CHAPTER

5 Cellular signals

KEY KNOWLEDGE

This chapter is designed to enable students to:

- recognise the various forms through which signals can be conveyed
- understand that chemical signals are the form through which cells most commonly communicate
- gain knowledge of cell-surface receptors and intracellular receptors
- understand signal transduction as it applies to hydrophilic and hydrophobic signals
- list examples of different kinds of chemical signals occurring in animal and plant cells
- become familiar with apoptosis as a process of programmed cell death, and its signal pathways.

FIGURE 5.1 This zebra is not sniffing the wind but is displaying flehmen behaviour. Typically, the animal opens its mouth, curls its upper lip, holds its mouth open and draws air into its mouth. It is a way of detecting pheromones that perhaps signal a nearby male rival or a female ready to mate.

Signals for communication

In our daily lives, communication is a constant component. Communication is variously defined as:

- the imparting of information by speaking, writing or some other medium (*Oxford English Dictionary*)
- the act or process of using words, sounds, signs, or behaviours to express or exchange information or to express your ideas, thoughts, feelings, etc., to someone else (Merriam-Webster).

We are constantly in communication, either receiving information from people and objects around us or imparting information to others through various channels.

Communication may involve a visual signal such as a red traffic light, an Instagram image, printed words in a textbook, an SMS message on an iPhone (see figure 5.2), a smile on a person's face, a hand gesture or the nod of a head. Communication may involve auditory signals, such as a spoken phrase: 'Don't do that!', a melody on an MP3 player, an announcement over a PA system or the screech of brakes. Communication may involve tactile signals, such as a tap on the shoulder, the heat of the handle of a saucepan on the stove, a hug, a handshake or the pain of a pinprick.

FIGURE 5.2 A couple receiving a visual signal transmitted via an SMS message on a mobile phone. What might you infer about the visual signal from the signal given by the couple's facial expressions?

ODD FACT

The bitter taste receptor TAS2R38 can detect glucosinolates, a class of compounds with anti-thyroid activity. Genetically based differences in this receptor determine whether or not individuals perceive the bitter taste of foods (such as broccoli, watercress, kale and turnips) that contain glucosinolates.

Other communication can come via olfactory signals, such as the smell of food cooking, the smell of the smoke of a bushfire or the scent of a flower. Communication may also be transmitted in gustatory signals, such as the sweet taste of chocolate or, for *some* people, the bitter taste of broccoli (see Odd fact).

A signal has no effect unless it is received. Only after it is received can the signal be processed. Only after it is processed can a signal produce a response. Without the reception and the processing of a signal, no response to the signal can occur.

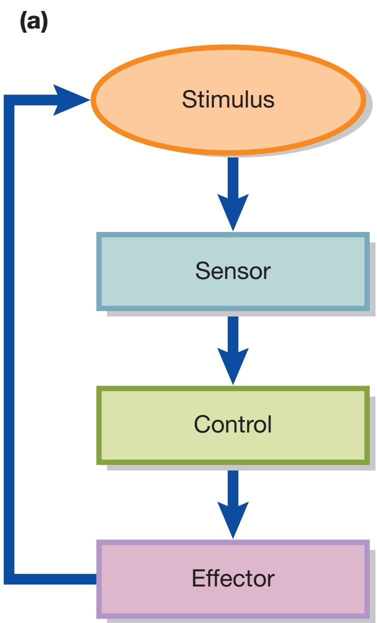
When we receive a signal, we process it and respond with a specific behaviour. The process by which a received signal is converted into a specific response is termed signal transduction. The driver of a car approaching an intersection who sees a red traffic light receives the visual signal and processes the information that the signal conveys as: 'I must stop!' The driver then responds by applying pressure to the foot brake, and the car comes to a stop just before the intersection. Note that it is *not* the signal that stops the car; it is the response triggered in the person who receives and processes this signal and takes relevant action.

The efficient functioning of cells depends on their ability to receive and respond to a variety of signals from the environment and from other cells. Cells are in constant communication, receiving signals from other cells and sending signals to other cells. This communication is sometimes called 'the constant chatter between cells.'

Just as we receive, process and respond to signals from our outside world, a similar process occurs in cells. The three components of cellular communication or 'cell chatter' may be summarised as:

1. **Reception** of a signal from a cell's external environment; such a signal may be a hormone or a neurotransmitter, a cytokine or a pheromone
2. **Transduction** of the signal into a form that can bring about a cellular response
3. Cellular **response** to the signal that comprises physical, biochemical or physiological changes brought about by effector proteins in the cell.

Figure 5.3 shows these processes as a stimulus-response model.



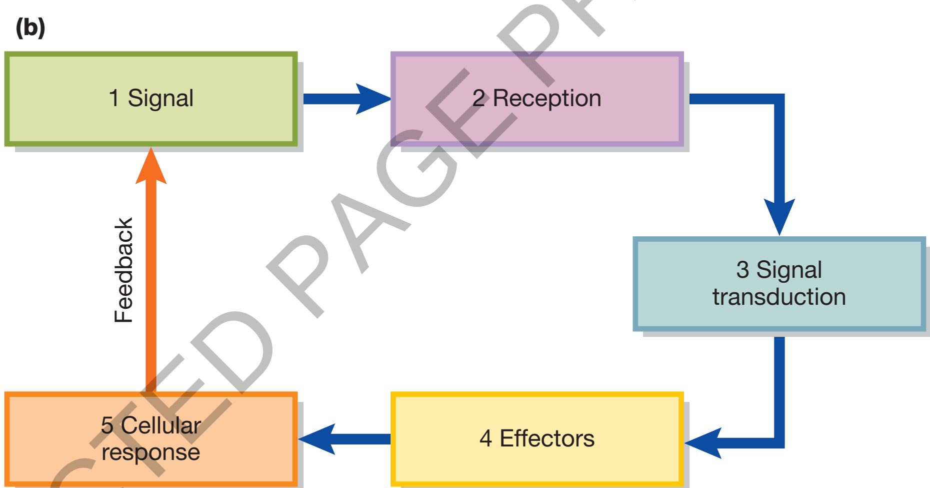


FIGURE 5.3 **(a)** A generalised stimulus-response model. **(b)** Cellular communication shown as a stimulus-response model. The signal is like the stimulus in a stimulus-response model that is received and translated by effectors into a response. In the signalling process, a signal is received by a specific receptor at the cell surface and, within the cell, is converted via a signal transduction pathway into effector molecules that produce the cellular response. As in a stimulus-response model, feedback regulates the entire signalling process.

In this chapter, we will explore some of the features of this constant chatter between cells, with a focus on chemical signals, the most common type of signalling in cell communication.

Communication between cells

The most common signals that carry information between cells are chemical signals. Other types of signals received by cells include mechanical signals, such as touch and pressure, and electromagnetic signals, such as light.

Signals can communicate different messages to cells, such as to stay alive and functioning, to self-destruct, to undergo cell division for growth or repair, to differentiate into a particular cell type, to eliminate a pathogen that has invaded the body, to activate a gene and produce the protein encoded by the gene, to silence a gene, or to produce an enzyme or a structural protein.

Let's first look at the various chemical signals involved in cellular communication.

Signalling molecules

The most common signals are chemical molecules. Many different kinds of signalling molecules are involved in transmitting information between the cells of plants and between the cells of animals, and they come in a variety of shapes and sizes. Variation in signalling molecules includes:

- *differences in chemical structures*
  Molecules that act as chemical signals include amino acids, peptides, polypeptides, proteins and steroids
  - these differences mean that signalling molecules vary in size
  - these differences mean that signalling molecules differ in their affinity for water, some being hydrophilic and some hydrophobic.
- *differences in function*
  Signalling molecules belong to different functional groups: for example, animal hormones, plant hormones, neurotransmitters of nerve cells, antibodies of immune cells, cytokines and pheromones.
- *differences in scope*
  Some signalling molecules exert their effect over a distance while others only act locally.

More details of the various kinds of signal molecules are given throughout this chapter.

Whatever their differences, all signal molecules share the same characteristic, namely: they bind to sites on specific receptors on their target cells. Receptors are proteins that receive the various signals, and a specific protein receptor exists for each different signalling molecule. (Note that any molecule that binds to a specific target to form a biologically active complex is termed a **ligand**. In cells, common ligands are signalling molecules.)

Signals move from source to target

A signalling molecule can only be effective if it reaches and binds to its specific receptor. The distance that a signalling molecule must travel to reach its targets can vary. Some signals are secreted by cells at a distance from their target cells, some are secreted by cells very close to their target cells, and some signals are produced and received by the same cells. The following sections identify an example of each situation.

1. **Long-distance travel to target cells:** Some signalling molecules must travel long distances to reach their target cells. Hormones secreted by various endocrine glands are the classic example of chemical signals that travel via the circulatory system over long distances to reach their target cells (see figure 5.4). For example, follicle stimulating hormone (FSH) that is secreted by cells in the pituitary gland travels via the blood to its target cells in the ovary.

