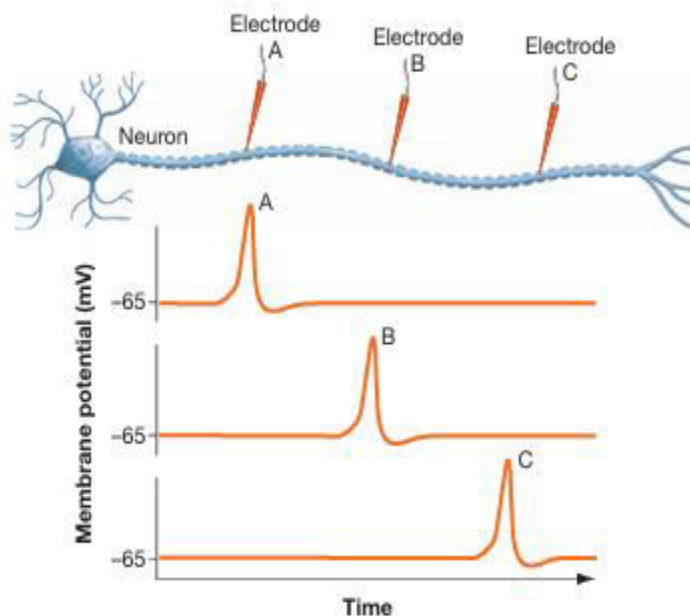
- 5) Repolarization of the axon allows sodium ions to be actively transported out and potassium ions to be actively transported in, once again returning the axon to its resting potential in readiness for a new stimulus if it comes. The people who have just sat down settle back in their seats and readjust themselves ready to repeat the process should they be stimulated to do so again.



Propagation of an impulse in a myelinated axon



Action potential spreads as a wave of depolarization.



Action potentials propagate because charge spreads down the membrane.

(a) An action potential starts with an influx of Na^+

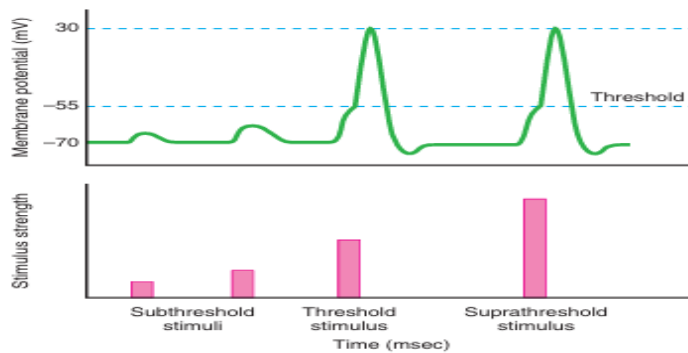
(b) Action potentials propagate down the axon without getting smaller, because new action potentials are continuously generated along the axon membrane.

TABLE SUMMARISING STATE OF THE NEURON BEFORE, DURING AND AFTER AN ACTION POTENTIAL

	Resting	Depolarization	Repolarization	After-hyperpolarization
<i>Membrane potential</i>	-70 mV	-70 mV to +30 mV	+30 mV to -70 mV	-70 mV to -85 mV
<i>Voltage-gated sodium channel</i>	Closed	Open	Closed	Closed
Activation gate	Closed	Open	Open	Closed
Inactivation gate	Open	Open	Closed	Open
<i>Sodium flow</i>	Low inward, through leak channels	High inward, through voltage-gated channels*	Low inward, through leak channels	Low inward, through leak channels
<i>Voltage-gated potassium channel</i>	Closed	Closed	Open	Closing
<i>Potassium flow</i>	Low outward, through leak channels	Low outward, through leak channels	High outward, through voltage-gated channels*	High outward, through voltage-gated channels, but decreasing*

PROPERTIES OF IMPULSES AND NEURONS

- ❖ **Stimulation:** A neuron cannot generate an impulse unless it's stimulated. However there is need for a threshold stimulus to generate an action potential, once the threshold stimulus is reached, the size of the action potential remains the same even when the intensity of the stimulus is increased beyond the threshold. This is known as the "All or nothing law". Nerve impulses are described as **all or nothing responses**. There is a certain level of stimulus, called the **threshold value**, which triggers an impulse. Below the threshold value no impulse is generated; above the threshold value an impulse is generated. The action potential, however, is the same regardless of how much the stimulus is above the threshold value.



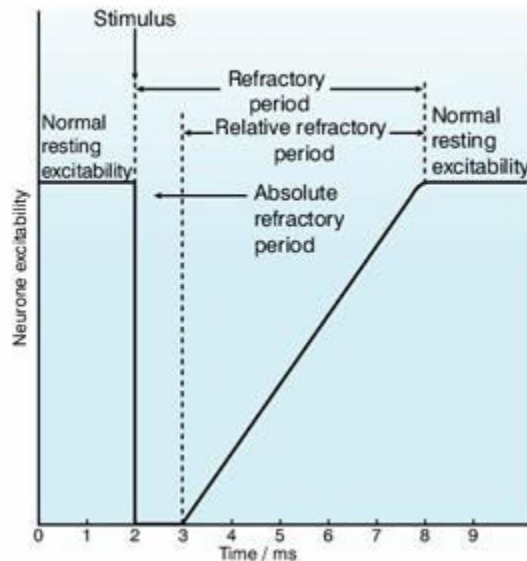
NOTE: Graded potentials are small changes in membrane potential that occur when ion channels open or close in response to a stimulus acting on the cell.

❖ The refractory period

Once an action potential has been created in any region of an axon, there is a period afterwards when inward movement of sodium ions is prevented because the sodium **voltage-gated channels** are closed and temporarily inactivated. During this time it is not possible for a further action potential to be generated. This is known as the **refractory period**. The refractory period is made up of two portions:

- 1) **The absolute refractory** period lasts for about 1 ms, during which no new impulses can be passed, however intense the stimulus.
- 2) **The relative refractory** period lasts around 5 ms, during which a new impulse may be propagated provided **the stimulus exceeds the normal threshold value**. The degree to which it needs to exceed the threshold value becomes less over the period. At normal resting excitability the voltage-gated channels are returned to their resting potential state.

A graph showing the variation of excitability of a neuron with time after providing a threshold stimulus



THE REFRACTORY PERIOD SERVES TWO PURPOSES:

- The action potential cannot be propagated in the region that is refractory, i.e. it can only move in a forward direction. This prevents the action potential from spreading out in both directions, which it would otherwise do.
 - Because a new action potential cannot be formed immediately behind the first one, it ensures that action potentials are separated from one another and therefore limits the number of action potentials that can pass along an axon in a given time, i.e. it determines their frequency.
- ❖ **Transmission speed:** the speed of conducting impulses is not the same in all neurons. Below are the factors affecting the transmission speed:

FACTORS AFFECTING IMPULSE TRANSMISSION SPEED

- **The myelin sheath:** Myelin sheath acts as an electrical insulator, preventing an action potential forming in the part of the axon covered in myelin. It does, however, leap or “jump” from one **node of Ranvier** to another node of Ranvier (**saltatory conduction**), speeding transmission from 0.5 ms^{-1} in an unmyelinated neuron to 100 ms^{-1} in a similar myelinated one.
- **The diameter of the axon:** The greater the diameter of an axon, the faster the speed of transmission. When sodium ions enter the axon interior at the start of an action potential, they repel intra cellular cations, causing them to spread along the inside of the membrane. Cations moving down axons with larger diameters meet **less resistance** than those moving down narrow axons. As a result, the charge spreads along the membrane more quickly.
- **Temperature:** Affects the rate of diffusion of ions and therefore the higher the temperature the faster the nerve impulse. Above a certain temperature, the cell surface membrane proteins are **denatured** and impulses fail to be conducted at all. Temperature is clearly an important factor in response times in **ectothermic** animals, in which body temperature varies with the environment.