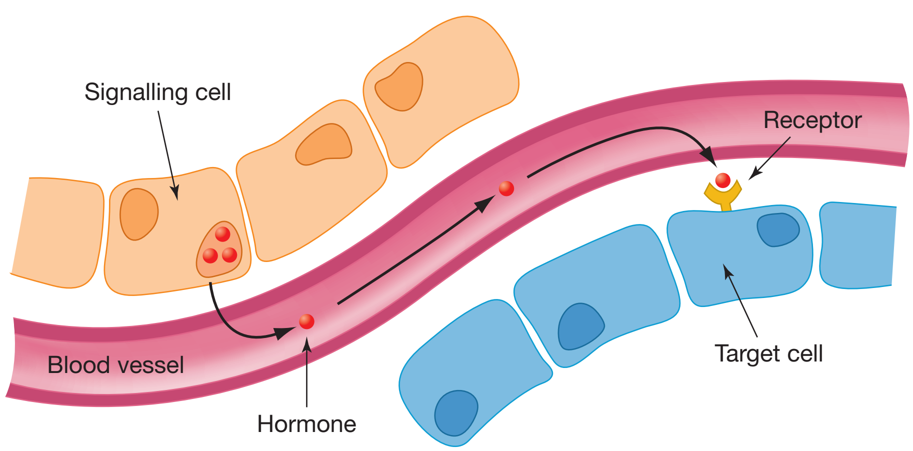


FIGURE 5.4 Hormones (shown in red) are secreted by various endocrine glands. These chemical signalling molecules are carried by the bloodstream to target cells that are a distance away, where they are received by receptors (shown in yellow).

ODD FACT

Communication between two nerve cells is a situation in which a chemical signal released by one neuron needs to travel only a submicroscopic distance to reach its target, which is the next neuron. The distance involved is across a synaptic cleft, the gap that separates two nerve cells in a neural network. The width of a synaptic cleft is about 0.02 micrometre.

2. **Travel to nearby cells:** Some chemical signals are released by signalling cells and travel short distances to their nearby target cells. These signals move by diffusion through the interstitial fluid around cells (see figure 5.5). These signalling molecules are often called **local mediators**.

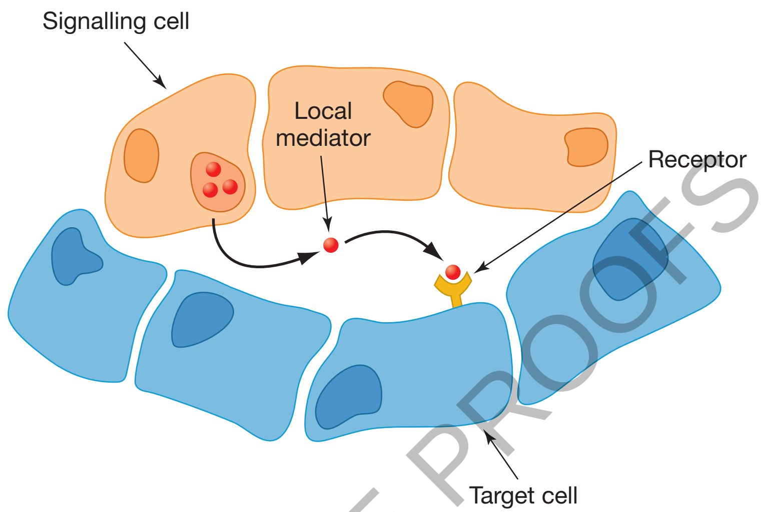
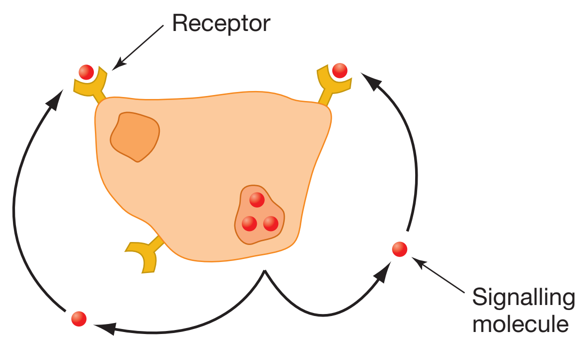


FIGURE 5.5 Some signalling molecules (shown in red) diffuse over short distances from signalling cells to nearby local cells where the signal is received (receptors shown in yellow).

3. **One cell sends and receives a signal:** Chemical signals released by one cell may be received by the same cell (see figure 5.6). This can be seen in some immune cells, known as T cells. In the presence of a foreign antigen, one kind of T cell responds to the signal created by the foreign antigen by producing a growth factor (interleukin 2) that binds to receptors on the same type of cell and stimulates their replication. (This of course makes more T cells to attack the source of the foreign antigen.)

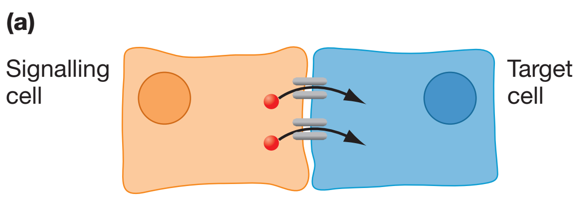
FIGURE 5.6 In some cases, the signalling cell and the target cell are the same. Signalling molecules (shown in red) are produced and received by one type of cell that functions as both the signalling cell and the target cell.



4. **Direct cell-to-cell contact:** In some cases, a signal can move directly from the cytosol of one cell to that of another cell. This signalling involves direct cell-to-cell contact. Several structural features enable this direct contact between cells, as, for example:

- ***Gap junctions**, also known as communicating junctions, between adjacent cells in animal tissues*. In animal cells, gap junctions consist of protein-lined pores in the plasma membranes of adjacent cells (see figure 5.7a). Gap junctions allow various small molecules to pass between cells and also enable the transmission of electrical signals. For example, gap junctions between cells of your heart muscle enable the spread of an electrical impulse throughout the entire heart so that the cells 'beat as one'.

- ***Plasmodesmata** between adjacent cells in plant tissues*. Plant cells have relatively thick cell walls that lie outside their plasma membranes. Cell-to-cell communication in plants is achieved through gaps, known as plasmodesmata (singular: plasmodesma), through cell walls (see figure 5.7b). The plasma membranes of the cells are continuous and form the lining of the plasmosdesmata.



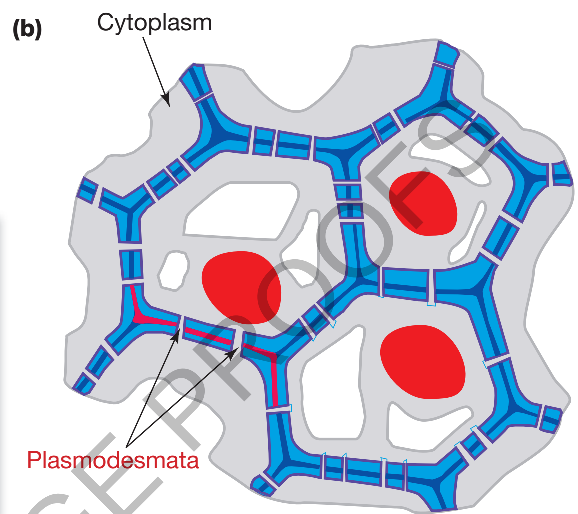


FIGURE 5.7 Communicating junctions between adjacent cells. **(a)** In animal tissues, communicating junctions (gap junctions) are protein-lined pores that connect adjacent cells. **(b)** In plant tissues, communicating junctions (plasmodesmata) are lined with the continuous plasma membrane of the adjoining cells. What would you predict about the relative lengths of the pores in a gap junction and in a plasmodesma?

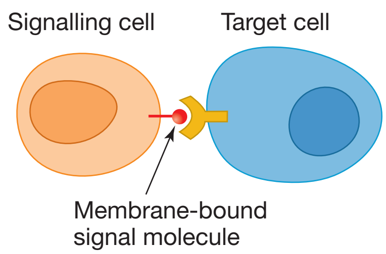


FIGURE 5.8 Diagram showing a highly simplified version of cell-to-cell signalling where the signalling cell migrates to its target cell to deliver the signal.

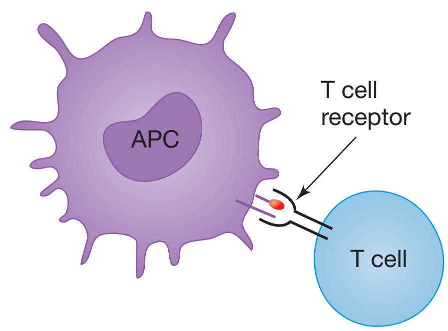
Some signalling cells carry signals to target cells: In some cases, signalling cells are highly mobile and deliver their signal to their target cells. Figure 5.8 shows a highly simplified version of this type of direct cell-to-cell signalling.

This type of cell-to-cell signalling occurs between cells of the body's immune system. Figure 5.9 shows a diagrammatic representation of cell signalling between two kinds of immune cells:

- The signalling cell (APC) carries, on its surface, a chemical signal (shown as a small red oval) that is a foreign antigen from part of a pathogen.
- The receiving cell is a T cell with a receptor (shown in black) for this signal.

The binding of the foreign antigen to the T cell receptor activates that cell so that it is ready to recognise and attack any cell it meets that carries the antigen.

FIGURE 5.9 Diagram showing the cell-to-cell communication between a signalling cell (APC = antigen presenting cell) and its target T cell. Both of these cells are part of the human immune defence system. The signalling cell carries a signal molecule (shown in red), which is a foreign antigen. This signal molecule binds to the T cell receptor and activates that cell.



KEY IDEAS

- Cells are in constant communication with other cells, both receiving and sending signals.
- Signals, most commonly, are chemical molecules, but they can be other environmental signals as well, such as light.
- Cellular communication comprises three stages: signal reception, signal transduction, and cellular response to the signal.

- Various kinds of signals may be received by cells, but the most common signals are chemical signals.
- The different chemical signals include animal hormones, plant hormones, cytokines, neurotransmitters, antibodies, and pheromones.
- Some chemical signals, such as mammalian hormones, exert their effect over a distance while others only act locally, yet others are transmitted by cell-to-cell contact.

QUICK CHECK

1 What are the three stages of cellular communication?
2 Only certain cells respond to a chemical signal. What prevents all body cells from responding to a chemical signal?
3 Identify one key difference between:
  a a receptor cell and a target cell
  b a signalling molecule and a signalling cell
  c a gap junction and a plasmodesma.
4 By what main means do the following signals travel from their signalling cell to their target cell:
  a a mammalian hormone signal
  b a signal from a local mediator?

Stages in 'cell chatter'

The three stages in cellular communication are signal reception, signal transduction and cellular response. Figure 5.10 shows a simple diagrammatic representation of this process. In the following sections we will explore each of these stages in turn.

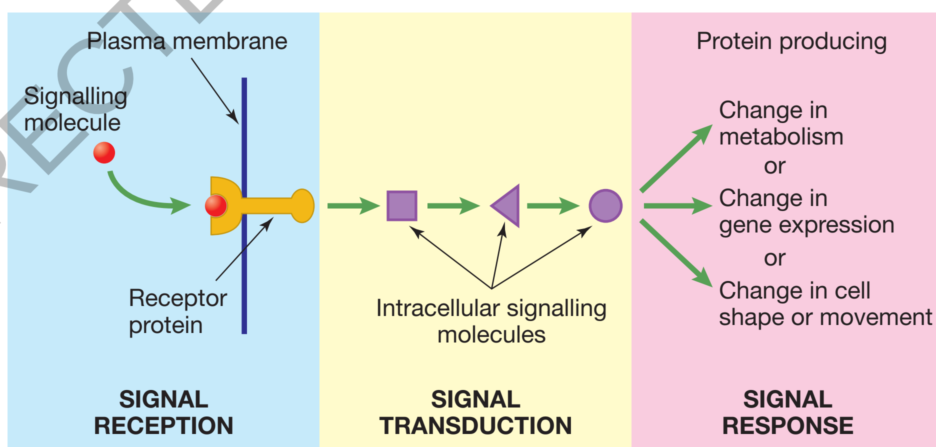


FIGURE 5.10 Diagram showing a simple representation of the three stages in cellular communication.

Cell signalling stages:
1. **Signal reception**
2. Signal transduction
3. Cellular response

Signal reception

The first step of cellular communication is the reception of a signalling molecule (ligand) from a cell's external environment. When signalling molecules (ligands) reach their target cells, they bind to a specific receptor.

Receptors are proteins and they are highly specific: each type of receptor protein binds to one signalling molecule with a specific shape. This specificity is achieved because the ligand and the binding site of its receptor have complementary shapes that fit together, just like a lock that will only fit a certain key. So, many different receptors exist.

Consider just the receptors concerned with the sense of smell, the so-called odorant receptors. A clue to the number of different odorant receptors came from the research of Richard Axel and Linda B. Buck, who asked the question: *How many different receptors do we have for the different odours, such as the perfume of a rose, the smell of rotting fish or burning gum leaves, that we can detect in our environment?*

The 2004 Nobel Prize in Medicine or Physiology was awarded to these researchers for their discovery of '*odorant receptors and the organization of the olfactory system*'. These researchers identified a large gene family comprising about 1000 different genes that encode an equivalent number of different olfactory receptors. These olfactory receptors are located on cells in the upper lining of the nose. Unexpectedly, it was discovered that each olfactory cell has just one kind of olfactory receptor on its surface.

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Odorant receptors research

In most cases, the receptors involved in cell signalling are located on the plasma membrane of a specific target cell — such receptors are called **cell-surface receptors**. However, in other cases, the receptors are located either in the cytosol or in the nucleus of the target cell — such receptors are called **intracellular receptors**. Why are there two different locations for signal receptors?

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We noted (refer back to page 162) that signalling molecules differ in their chemical structure and size. Some signalling molecules are small **polar** molecules, such epinephrine (adrenalin), other signalling molecules are larger **hydrophilic** molecules, such as the protein hormones, while yet others are **hydrophobic** molecules, such as the steroid hormones. Steroids are lipids, and they have four fused hydrocarbon rings in their chemical structures. The various steroid hormones are distinguished by the different functional groups attached to these rings (see figure 5.11), and these molecules are hydrophobic, and hence are lipophilic.

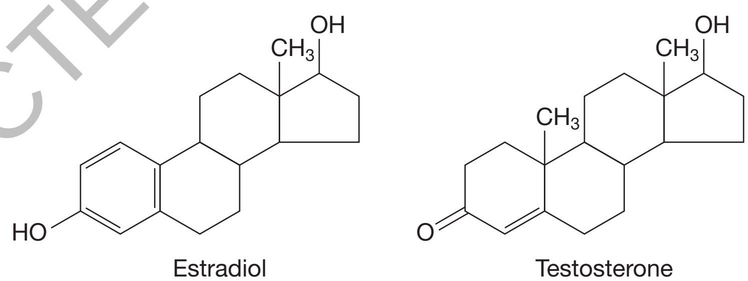
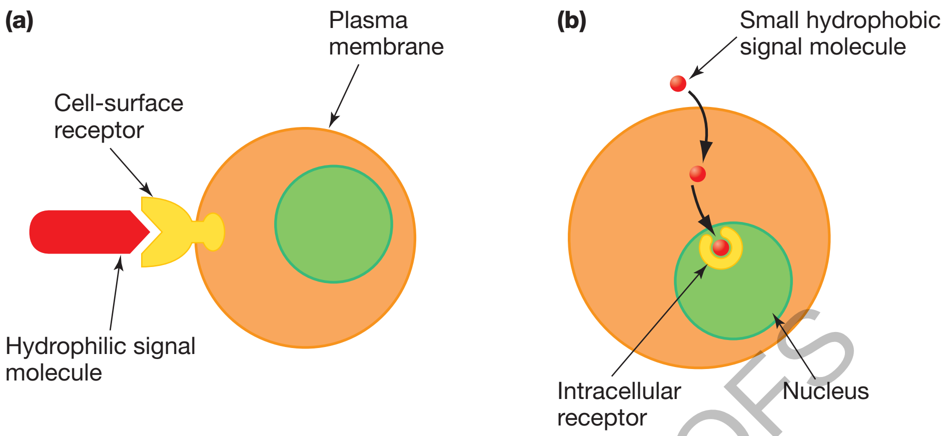


FIGURE 5.11 The structures of two steroid hormones. Note the four hydrocarbon rings. How does estradiol differ from testosterone?

Polar and hydrophilic signalling molecules cannot cross the lipid bilayer of the plasma membrane. These signalling molecules can only bind to receptors at the cell surface. The binding site is that part of the receptor protein that is exposed to the extracellular environment (see figure 5.12a). All cell-surface receptors are either trans-membrane proteins on their own, or they operate as part of a complex that links the exterior and interior of the cell. One such complex receptor is the G protein coupled receptor.

In contrast, hydrophobic signalling molecules can readily cross the lipid bilayer of the plasma membrane. Hydrophobic signalling molecules, such as the steroid hormones, bind to receptors that are located within the target cell, either in the cytosol or in the nucleus (see figure 5.12b).

FIGURE 5.12 **(a)** Hydrophilic signalling molecules can only bind to cell-surface receptors. **(b)** Hydrophobic signalling molecules that can readily pass across the lipid bilayer of the plasma membrane bind to intracellular receptors located either in the nucleus or in the cytosol. Can you name a hydrophobic signalling molecule?



The difference between signalling molecules in their affinity to water means that the receptors for hydrophilic signalling molecules are cell-surface receptors, while receptors for hydrophobic signalling molecules are intracellular receptors.

Look at the cell-surface receptor in figure 5.12a. Receptors of this type are trans-membrane proteins that are embedded in the plasma membrane. Each trans-membrane receptor has several regions or domains. One region is exposed to the outside of the cell — this is the **signal-binding domain**. Another region is in contact with the cytoplasm — this is the intracellular domain. (Trans-membrane receptors also have a hydrophobic domain. Where do you think the region of such a trans-membrane receptor might be located?)

When a signalling molecule binds to its receptor, the 3D shape of the receptor is altered, activating the receptor and indicating 'Message received!' However, for cell-surface receptors, there is a problem: the message is at the cell surface. It's bit like an unread message on a smart phone: C U @ 8 2NITE:-) Unless the message is read and its contents acted upon, the communication has failed. The same applies to a signalling molecule at the cell surface. The control centre of the cell, the nucleus, is where the message must arrive. The nucleus is where the cellular response to the signal will be made, typically involving the gene activation and the production of effector proteins.

Getting the message from the cell surface to the nucleus is achieved through signal transduction, the second step in cell communication.

Cell signalling stages:
1. Signal reception
2. **Signal transduction**
3. Cellular response

Signal transduction

The second stage of cell signalling is termed **signal transduction**, a process that converts a signal from outside a cell into a response within the cell. In signal transduction, a signal is received in one form, is changed to another mode or molecule, and is relayed to the appropriate target within the cell that responds through an effector protein. The signal transduction pathway links the signal reception to the cellular response to the signal:

① Reception → ② Transduction → ③ Response

The process of signal transduction starts after a signalling molecule binds to its specific receptor, changing its 3D shape and activating it.

We have seen in the previous section that some signalling molecules are hydrophilic (and hence lipophobic): for example, a peptide hormone such as insulin and a protein hormone such as growth hormone. Other signalling molecules are hydrophobic (and hence lipophilic): for example, the steroid hormones such as estrogen and testosterone. **The hydrophilic or the**

hydrophobic nature of signalling molecules determines the location of the specific receptor where the signal is received.