QUESTION: *Explain the significance of warm-ups before physical activity and the use of cold packs in first aid, with specific reference to nerve impulses and coordination.*

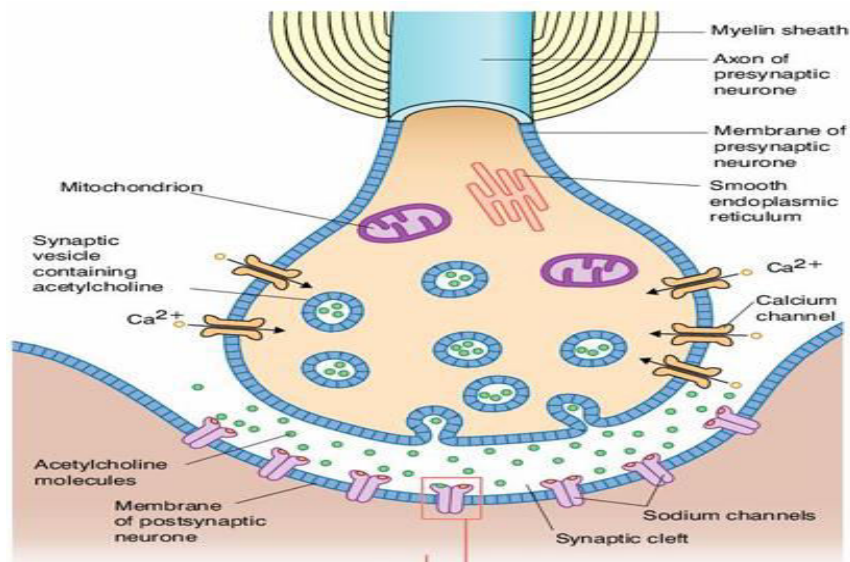
- ❖ Warm-ups raise body temperature, which speeds up the rate of nerve impulse conduction along motor neurons. This allows quicker and more accurate responses to stimuli.
- ❖ Gradual activation of sensory receptors in muscles and joints enhances the central nervous system’s ability to coordinate movements smoothly.
- ❖ Cooling decreases the excitability of nerves, reducing the frequency of pain impulses sent to the brain (pain relief).

THE SYNAPSE

A **synapse** is the point where the **axon of one neuron** connects with the **dendrite** of another or with an effector. There are two types of synapse;

- ❖ Electrical synapse and
- ❖ Chemical synapses

STRUCTURE OF A CHEMICAL SYNAPSE



Chemical synapses are the most common type and transmit impulses from one neuron to the next by means of chemicals known as **neurotransmitters**. Neurons are separated by a small gap called the **synaptic cleft** which is 20–30 nm wide. The neuron that releases the neurotransmitter is called the **presynaptic neuron** and it has a swollen portion of axon, the **synaptic knob**, at its end. This possesses many mitochondria, large quantities of endoplasmic reticulum and **synaptic vesicles** containing the neurotransmitter which, once released from the vesicles by **exocytosis**, diffuses across to the postsynaptic neuron, which possesses **receptor molecules** on its membrane to receive it.

FUNCTIONS OF SYNAPSES.

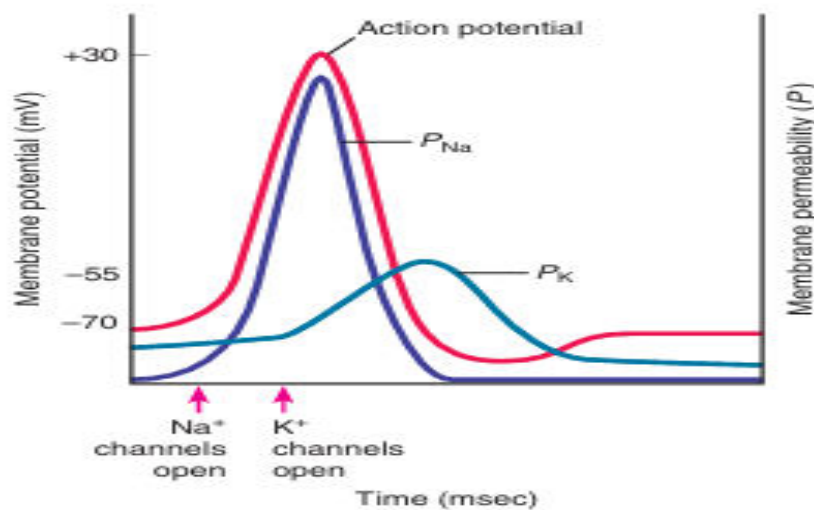
Synapses perform a number of important functions:

- ❖ **Transmit information between neurons:** Synapses convey impulses from one neuron to the next and it is from this basic function that all the others are able to occur.
- ❖ **Are unidirectional:** Synapses can only pass impulses in one direction. This is because only the presynaptic neuron has vesicles containing the neurotransmitter and only the postsynaptic membrane has receptors for the neurotransmitter. Any action potential arriving at the postsynaptic neuron would simply stop at this point.
- ❖ **Act as junctions:** Allowing nerve impulses to diverge and converge. In divergence a single impulse along one neuron can be conveyed to a number of different neurons at a synapse. This allows a single stimulus to create a number of simultaneous (all at the same time) responses. In convergence, a number of impulses can be combined into a single impulse. This occurs in the retina of the eye, for example.
- ❖ **Filter out low-level stimuli:** Background noise (e.g., traffic, machinery) produces low-frequency impulses that release only small amounts of neurotransmitter, insufficient to create a new impulse in the postsynaptic neuron, so no response occurs.
- ❖ **Summation:** Low-frequency impulses that cannot trigger an action potential alone can do so by building up neurotransmitter levels:
 - **Spatial summation:** several presynaptic neurons release enough neurotransmitter together to trigger a new action potential.
 - **Temporal summation:** A single presynaptic neuron releases neurotransmitter many times over a short period; if the total amount exceeds the threshold, a new action potential is triggered.
- ❖ **Prevent overstimulation and fatigue** – Prolonged, powerful stimuli cause high-frequency impulses and excessive neurotransmitter release. Synapses become *fatigued* to reduce overstimulation, protecting effectors from damage.
- ❖ **Involved in memory and learning** – Synapses help the brain recall events and recognize individuals, playing a role in learning and memory formation.
- ❖ **Inhibition** – At some synapses, chloride ion (Cl^-) channels on the postsynaptic membrane open, causing an inward diffusion of Cl^- ions. This makes the inside more