Let's look at signal transduction for each type of signalling molecule, starting with the transduction of a lipophilic signalling molecule such as a steroid hormone. This transduction process is less complex than that for a hydrophilic signalling molecule.

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Unit 3	**Signal transduction** Summary screen and practice questions
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Transduction of a hydrophobic signal:

Steroid hormones are hydrophobic and can readily cross the lipid bilayer of the plasma membrane by a process of diffusion. Once in the cell, the steroid hormone binds with its specific receptor. The receptor is a protein in solution either in the cytosol (as shown in figure 5.13) or in the fluid component of the nucleus.

The transduction pathway is as follows:

1. The binding of the steroid hormone to its specific receptor produces a change in the 3D shape of the receptor protein, exposing a region of the receptor that was previously within the molecule.
2. The hormone-receptor protein complex moves from the cytoplasm into the nucleus.
3. The exposed segment of the receptor protein attaches to a target DNA sequence next to certain genes, and activates those genes.

Figure 5.13 shows a diagram of this process. Note that steroid hormones directly regulate gene expression.

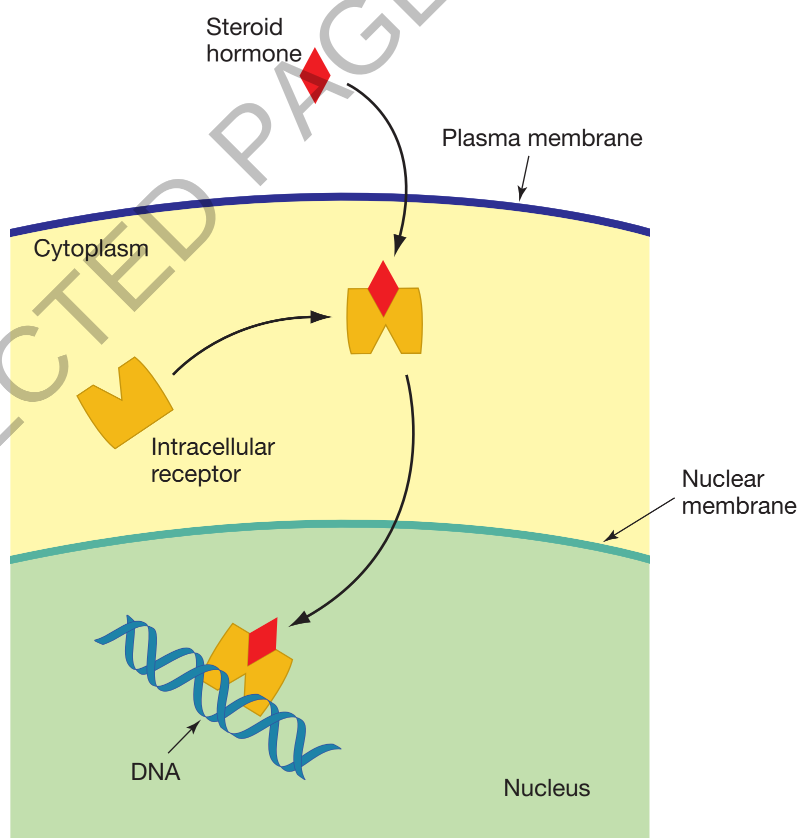

FIGURE 5.13 Transduction of the signal from a hydrophobic signalling molecule, in this case a steroid hormone, is a very direct process.

Transduction of a hydrophilic signal:

Now, let's look at the transduction of the signal from a peptide hormone that cannot cross the lipid bilayer of the plasma membrane. The process of signal

Proteins that can attach to DNA and influence levels of transcription are called **transcription factors**.

ODD FACT

The second messengers for plant hormone signals are often calcium ions (Ca^{++}).

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See more
Signal transduction

transduction starts when the hormone binds to its specific receptor on the cell surface. The signalling molecule in this case is called the '**first messenger**' and, if its message remains on the cell surface, it will be ineffective. The message must reach the nucleus where the cellular response to the signal will occur. For this to happen, the signal must be transferred from the receptor to a '**second messenger**' within the cytoplasm.

The transfer of the signal from receptor to nucleus occurs through a signal transduction pathway within the cytoplasm that involves production of large numbers of molecules of a second messenger. This amplifies the original signal by a factor of up to 10 000. Second messengers are small molecules, for example, cAMP, and they are *not* enzymes, but they activate a key enzyme at the start of an enzyme relay.

The enzyme relay is not like a relay race in which a baton is passed from one person to the next. In the enzyme relay of signal transduction, the signal is amplified because, as each enzyme is activated, it activates multiple copies of the next enzyme in the relay, and so on. Molecules of the last enzyme in the relay to be activated finally carry the signal to the nucleus where the gene activation occurs.

Figure 5.14 provides a simplified version of the sequence of events in a signal transduction pathway.

1. The binding of the peptide hormone to its cell-surface receptor causes a change in the 3D shape of the receptor protein that activates it.
2. The receptor in turn activates an enzyme embedded in the inner surface of the plasma membrane.
3. This activated enzyme in turn catalyses the production of multiple copies of a **second messenger** (for example, cyclic AMP (cAMP)). This step amplifies the signal, because the binding of one external signalling molecule results in the production of multiple copies of second messenger molecules.
4. The second messenger molecules activate copies of a key enzyme (protein kinase) that, in turn, activate the next enzyme in the relay, and so on. This step further amplifies the signal.
5. This signal is finally relayed to the nucleus, where specific genes are activated and effector proteins are produced.

Note that signals from hydrophilic hormones indirectly bring about gene action, while signals from hydrophobic hormones directly activate genes.

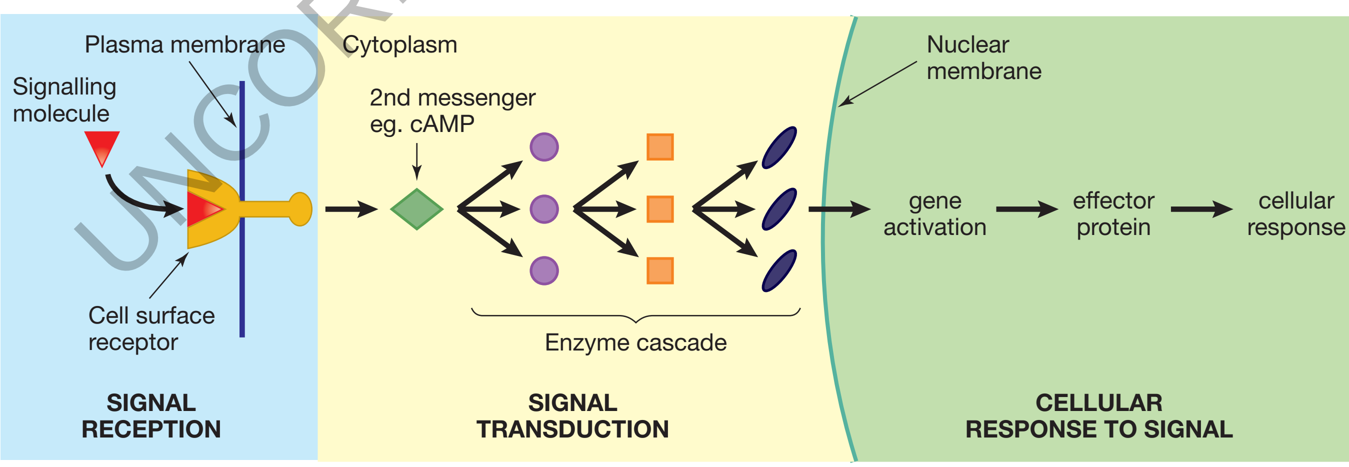

FIGURE 5.14 Diagram showing a simplified version of the signal transduction pathway for a peptide hormone. The final cellular response differs, depending on the identity of the original signalling molecule.

Table 5.1 summarises the differences between the hydrophilic and the lipophilic hormones.

TABLE 5.1 A summary of key differences between different groups of hormones, depending on their different affinities (love or hate) for water molecules.

Steroid hormones	Peptide/protein hormones
hydrophobic: insoluble in water	hydrophilic: soluble in water
lipophilic: soluble in lipid solvent	lipophobic: insoluble in lipid solvents
transported in blood but only with the aid of carrier proteins	transported in solution in blood plasma
readily diffuse across the lipid bilayer of the plasma membrane	unable to cross the lipid bilayer of the plasma membranes
bind to intracellular receptors	bind to cell-surface receptors
directly regulate gene expression	indirectly act on genes
no second messenger involved	second messenger produced during signal transduction
longer lasting response	shorter period of response

Figure 5.15 shows a comparison of signal transduction in lipid-soluble and water-soluble hormones.

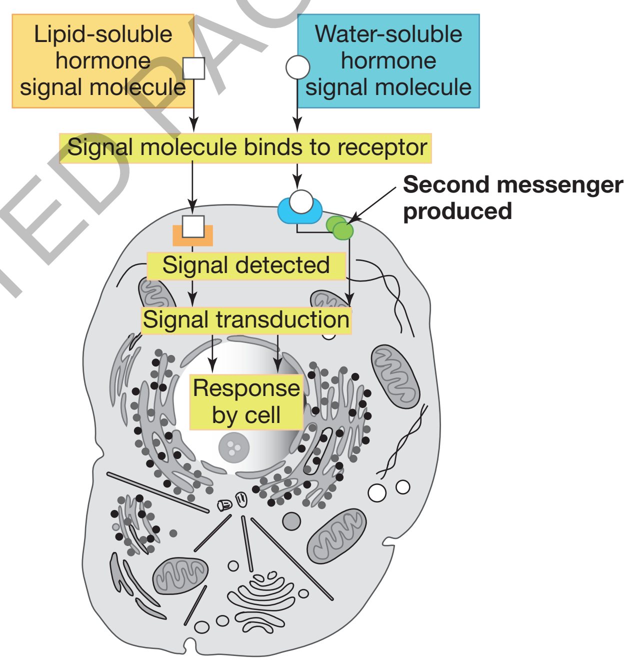

FIGURE 5.15 A comparison of signal transduction in lipid-soluble and water-soluble hormones, showing the location of events within a cell.