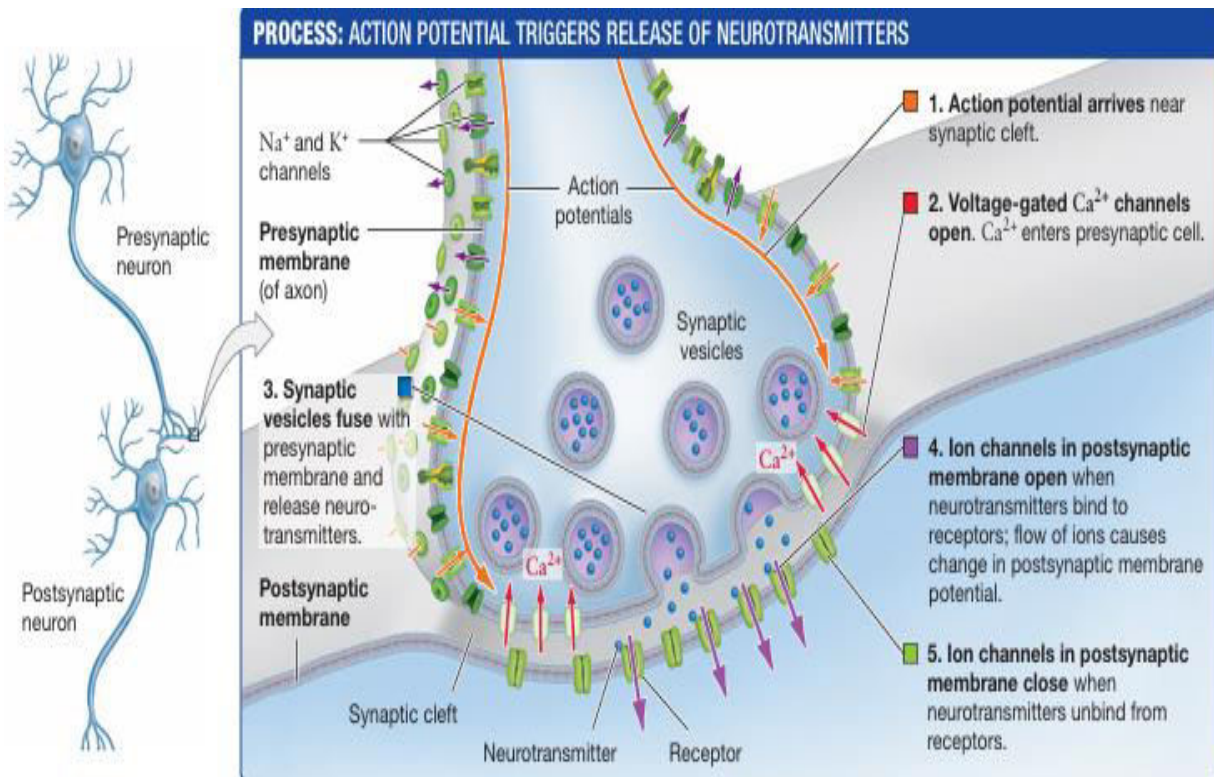
negative (hyperpolarization), reducing the likelihood of generating a new action potential. These are called **inhibitory synapses**.

QUESTION: In a nervous coordination class discussion, your teacher Mr. Modest Trust displays the following graph, which tracks the electrical activity of a neuron. To test the class's understanding of how an action potential is generated, she poses a challenge:

We can see a clear sequence of events here. The membrane permeability to sodium ions rises and falls first, followed by a similar curve for potassium ions. Based on this precise timing and magnitude of permeability changes shown in the graph, describe the specific causal relationship between the rise and fall of each permeability curve and the resulting changes that create the depolarization and subsequent repolarization of the membrane potential. Write your response.



SYNAPTIC TRANSMISSION



- 1) An action potential arrives at the end of the axon, near the synaptic cleft.
- 2) The depolarization created by the action potential opens voltage-gated calcium channels located near the synapse, in the plasma membrane of the presynaptic neuron. The electrochemical gradient for Ca²⁺ results in an inflow of calcium ions through the open channels.
- 3) In response to the increased calcium ion concentration inside the axon, synaptic vesicles fuse with the presynaptic membrane and release neurotransmitters into the synaptic cleft by exocytosis.
- 4) Neurotransmitters bind to receptors on the post synaptic cell. Thus, each neurotransmitter functions as a ligand, a molecule that binds to a specific site on a receptor molecule. Neurotransmitter-receptor binding causes sodium ion channels in the postsynaptic membrane to open, leading to influx of sodium ions. The influx of sodium ions generates a new action potential in the postsynaptic neuron. Changes in the membrane potential of a postsynaptic cell that make the cell more likely to produce an action potential are called **excitatory**

postsynaptic potentials (EPSPs). When several EPSPs sum up to reach a threshold, an action potential is generated in the post-synaptic neuron.

5. The response ends when the neurotransmitters unbind from their receptors, causing the ion channels in the postsynaptic membrane to close. After an action potential ceases, the neurotransmitters diffuse out of the synaptic cleft, and then are broken down or taken back up by the presynaptic cell. The enzyme acetylcholinesterase hydrolyses acetylcholine into choline and acetate, which diffuse back across the synaptic cleft into the presynaptic neuron (= **recycling**).

ATP released by mitochondria is used to recombine choline and acetate into acetylcholine. This is stored in synaptic vesicles for future use. Sodium channels close in the absence of acetylcholine in the receptor sites.

INHIBITORY SYNAPSES

If neurotransmitter-receptor binding leads to an outflow of potassium ions or an inflow of chloride ions or other anions in the postsynaptic cell, the postsynaptic membrane **hyperpolarizes**; making action potentials less likely to occur in the postsynaptic cell. Changes in the membrane potential of a post synaptic cell that make the cell less likely to produce an action potential are called **inhibitory postsynaptic potentials** (IPSPs). If an EPSP and an IPSP occur at the same time in the same postsynaptic cell, they may cancel each other out

CLINICAL CONNECTION OF NERVOUS COORDINATION

Local anesthetics

Local anaesthetics are drugs e.g **procaine/novocaine** and **lidocaine/xylocaine** used to block nerve activity in a specific region of the body, producing temporary loss of sensation. Local anaesthetics such as novocaine and lidocaine work by **blocking voltage-gated sodium channels in sensory neurons**. When these channels are unable to open, sodium ions cannot enter the neuron, which means depolarization does not occur. Without depolarization, the neuron cannot generate an action potential, and without action potentials, sensory signals cannot be transmitted to the central nervous system. The overall effect is a temporary **loss of sensation (numbness)** in the targeted region, so the patient does not perceive pain, touch, temperature, or pressure during the procedure.

DIFFERENCE BETWEEN ANAESTHETICS AND ANALGESICS

Feature	Local anaesthetics	Analgesics
Action	Block all sensory signals (pain, touch, pressure, temperature)	Block only pain signals

Feature	Local anaesthetics	Analgesics
Mechanism	Inhibit sodium channel opening → stop action potential generation	Interfere with synaptic communication of pain pathways
Use	Produce complete numbness in a region	Reduce pain after procedures

SENSORY RECEPTORS

Our central nervous system gathers sensory information from both our internal and external environments. This is accomplished by a variety of **sensory receptors** which are specialized to detect different kinds of stimuli. These can be part of larger sense organs or can be individual receptor cells. **Sensory reception** is the process of detecting a stimulus, while **sensory perception** is how our brain interprets and makes sense of that information.

Sensory receptors are membrane proteins that are categorized by type of stimulus:

- ❖ Mechanoreceptors respond to distortion caused by pressure.
- ❖ Photoreceptors respond to particular wavelengths of light.
- ❖ Chemoreceptors detect specific molecules.
- ❖ Thermoreceptors detect changes in temperature.
- ❖ Nociceptors/ pain receptors sense harmful stimuli such as tissue injury.
- ❖ Electoreceptors detect electric fields.
- ❖ Magnetoreceptors detect magnetic fields.