Cellular response to signal

The cellular response to the signal is the final stage in cellular signalling. Effector proteins are produced by gene activity stimulated directly by steroid hormones, or indirectly by peptide or protein hormones. These effector proteins produce the cellular responses to the original external signal molecule.

These cellular responses to different signals are extremely varied and may include:

- cell migration entailing the production of structural proteins, such as the microtubules of the cytoskeleton
- changes in metabolism that involve either the production of specific enzymes or a regulated increase in enzyme activity

Cell signalling stages:
1. Signal reception
2. Signal transduction
3. **Cellular response**

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Cellular responses
Summary screen and practice questions

- cell division involving DNA synthesis and the action of enzymes such as DNA polymerase
- apoptosis or programmed cell death involving the production of caspase enzymes.

Finally, cellular signalling pathways, once activated, do not stay switched 'on'. After a limited period of time, the system returns to its resting state, ready to receive and respond to the next signal.

KEY IDEAS

- The three stages in cellular communication are signal reception, signal transduction and cellular response.
- The nature of signalling molecules, either hydrophilic or hydrophobic, determines the location of the receptor where the signal is received.
- Hydrophilic signalling molecules are received by cell-surface receptors, while the receptors for hydrophobic signalling molecules are in the cytoplasm or the nucleus.
- Signal transduction of a hydrophilic signalling molecule involves a series of chemical reactions during which the signal is transferred and amplified before it reaches the cell nucleus.
- The cellular response involves changes in gene activity and the production of effector proteins that bring about the particular cellular response to the signal.

QUICK CHECK

5 List the three stages involved in cellular communication.
6 Identify the following statements as true or false:
  a Hormones are an example of signals that originate at a distance from the receiving cell.
  b Receptors for hydrophilic signalling molecules are located at the cell surface.
  c Steroid hormones are examples of hydrophobic signalling molecules.
  d Cellular response to signals involves effector proteins that bring about specific changes in the cell.
  e The receptor for a peptide hormone would be expected to be located on the surface of the receiving cell.
  f During signal transduction, the original signal is greatly amplified.
7 Identify one key difference between:
  a a hydrophilic and a hydrophobic signalling molecule
  b the first messenger and the second messenger.
8 Give an example of a cellular response to a signal.

Chemical signals in animals

Earlier in this chapter, we met some chemicals that are signalling molecules in various animal cells. Among these were:

- hormones
- neurotransmitters.

In this section, we will explore these and other chemical signals that are involved in cellular communication in the animal world.

Chemical signals: human hormones

Figure 5.16 shows the human endocrine system and the major hormones secreted by each endocrine gland.

The human hormones can be organised into three groups, as follows:

- **amino acid derivatives** — these hormones are derived from amino acids; they dissolve readily in water and therefore are hydrophilic. The names of hormones in this group typically end with the suffix ***-ine***, as, for example, thyroxine and epinephrine.

- **lipid-derived hormones** — these hormones are derived from lipids; they are not water-soluble and therefore are hydrophobic. The names of hormones in this group typically end with the suffix ***-ol*** or ***-one***, as, for example, testosterone and cortisol.
- **peptide and protein hormones** — some of these hormones are composed of shorter polypeptide chains; these are the peptide hormones, such as oxytocin and insulin. Other hormones in this group are made of long polypeptide chains — these are the protein hormones, such as growth hormone. These hormones are hydrophilic.

These groups are colour-coded in this figure. (Refer back to table 5.1 to check some of the differences between the lipid-derived hormones and the other groups of hormones.)

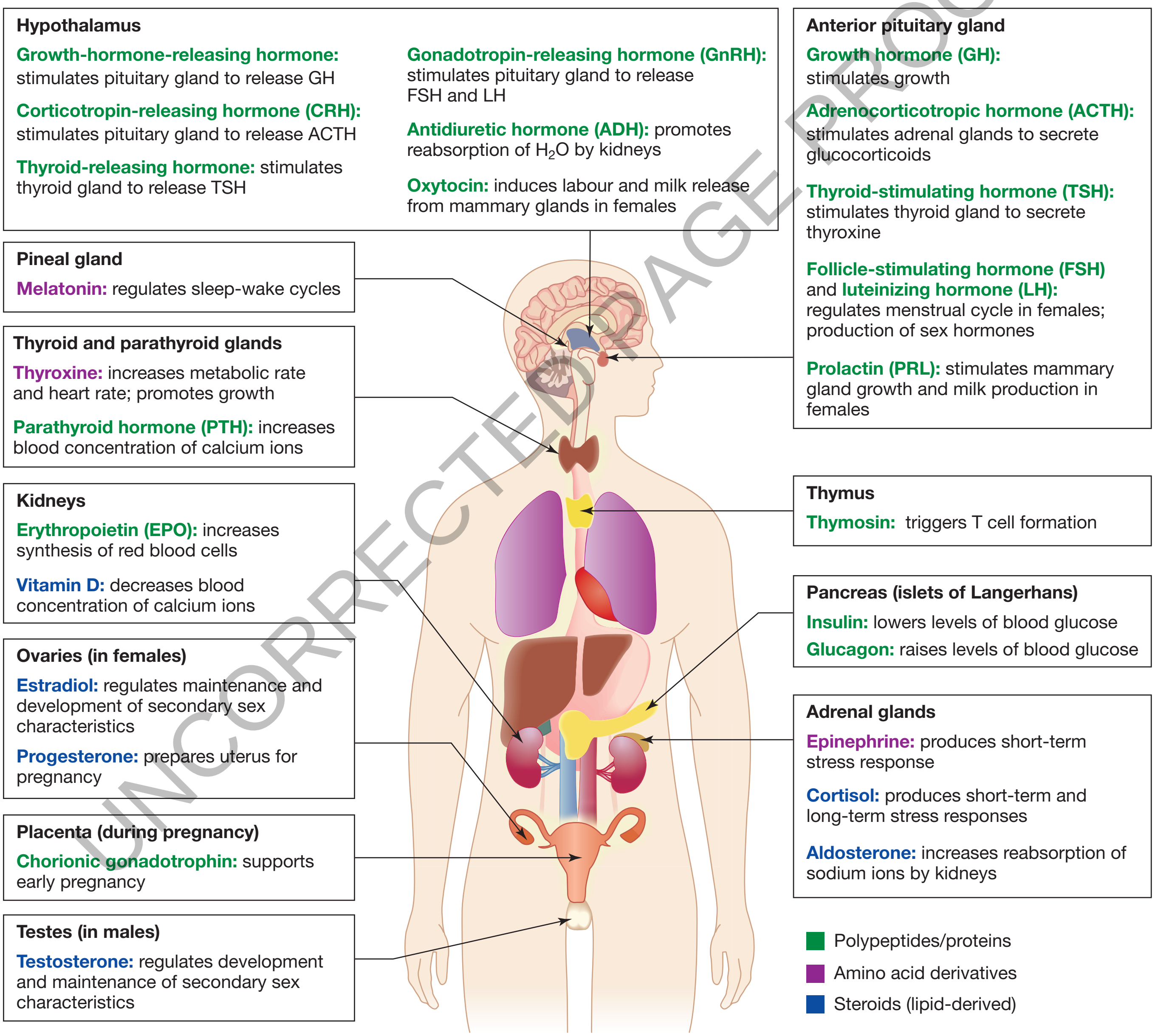

FIGURE 5.16 The endocrine organs and the major hormone signalling molecules that they produce. Note the three major chemical classes into which the various hormones fall. Based on this figure, which class is the most common?

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How steroid hormones work

Hydrophilic hormones are transported in solution in the blood from their site of production to their specific targets, while hydrophobic hormones are also transported in the blood but they are attached to protein carriers.

Hormones act as signalling molecules that carry messages to their specific target cells:

- The hormone prolactin carries the message 'Produce milk' to its target cells in the mammary glands.
- The hormone insulin carries the message 'Take up glucose and convert it to glycogen' to target cells in the liver.
- The hormone vitamin D carries the message 'Absorb calcium' to its target cells in the small intestine.

In addition to the hormones produced by the endocrine glands, many other tissues of the human body also produce hormones. Some of these are listed in table 5.2 below.

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Hormones
Summary screen and practice questions

TABLE 5.2 Examples of hormones produced by organs and tissues other than the endocrine glands.

Tissue/organ	Hormone	Major action
adipose tissue	leptin	suppresses appetite
skin	1,25-dihydroxy vitamin D	stimulates uptake of Ca^{2+} from small intestine
stomach	gastrin	stimulates acid secretion
heart	atrial natriuretic hormone	acts on kidney, promoting excretion of Na^{+} ions
small intestine	cholecystokinin	inhibits gastric motility and stimulates secretion of bile and pancreatic juice

The release of hormones operates within a negative feedback system. Figure 5.17 shows the signals that are exchanged between the hypothalamus, the anterior pituitary and the peripheral organs. Note the negative feedback loops, shown as red arrows, which ensure that the biological effects produced by the hormones are maintained within narrow limits. (This is the concept of homeostasis that is discussed in *Nature of Biology Book 1 Fifth Edition,* chapter 6).