CHARACTERISTICS OF RECEPTOR CELLS

1. Transduction: Receptor cells are **transducers**; they convert the energy of a stimulus into an electrical impulse. For example, a **Pacinian corpuscle**, a type of mechanoreceptor found deep in a mammal's skin, responds to pressure. Thus sensory receptors are biological transducers.
2. Specificity: Each type of mammalian receptor is highly specific to a particular kind of stimulus. E.g chemoreceptors on the tongue are specific to certain chemical molecules associated with taste. This specialization ensures that a sensory signal is accurately sent to the correct part of the brain for interpretation.

3. Sensitivity: Receptor cells are exceptionally **sensitive**, capable of detecting even weak stimuli. A great example of this is the high sensitivity of rod cells in the human eye, which can respond to a single photon of light. This allows for vision in very low-light conditions.

4. Adaptation: **Adaptation** is a crucial property where a receptor's response to a continuous, unchanging stimulus decreases over time. This allows the nervous system to focus on new and important changes rather than being constantly bombarded with the same information.

- ❖ **Phasic receptors**, such as those for touch and pressure in the skin, adapt rapidly. If a mammal puts on a piece of clothing, the initial sensation is strong, but it quickly fades as the receptors adapt.
- ❖ **Tonic receptors**, like those that monitor body position and muscle tension (proprioceptors), adapt slowly. This is essential for a mammal to maintain posture and balance, as these receptors need to provide continuous information to the brain.

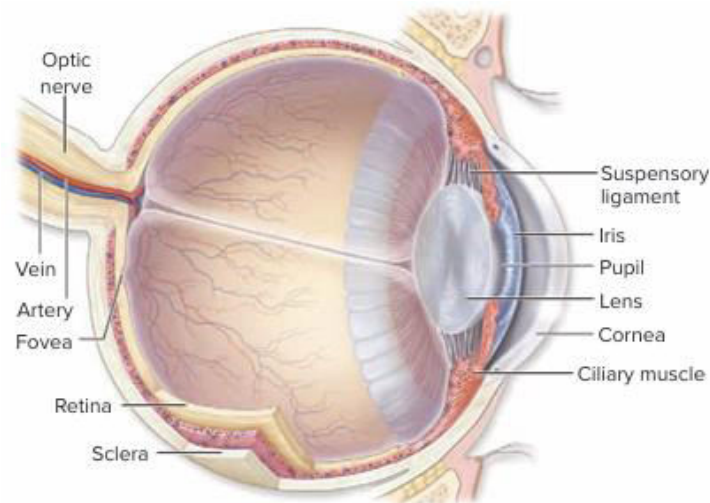
5. Specialization in structure and position: Mammalian receptors are highly **specialized** in their structure and location to maximize their effectiveness. For example in the eye, photoreceptors are precisely positioned in the retina to absorb light, while the hair cells in the inner ear are arranged to detect vibrations from sound waves.

6. Spontaneous activity: Some receptors produce nerve impulses in sensory neurons in the absence of stimulation. This system is not as meaningless as it might at first seem as it has two important advantages.

- ❖ Firstly it increases the sensitivity of the receptor by enabling it to make a response to a stimulus that would normally be too small to produce a response in the sensory neuron.
- ❖ The Secondly the direction of the change in stimulus can be registered by this system as an increase or decrease in the frequency of the response in the sensory neuron. For example, infra-red receptors in pits in the face of the rattlesnake, which act as direction finders in locating prey and predators, show spontaneous activity and are able to discriminate increases or decreases in temperature of 0.1°C.

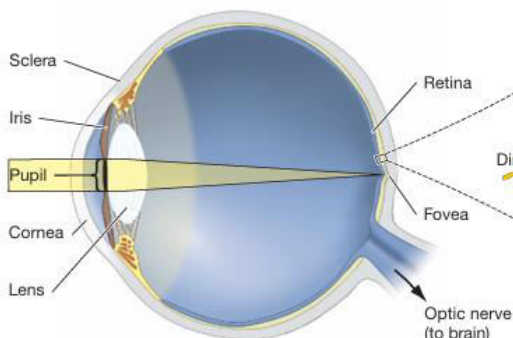
7. Convergence and summation: A high degree of sensitivity is achieved in many sense organs by an arrangement of sense cells and sensory neurons known as convergence. In such cases, several sense cells are connected to (converge on) a single sensory neuron.

STRUCTURE AND FUNCTION OF THE HUMAN EYE

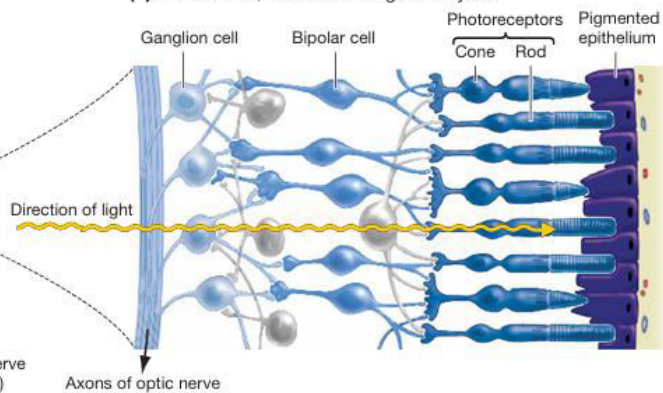


THE RETINA

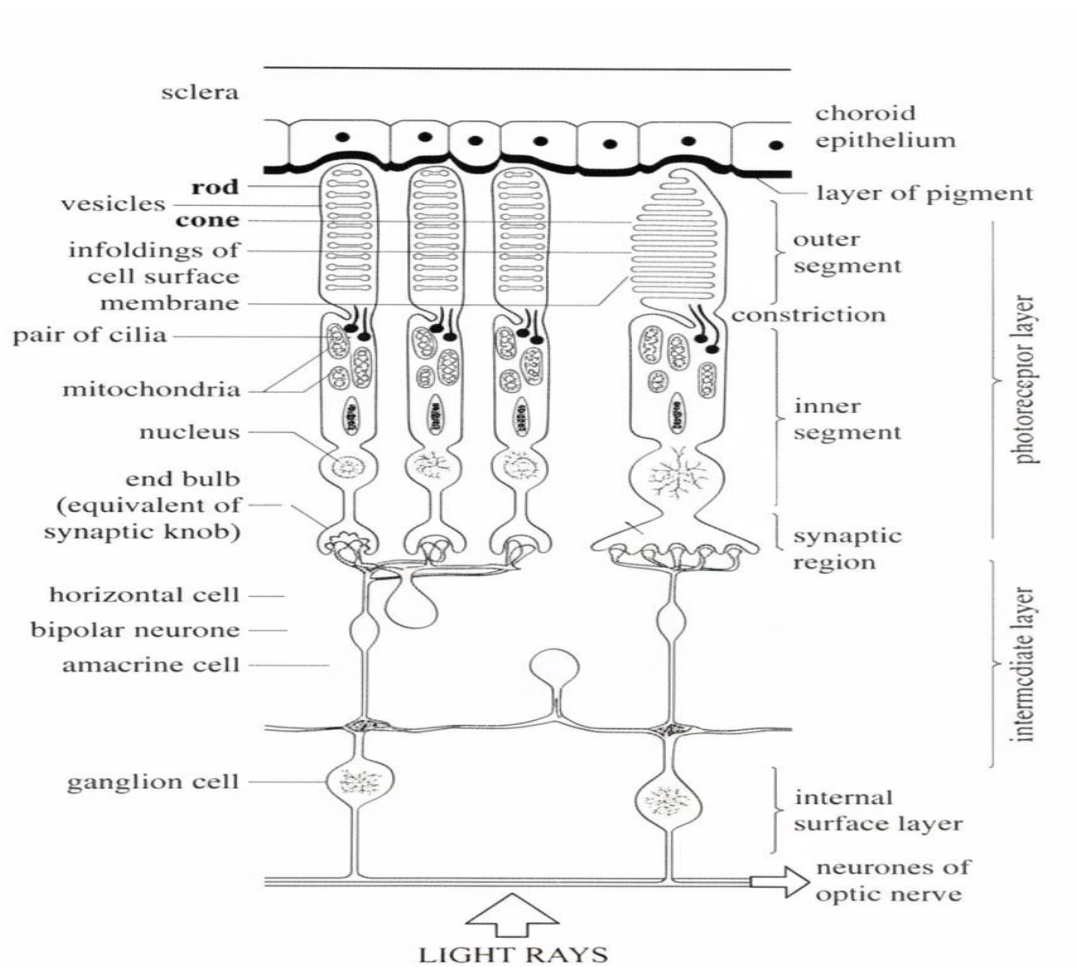
(a) The structure of the human eye



(b) In the retina, cells are arranged in layers.



STRUCTURE OF THE RETINA



The photoreceptor cells of the retina face towards the choroid layer. The cells are therefore covered by the cell bodies and axons linking the photoreceptor cells to the brain. The retina is composed of **three layers** of cells each containing a characteristic type of cell.

- 1) First there is the photoreceptor layer (outermost layer) containing the photosensitive cells, the **rods and cones**, partially embedded in the pigmented epithelial cells of the choroid.
- 2) Next is the intermediate layer containing bipolar neurons with synapses connecting the photoreceptor layer to the cells of the third layer. Cells called **horizontal and amacrine cells** found in this layer enable lateral inhibition to occur.
- 3) The third layer is the internal surface layer containing ganglion cells with dendrites in contact with bipolar neurons and axons of the optic nerve.

STRUCTURE AND FUNCTION OF RODS AND CONES

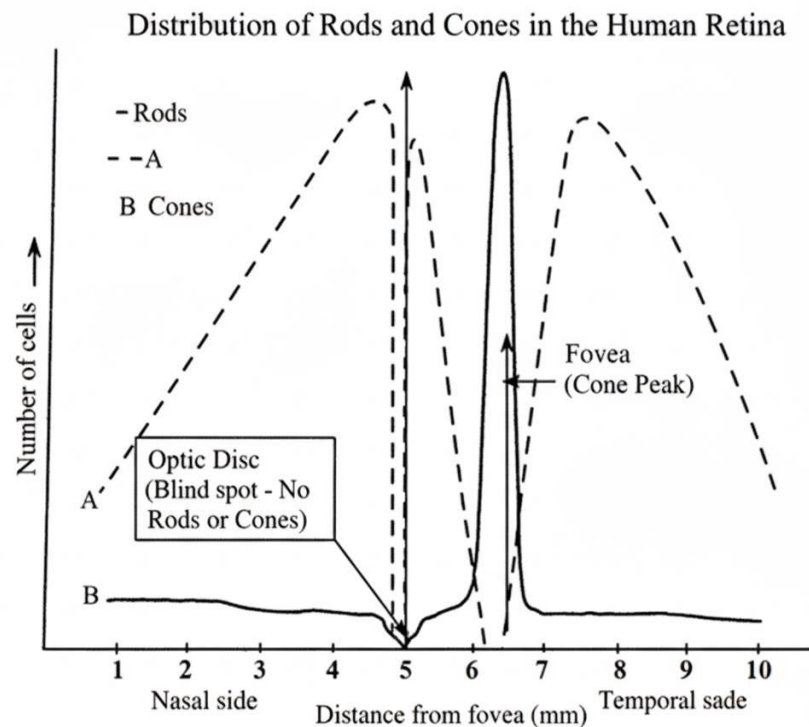
Rods and cones have an essentially similar structure, and their photosensitive pigments are attached to the outer surfaces of the membrane in the **outer segment**. They have four similar regions.

- 1) **Outer segment:** This is the photosensitive region where light energy is converted into a generator potential. The entire outer segment is composed of flattened membranous vesicles containing the photosensitive pigments. Rods contain 600-1000 of these vesicles stacked up like a pile of coins and they are enclosed by an outer membrane. Cones are so-called because outer segments are essentially **cone-shaped**. These have fewer membranous vesicles are formed by repeated infoldings of the outer membrane.
- 2) **Constriction:** The outer segment is almost separated from the inner segment by an infolding of the outer membrane. The two regions remain in contact by cytoplasm and a pair of cilia which pass between the two. These cilia consist of nine peripheral fibres only, the usual central two being absent. These no longer have a function.
- 3) **Inner segment:** This is an actively metabolic region. It is packed with mitochondria, which make energy available for visual processes, and polyribosomes for the synthesis of proteins involved in the production of the membranous vesicles and visual pigment. The nucleus is situated in this region.
- 4) **Synaptic region:** Here the cells form synapses with bipolar cells. Some bipolar neurons may synapse with several rods. This is called **synaptic convergence**, and while it lowers **visual acuity**, it increases **visual sensitivity**. Other bipolar cells link one cone to one ganglion cell and this gives the cones greater visual acuity than rods. Horizontal cells and amacrine cells link certain numbers of rods together and cones together. This allows a certain amount of processing of visual information to occur before it leaves the retina. For example these cells are involved in lateral inhibition.

DISTRIBUTION OF RODS AND CONES IN THE VERTEBRATE RETINA

The distribution of rods and cones in the vertebrate retina reflects the basis visual acuity and sensitivity.

- **Cones** (~6 million): Densely concentrated at the **fovea**, with about 90% located in this central region. Their tight packing, combined with minimal synaptic convergence (one cone connecting to a single bipolar and ganglion cell), produces maximum acuity. Cones function best in bright light and mediate colour vision and fine detail.
- **Rods** (~120 million): Almost absent from the fovea, but uniformly distributed across the **retinal periphery**. They show extensive synaptic convergence, with many rods pooling signals onto single bipolar and ganglion cells. This increases light sensitivity, making rods crucial for vision in dim conditions, but reduces acuity since individual light sources cannot be precisely localized.



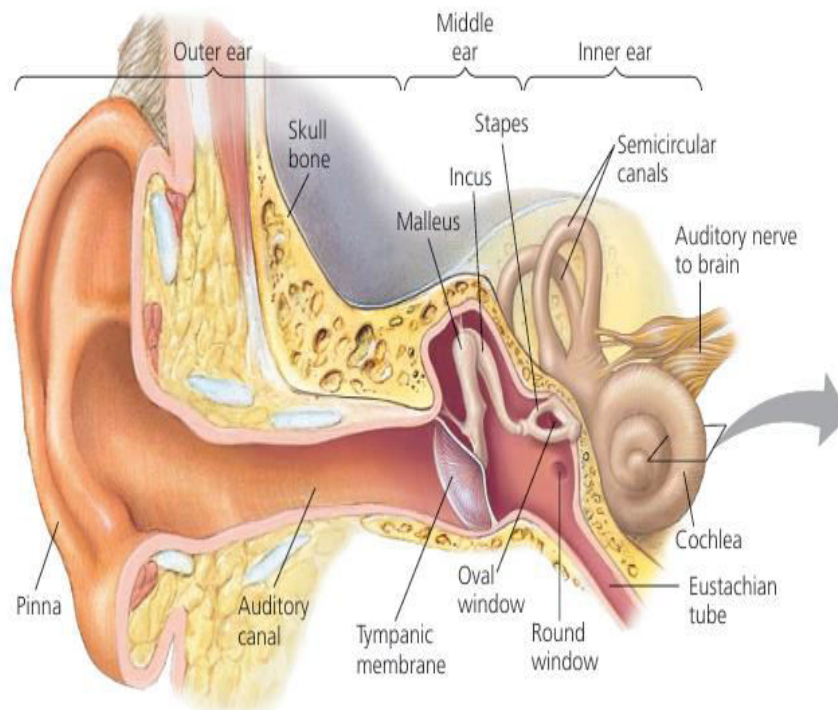
SUMMARY: The specialized distribution of photoreceptor cells in the retina is crucial for optimizing the two complementary aspects of vertebrate vision: **high visual acuity** and **maximal light sensitivity**. This is achieved by concentrating **cones** in the central **fovea** and **rods** in the peripheral retina. The fovea, which is **rod-free**, contains the highest packing density of cones, each typically connecting to a single bipolar and ganglion cell (low convergence). This 1:1 pathway minimizes signal summation, enhancing visual acuity with sharp detail. Conversely, the **rods** are highly concentrated in