Refer to this figure and follow the signal pathway that occurs if the body's metabolic rate falls to levels below normal limits:

1. The hypothalamus increases the release of thyroid releasing hormone (TRH).
2. TRH signals the anterior pituitary gland to increase the release of thyroid stimulating hormone (TSH).
3. TSH levels signal its target gland, the thyroid gland, to increase its release of the hormone thyroxine.
4. Increased thyroxine travels throughout the body, signalling changes in various target organs, and the resulting cellular responses produce an increase in the metabolic rate.

The increase in metabolic rate is kept within normal limits by the operation of two negative feedback loops as follows:

- The increased level of TSH gives negative feedback to the hypothalamus, stopping the release of TSH.
- The increased level of thyroxine gives negative feedback to both the anterior pituitary gland and the hypothalamus.

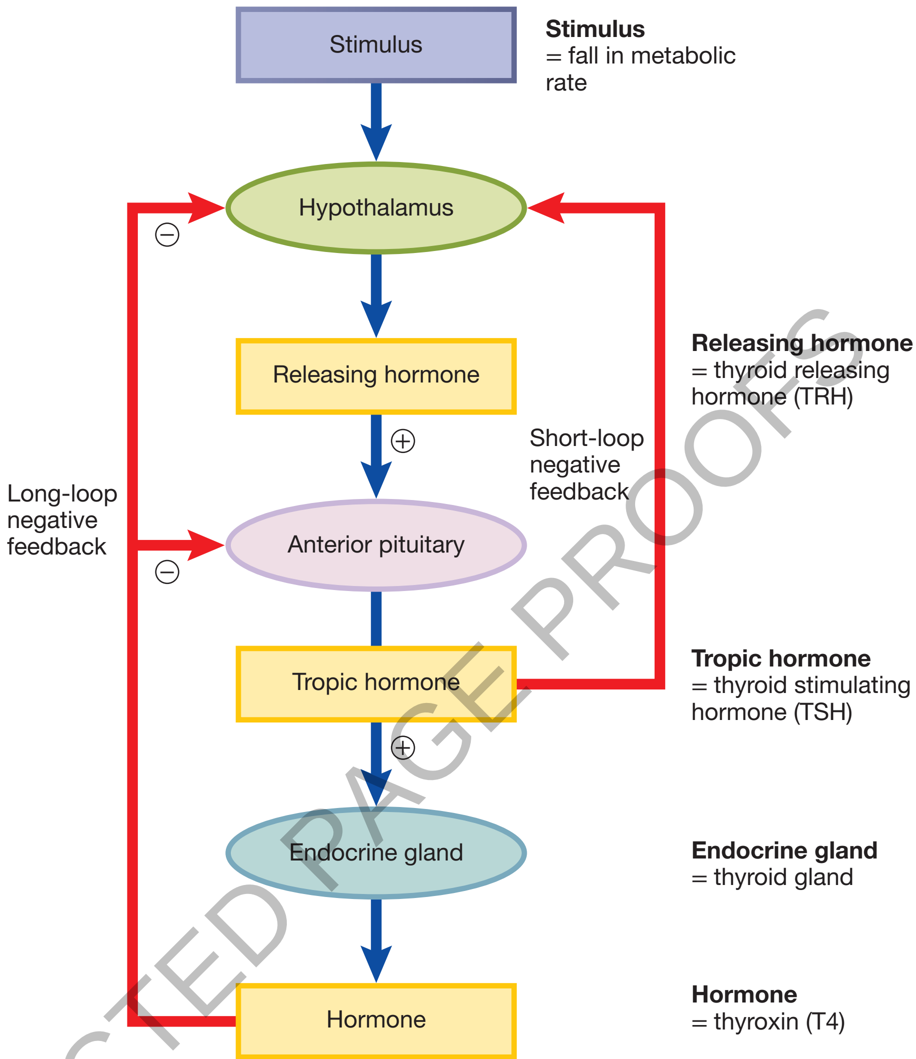

FIGURE 5.17 The action of hormones typically involves negative feedback loops (shown as red arrows), ensuring that cellular responses to hormone signals are maintained within narrow physiological limits.

KEY IDEAS

- **The hormones of the human endocrine system are a major group of signalling molecules.**
- **Hormone signals travel to their target cells via the bloodstream.**
- **In addition to the major hormones produced by the endocrine glands, other tissues and organs also produce hormones.**
- **The cellular responses to hormone signalling molecules are maintained within narrow limits principally through the operation of negative feedback loops.**
- **A hormone can communicate with cells only if the cells have receptors to receive the specific signal from that hormone.**

QUICK CHECK

9. Identify the target cells and organs of the following hormones:
   a. insulin
   b. prolactin.
10. What is the cellular response to the hormonal signal of thyroxine?
11. How do hormonal signals reach their targets?

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Neurotransmitters
Summary screen and practice questions

Chemical signals: neurotransmitters

Neurotransmitters are the chemical signalling molecules of nerve cells (neurons).

Neurons use two types of signals:

1. Communication *within* a nerve cell depends on electrical signals, known as action potentials, that transmit a nerve impulse along the axon of a neuron. Action potentials are produced by the local movements of charged particles (sodium ions into the neuron and potassium ions out of the neuron). The electrical signal box at the end of this section provides a brief outline of how the electrical signal is produced.
2. Communication *between* nerve cells uses chemical signals, known as **neurotransmitters**, that diffuse across very small gaps, known as **synaptic clefts**, that separate one neuron from the next in a neural network.

Figure 5.18 shows these two types of signals — electrical signals that move a nerve impulse along the axon of a neuron, and chemical signals (neurotransmitters) that transmit the impulse from one neuron to the next.

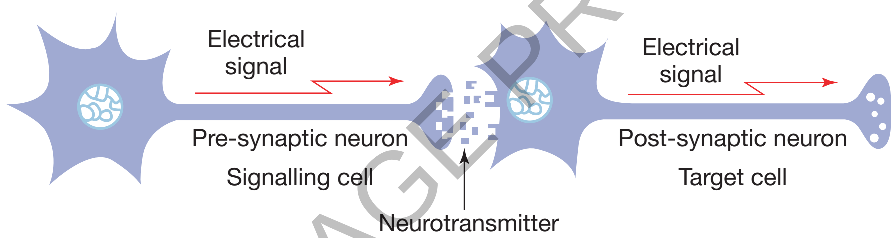


FIGURE 5.18 The movement of a signal in nerves involves an electrical signal that travels *within* each neuron. A chemical signal, known as a neurotransmitter, transmits the signal across the synaptic cleft that separates the pre-synaptic neuron from the post-synaptic neuron.

In addition to carrying signals from one neuron to another, neurotransmitters transmit nerve impulses from neurons to muscle cells, stimulating their contraction, and to some glands.

Neurotransmitters include chemicals such as acetylcholine, epinephrine (adrenalin) and serotonin; these are excitatory neurotransmitters. Another neurotransmitter, gamma amino butyric acid (GABA), is an inhibitory neurotransmitter. Figure 5.19 shows one possible outcome of the action of excitatory and inhibitory neurotransmitters on target cells supplied by the branches of the axon of one neuron.

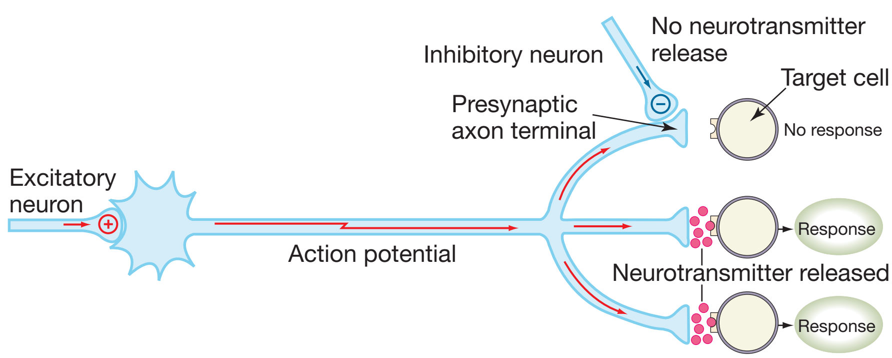


FIGURE 5.19 One possible arrangement of excitatory and inhibitory inputs to neurons, and the result in three target cells. What neurotransmitter might be involved at the excitatory junction? At the inhibitory junction?

ELECTRICAL SIGNAL WITHIN A NEURON

A resting nerve cell maintains a charge difference, known as the **resting membrane potential**, between the inside and the outside of the neuron. This difference is maintained in part by a channel in the plasma membrane of the neuron that is known as the Na^+/K^+ pump. The Na^+/K^+ pump actively transports sodium ions (Na^+) out of the cells and potassium ions (K^+) into the cells. From the energy supplied by one ATP molecule, three sodium ions are pumped out of the cell but only two potassium ions are pumped into it. This produces a net excess of positive charge outside the cell and a net negative charge of the cytosol inside the cell (see figure 5.20).

When neurotransmitter molecules bind to their receptors on the surface of the post-synaptic neuron, the situation changes. The receptors are activated, causing channels to open that allow large numbers of sodium ions (Na^+) to rush into the neuron (see figure 5.21a). The inflow of sodium ions causes a local **depolarisation** of the plasma membrane so that, at this point, the inside of the cell temporarily has a positive charge and the outside has a negative charge (see figure 5.21b). The region of depolarisation advances as an electrical signal along the axon carrying the nerve impulse. (A moving region of depolarisation is called an action potential.)