the **periphery** and are far more sensitive to light due to a high degree of **retinal convergence**, where multiple rod signals are funneled into a single bipolar cell. This convergence sums the weak light signals, increasing overall sensitivity necessary for dim-light vision and detecting motion in the periphery, though at the expense of colour and fine spatial acuity.

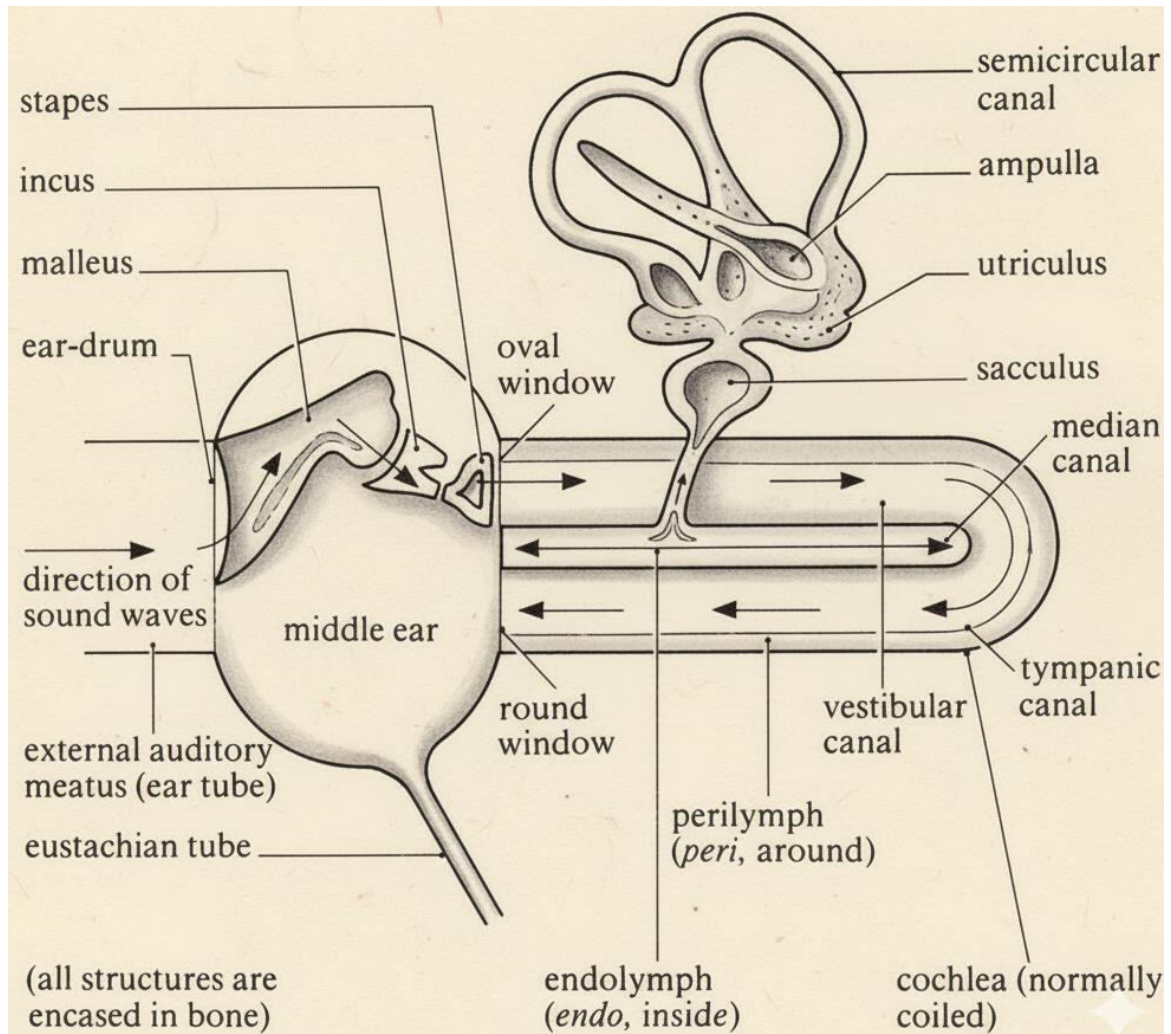
THE MAMMALIAN EAR

The mammalian ear is the site of two important mechanosensations: hearing, the sensation produced by the wavelike changes in air pressure called sound, and equilibrium, the sensation of orientation, rotation, and acceleration. Both of these senses use hair cells in similar ways to sense remarkably different stimuli.

Structure of the ear



HEARING



The ear transduces sound waves into action potentials that carry information to the brain. To understand how changes in the membrane potential of hair cells result in hearing, let's focus on the human ear as a case study. The human ear has three sections: the outer ear, middle ear, and inner ear. A membrane separates each section from the next. The initial stage of hearing involves the transmission of mechanical vibrations from the middle ear into the fluid-filled inner ear. Sound waves, received by the eardrum, are amplified by the three small bones (ossicles), with the stapes pushing on the oval window. This action generates pressure waves in the perilymph

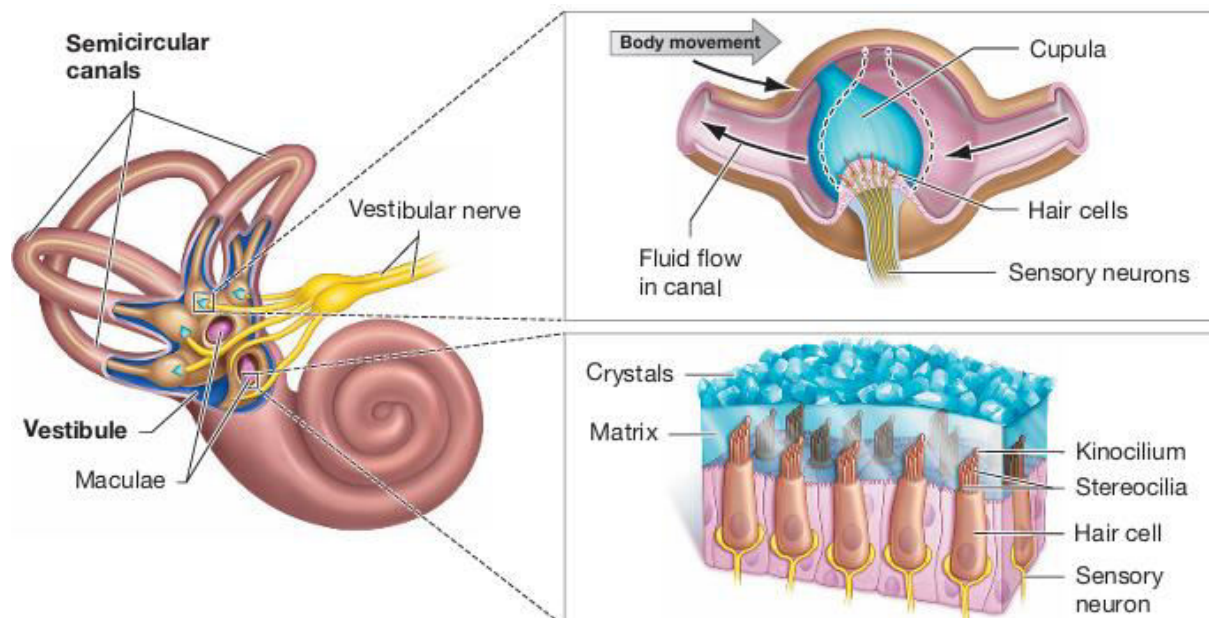
fluid within the upper vestibular canal. These vibrations are then transferred through a membrane to the endolymph in the central median canal (cochlear duct), causing the basilar membrane, which separates the median and lower tympanic canals to oscillate. Ultimately, these pressure waves are relieved and dissipated by the movement of the round window.

The critical event for converting sound into a nerve signal occurs within the Organ of Corti, which sits atop the basilar membrane. As the basilar membrane vibrates in response to pressure waves, it moves the attached sensory hair cells toward the rigid, shelf-like tectorial membrane that lies just above them. This relative motion creates a shearing force between the two membranes. This force mechanically bends and distorts the delicate hairs (stereocilia) projecting from the sensory cells, a process believed to be the trigger for transduction.

This mechanical distortion of the hair cells is immediately converted into an electrical signal. The bending of the hairs causes a change in the cell's electrical potential, leading to depolarization and the formation of generator potentials. If these potentials reach a sufficient threshold, they initiate action potentials in the axons of the auditory nerve. In this way, the cochlea successfully translates the physical energy of sound waves into the electrochemical signals that travel to the brain, allowing for the perception of sound.

EQUILIBRIUM AND THE VESTIBULAR APPARATUS

Maintaining balance (**equilibrium**) at rest and during movement relies on a continual input of sensory information to the brain. While proprioceptors in joints and muscles provide data on limb position, the **vestibular apparatus** of the inner ear provides vital information relating to the position, movement, and orientation of the head in space. This system includes the **utricle**, **sacculle**, and three **semicircular canals**. The basic sensory receptors within all these structures are **hair cells**, which have hair-like extensions that, when mechanically displaced, produce a **generator potential** leading to action potentials in the vestibular neurons.



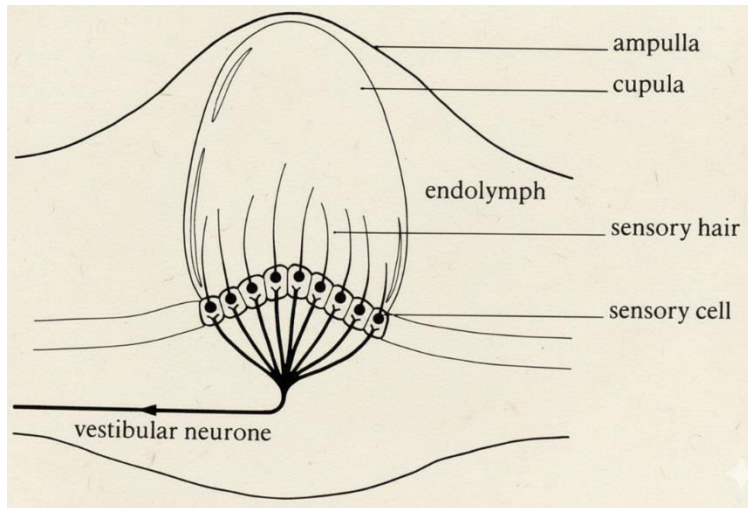
The **utricle** and **saccul**e are chambers situated in the vestibule that detect orientation (up, down, sideways), as well as linear movement and acceleration. Regions on the walls of these chambers are called **maculae**. Receptor cells within the maculae have their hair-like processes embedded in a **gelatinous mass** covered by a fibrous membrane. This membrane is weighted down by dense granules of **calcium carbonate** called **otoliths** or **otoconium**.

When the head is tilted or accelerated, the heavy otoliths/otoconium shift position due to the pull of gravity or inertia. The heavier fibrous layer shifts at a different rate than the underlying gelatinous layer, causing the hair cells' kinocilia and stereocilia to bend. This deflection depolarizes the maculae and signals the brain that the head is at an angle or accelerating.

The **utricle** responds to vertical movements and is maximally stimulated when the otoconia pull the hairs downwards (e.g., when the body is upside down). The **saccul**e responds to lateral (sideways) movement, where tilting the head produces a differential response (increased stimulation on one side, decreased on the other). One macula is situated horizontally, and the other vertically, providing detailed information about head orientation.

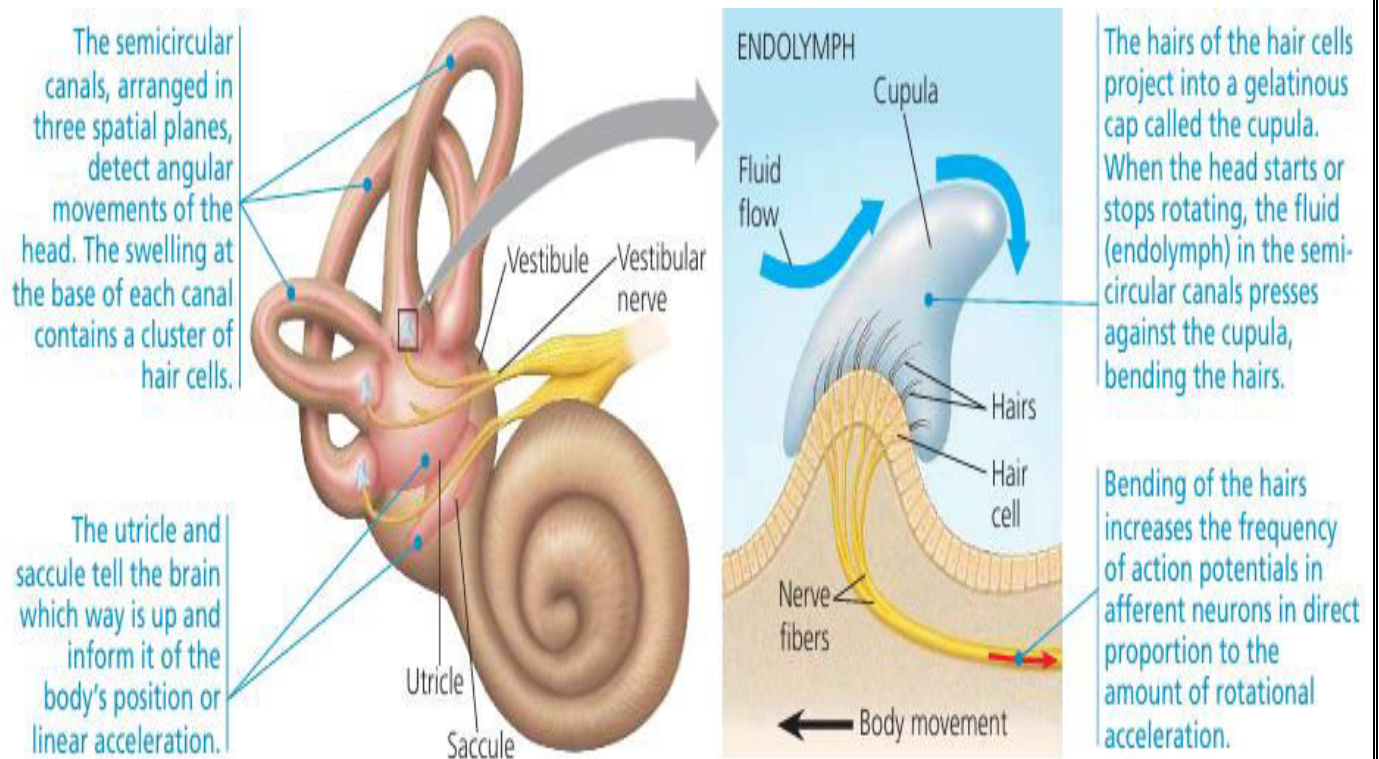
Role of semi-circular canals: The three fluid-filled **semicircular canals** are arranged in three planes at right angles to one another, allowing them to detect the direction and rate of change of rotational acceleration