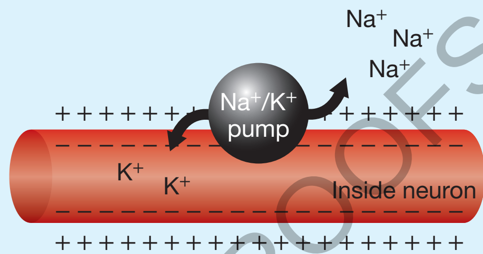
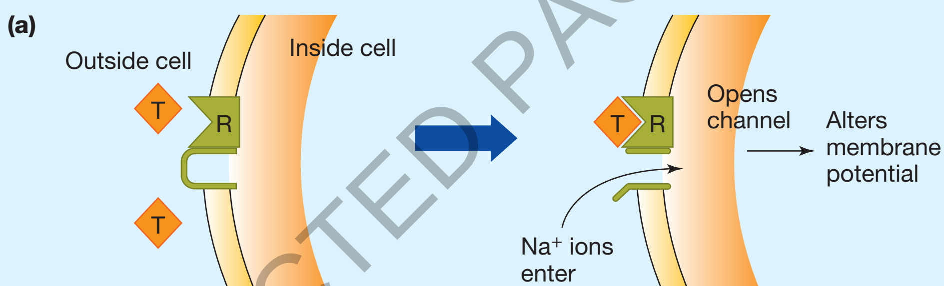


FIGURE 5.20 Diagram showing part of a resting nerve cell. Note that the cytosol inside the cell has a negative charge relative to the outside of the cell, which has a positive charge. What maintains this charge difference in a resting neuron?



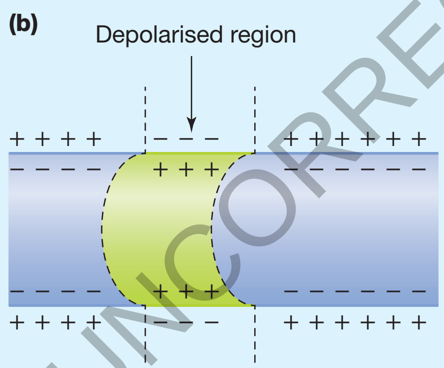


FIGURE 5.21 **(a)** Diagram showing the interaction between neurotransmitter molecules (T) and their specific cell-surface receptor (R). Note that the binding of the neurotransmitter activates the receptor and changes the configuration (shape) of the channel. The opening of the channel causes the sodium ions to flow into the neuron, producing a region of local depolarisation. **(b)** The inflow of sodium ions produces a region of local depolarisation that advances along the neuron, transmitting the electrical signal of the nerve impulse.

What happens at a junction between two neurons?

Look at figure 5.22, which shows a **synapse**, the term given to the junction of two neurons and the synaptic cleft that separates them. When a neuron is stimulated, it transmits a nerve impulse in the form of an electrical signal along its axon. At the end of the axon are packages or vesicles that contain neurotransmitters. The impulse is transmitted across the synaptic cleft by neurotransmitter molecules released from vesicles in the pre-synaptic neuron.

The neurotransmitter molecules diffuse across the synaptic cleft and bind with receptors on the surface of the post-synaptic neuron. Nerve impulses are transmitted in a one-way direction only across a synaptic cleft. Can you identify why the movement of the nerve impulse occurs in one direction only? Note the presence of an enzyme that destroys the neurotransmitter, ensuring that the nerve impulse has a limited duration.

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Do More
Neurotransmitters and synapses

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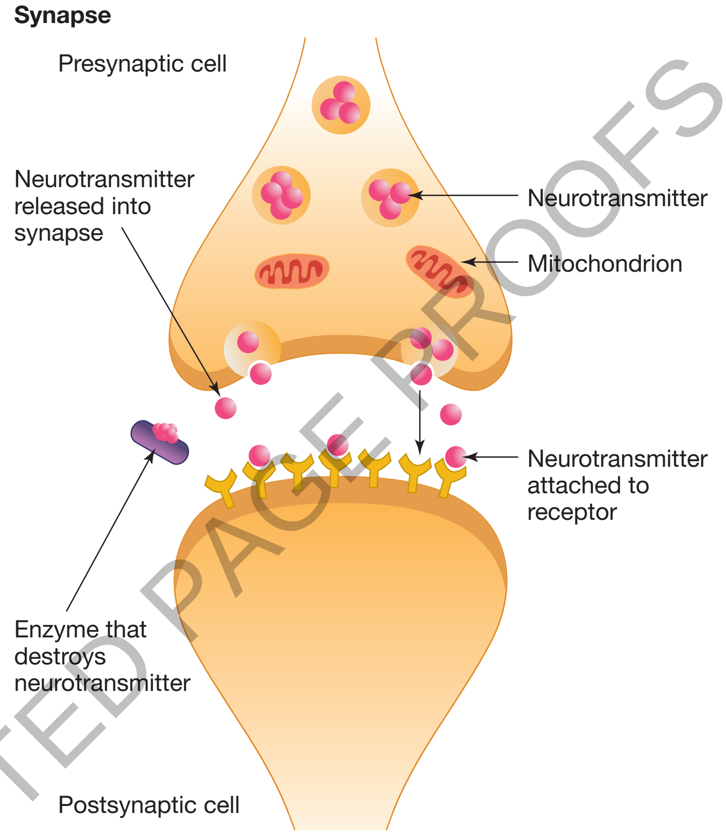

FIGURE 5.22 Diagram showing the junction of two neurons, which forms a structure called a synapse. Note the vesicles that contain neurotransmitter molecules, the chemical signals that transmit the nerve impulse across the synaptic cleft.

Motor nerves also send impulses to muscles. Every involuntary muscle movement in your body, such as the peristaltic movement of your gut, involves nerve impulses to smooth muscle fibres in the gut wall. Every contraction of your skeletal muscles occurring when you turn the page of a book, take a step, turn your head, kick a football or throw a basketball requires that the muscles concerned receive stimulatory impulses from motor neurons.

At a neuro-muscular junction, a neurotransmitter is released from the motor end plates at the terminal ends of an axon. This neurotransmitter diffuses across the small gap between the axon and the muscle, and binds to receptor molecules on the membrane of the striated muscle (see figure 5.23). The cellular response contracts the muscle. What stops the action of transmitter substances on muscle? Muscle tissue produces an enzyme that inactivates the transmitter substance. Further action can occur only if more transmitter substance is released from the nerve motor end plate.

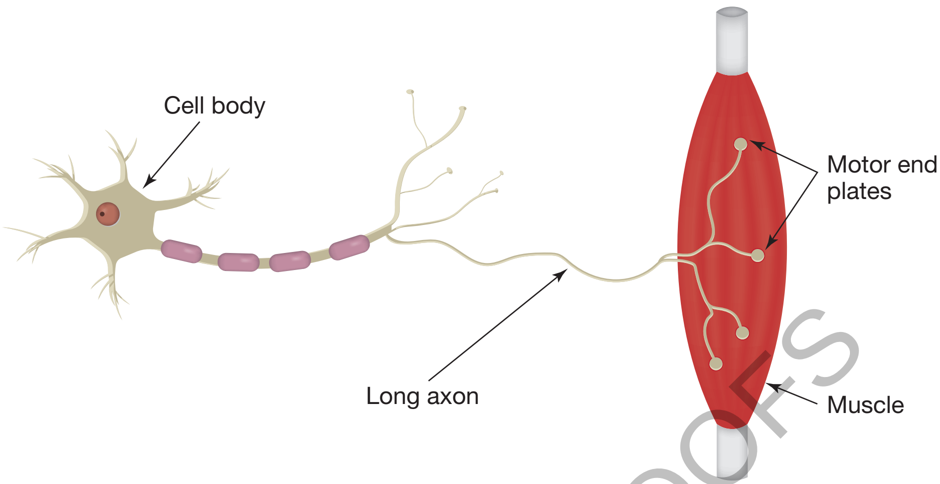

FIGURE 5.23 Simplified diagram showing a motor neuron with a long axon that extends from the cell body and divides into many small branches at its terminus. At the end of each branch is a **motor end plate** that forms a junction with muscle cells. Neurotransmitter is released from vesicles in the motor end plate.

The critical importance of nerve impulses to voluntary movement was tragically apparent during past epidemics of poliomyelitis (polio). Polio is an infectious disease caused by the poliovirus. Major epidemics of polio occurred in Australia in the late 1930s, early 1940s and the 1950s, with the last epidemic occurring in 1956.

After gaining entry to the body, typically through the mouth, poliovirus may reach the central nervous system. If this occurs, the virus replicates in motor neurons, resulting in damage to and death of these cells. Motor neuron cells control the muscles of the trunk, legs and arms, and the muscles involved in swallowing and breathing. When breathing muscles were affected, a patient was placed in a tank respirator, better known as an iron lung, which did the mechanical work of breathing (see figure 5.24). Fortunately, mass vaccination has made poliomyelitis a disease of the past.

ODD FACT

In tissue culture, replication of poliovirus has been shown to produce 10 000 to 100 000 virus particles per cell in a period of about eight hours.