At the base of each canal is a swelling, the **ampulla**, containing a conical gelatinous structure called the **cupula**. The cupula fully encloses the hair-like projections of the receptor cells.



When the head undergoes **rotational movement** (spinning), the canals and cupula move, but the fluid inside the canal (**endolymph**) resists this motion due to **inertia** and remains stationary. This relative movement causes the stationary endolymph to push against and bend the **cupula** in the **opposite direction** to the head movement.

The receptor cells within the bent cupula respond by producing generator potentials, leading to action potentials in the vestibular neurons. This system is crucial for detecting angular motion in any direction. If rotational movement ceases, the fluid may encounter a stationary cupula, triggering the false sensation of movement known as **dizziness**.



All impulses generated by the vestibular apparatus are ultimately passed to the **cerebellum**, where the overall orientation and movement of the head are perceived.

ANIMAL BEHAVIOR

Behavior can be defined as the observable actions or responses that an animal exhibits when exposed to internal or external stimuli. It includes all the ways animals interact with their environment, other organisms, and themselves.

Behavior is not limited to movement; it also involves social interactions, learning processes, and even internal activities shaped by evolution, genetics, and individual experience.

In biology, the **scientific study of behavior(ethology)** explores how and why animals act the way they do, with a special focus on understanding the significance of these actions for **survival, reproduction, and adaptation** to changing environments.

INNATE BEHAVIOR

Innate behavior is **inborn and determined by genetic factors**, typically performed in the same way by all members of a species without prior experience or learning.

CHARACTERISTICS

- ❖ **Inherited and inflexible:** Specific stimuli consistently trigger specific responses.
- ❖ **Predictable and uniform:** Highly predictable across a species, regardless of individual history.
- ❖ **Immediate Performance:** Often performed correctly the first time the animal attempts it.

TYPES AND EXAMPLES

- a) **Reflexes:** Simple, automatic responses to stimuli; e.g., the **knee-jerk reflex** in humans or a worm **withdrawing** instantly when touched.
- b) **Fixed Action patterns (FAPs):** Stereotyped, complex sequences released by specific stimuli (**releasers**); e.g., the **egg-rolling behavior** of a Graylag goose or the consistent mating dances of a specific bird species.
- c) **Orientation behaviors:** Includes **Kinesis** (random movement in response to intensity, e.g., woodlice moving faster in dry air) and **Taxis** (movement toward or away from directional stimuli, e.g., a moth flying toward a light source (**positive phototaxis**)).
- d) **Migration:** Seasonal long-distance movements to exploit better breeding or feeding sites; e.g., the annual journey of **monarch butterflies** or **Arctic terns**.
- e) **Biological rhythms:** Circadian (daily) and annual patterns; e.g., a bat's **nocturnal activity** pattern or the **hibernation** of bears.
- f) **Social behaviors:** Instinctive behaviors like **parental care** (e.g., a mother cat grooming her kittens) or the automatic formation of **dominance hierarchies** in wolf packs.

ADAPTIVE SIGNIFICANCE

- ❖ **Survival:** Rapid, well-coordinated responses help animals avoid predators, find food, and secure shelter **efficiently** even with no prior experience.

- ❖ **Reproductive success:** Instinctive courtship ensures correct species pairing and parental care enhances the survival of young.
- ❖ **Group Coordination:** Social behaviors improve resource distribution and defense.

LEARNED BEHAVIOR

Learned behavior is **acquired and modified by experience**, allowing animals to adapt responses based on changing environmental conditions.

CHARACTERISTICS

- ❖ **Acquired:** Not inherited but gained during the animal's lifetime.
- ❖ **Flexible:** Allows for adjustment to novel situations.
- ❖ **Individual Specificity:** Involves memory and can be unique to individuals, unlike innate behavior.

TYPES AND EXAMPLES

- a) **Habituation:** Decrease in response after repeated exposure to a non-harmful stimulus; e.g., a **scarecrow** initially frightening birds, but the birds quickly start to ignore it.
- b) **Imprinting:** Rapid learning at a specific age or stage; e.g., **newly hatched geese** following the first large moving object they see, typically their mother (as studied by Konrad Lorenz).
- c) **Associative Learning:**
 - ❖ **Classical Conditioning:** Associating a neutral stimulus with a meaningful one; e.g., **Pavlov's dogs** salivating at the sound of a bell after it was repeatedly paired with food.
 - ❖ **Operant Conditioning (Trial and Error):** Learning to associate a behavior with a reward or punishment; e.g., a **rat pressing a lever** in a Skinner box to receive a food pellet.
- d) **Latent Learning (Exploratory):** Knowledge acquired without immediate use but applied when needed; e.g., a **mouse learning the layout of a maze** during exploration, but only using that knowledge when food is introduced.
- e) **Insight Learning:** Solving new problems through reasoning; e.g., a **chimpanzee stacking boxes** to reach a banana hanging out of reach.

- f) **Imitation:** Copying the behavior of others; e.g., **young monkeys learning to wash sweet potatoes** in the ocean after watching an older monkey do it.

ADAPTIVE SIGNIFICANCE

- ❖ **Survival:** Enables **adaptation to dynamic or complex environments** and contributes to sophisticated predator avoidance via learned associations.
- ❖ **Reproductive success:** Social learning accelerates the transmission of survival skills across generations, and learning can influence mate selection.

COMPARISON TABLE: INNATE VS. LEARNED BEHAVIOR

Feature	Innate Behavior	Learned Behavior
Origin	Inherited (genetic)	Acquired via experience
Flexibility	Inflexible	Highly adaptable
Occurrence	Similar in all individuals	Varies among individuals
Survival Role	Rapid, reliable responses	Allows response to new challenges
Reproduction Role	Ensures correct mating, care	Enables new skills for mate attraction, care
Dependence on Experience	Little to no dependence	Little to no dependence

“Every science consists in the coordination of facts; if the different observations were entirely isolated, there would be no science.”-Auguste Comte. Thank you for studying these notes on coordination. The notes are open to review, and I welcome corrections or suggestions. I sincerely regret any errors. My contact information is provided in the header for any feedback or corrections.

THE END