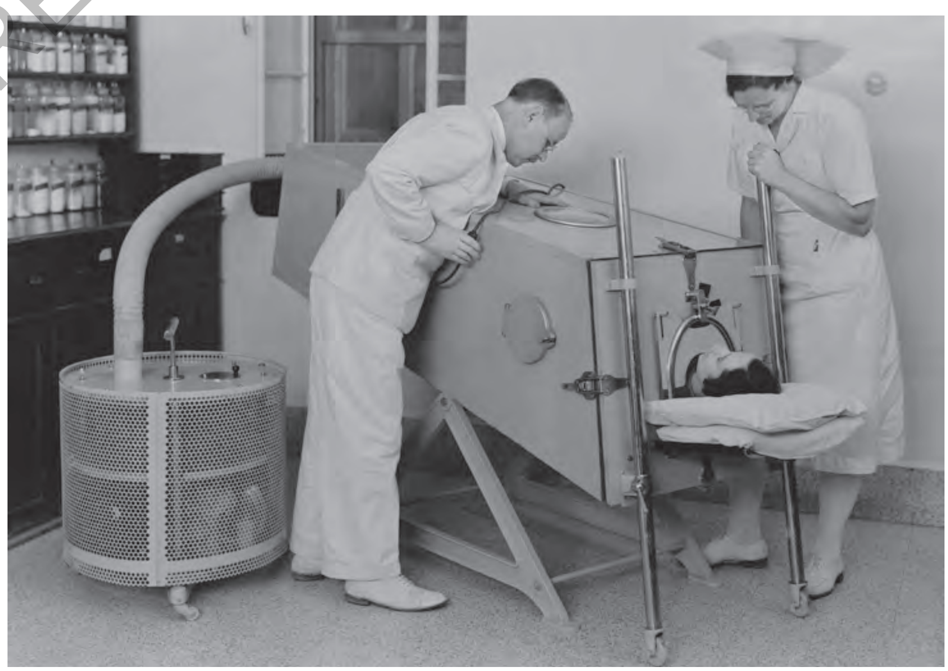

FIGURE 5.24 Historical photograph showing a victim of polio inside an Emerson respirator, also known as an 'iron lung' machine. Patients stayed in the iron lung until they were able to breathe independently.

KEY IDEAS

- Neurotransmitters are signalling molecules that enable communication between nerve cells.
- Communication from one neuron to another occurs when neurotransmitters are released from the pre-synaptic nerve cell and diffuse across the synaptic cleft to the post-synaptic nerve cell.
- Within a nerve cell, the signal moves as an electrical impulse.
- Communication between motor neurons and striated muscle cells is mediated by neurotransmitters released at motor end plates at the ends of the nerve axons.

QUICK CHECK

12 Identify the following as true or false:
  a Neurotransmitters can travel in either direction across a synaptic cleft.
  b Adjacent neurons are separated by a gap termed the synaptic cleft.
13 Identify an example of a neurotransmitter.
14 Where would you expect to find the following:
  a a synapse
  b a motor end plate
  c a neurotransmitter?
15 What stops a muscle from continuing to contract after it receives a signal to contract?

ODD FACT

The first pheromone was chemically identified in 1959. This was the chemical bombykol, a sex attractant that is released by female silkworm moths (*Bombyx mori*).

Chemical signals: pheromones

The dog sniffing around the lamppost, the two lemurs wiping secretions from their wrist glands onto their tails and waving their tails at each other, the ants forming a procession along a particular trail — these animals are receiving signals from and/or transmitting signals to other members of their species. The signal in each of these cases is a chemical signalling molecule called a pheromone.

Pheromones (*phero-* = to carry plus *-mone* from hor**mone**) are produced by a variety of animal species. As our understanding of pheromones has increased, so has the evidence that more and more animal species appear to communicate to each other using pheromones to convey particular messages.

Hormones and neurotransmitters are chemical signalling molecules that are involved in cellular communication within one organism. In contrast, pheromones are chemical signalling molecules released by one animal that can carry a signal to a second member of the *same* species (a conspecific) and, if this pheromone signal is received, the second animal produces a physiological or behavioural change.

The messages carried by different pheromones vary and include alarm signals ('Danger, predator approaching'), food trail signals ('Head this way to the food'), territorial signals ('This is my turf, so stay away!') and sexual attractant signals ('I'm ready to mate. Come find me!'). Communication by pheromones can be seen as being beneficial to the survival of individual animals and also to the survival of a population. For example, the individual worker ant who finds a source of food and lays a pheromone trail from the food source back to the ant colony provides a significant benefit to all members of the colony. The energy of the worker ants can then be concentrated on gathering food rather than on many non-productive searches for food.

ODD FACT

Ants use the chemical signal of a pheromone to mark a food trail. In contrast, bee species use the visual signal of a precise and elaborate dance for the same purpose.

FIGURE 5.25

Detecting pheromones

Pheromones are secreted by an animal into the external environment. Highly volatile pheromones disperse rapidly, some travelling on air currents over great distances, such as insect sex pheromones. Others, such as the territorial

FIGURE 5.26 The flehmen behaviour seen in many mammals involves drawing air into the mouth from where it can reach the vomeronasal organ.

pheromones of mammals that mark the perimeter of a territory, are less volatile and remain more localised.

A particular behaviour called the **flehmen** response may be seen in cats, dogs and ungulates, when they are investigating the urine, the faeces or the genital region of a conspecific, either up close or from a short distance. Figure 5.26 shows a horse displaying flehmen behaviour. Typically, the animal opens its mouth, curls its upper lip, holds its mouth open and draws air into its mouth. Flehmen behaviour in some animals may also involve licking and tongue flicking. A similar behaviour may be seen in dogs and cats. What is the purpose of this behaviour?

In addition to the olfactory system that detects smells and odours, mammals have a second system that detects pheromones. The detection of pheromone signals involves a different nerve pathway from the pathway for the detection of odours and smells. Can you identify a possible advantage of having a separate system for the detection of pheromones?

A structure called the **vomeronasal organ (VNO)** contains the detector cells of this second system. When an animal takes air into its mouth as part of the flehmen response, the animal is directing that air to the VNO. The VNO is located in the front portion of the nasal cavity. If cells detect pheromone molecules, a signal is relayed via several regions of the brain to the hypothalamus (H) (see figure 5.27). The hypothalamus is the brain centre where physiological and reproductive responses to pheromone signals are regulated.

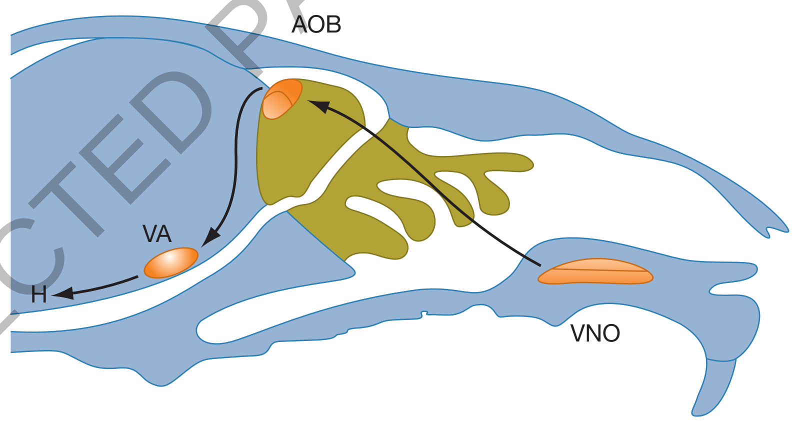

FIGURE 5.27 Diagram showing a longitudinal section of a dog skull. Note the vomeronasal organ (VNO), where sensory neurons detect pheromone signals. The signal is first transferred by axons of VNO cells to a region of the brain (AOB = accessory olfactory bulb). From there, the signal is relayed in two steps to the hypothalamus (H) of the brain. The hypothalamus plays a major role in regulating physiological or reproductive responses to the pheromone signal. (It is not surprising that the signal travels to the hypothalamus — refer back to figure 5.17 to check on the range of hormones secreted by the hypothalamus.)

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Pheromones
Summary screen and practice questions

Pheromones in the animal world

Some examples of pheromones in the animal world include:

Trail pheromones: Many insect species, in particular ant species, use pheromones to mark out a trail from a food source. While the food source remains, the trail continues to be renewed by pheromones released by more ants travelling to and from the food. The trail continues to be marked out as long as the food source exists. Would you predict that the pheromone involved would be a chemical that remained in place for an extended period?

ODD FACT

More than 4000 species of aphid have been identified, and many are serious pests in agriculture and forestry.

FIGURE 5.28 Wingless aphids on a plant stem. Note the paired cornicles near the rear of the abdomen.

Alarm pheromones: When some insect species are attacked by predators, they release alarm signals. Included among these species are aphids. Look at figure 5.28 and note the paired tubular structures, called cornicles, near the end of the aphid abdomen. Cornicles are present on most aphid species and it is from the cornicles that aphids release their alarm pheromones when attacked.

Territorial pheromones: Many mammals, including lions, tigers, dogs and wolves, define the perimeters of their territories by spraying urine on particular landmarks. Present in the urine are pheromones that proclaim the 'owner' of the territory to a passing member of the same species. Other mammals, including species of wildebeest and deer, mark their territories using strong-smelling secretions from scent glands on various parts of the animal's body. Ringtail possums (*Pseudocheirus peregrinus*), an Australian native marsupial species, also mark their territory with scent.

Sex pheromones: Females of many insect species, in particular species of moth and butterfly, release pheromones signalling that the females are ready to mate. These pheromones drift downwind in the air and can attract males from up to ten kilometres away. A female moth emits pheromones from brush-like scent organs that protrude from the distal end of her abdomen (see figure 5.29a). Male moths (see figure 5.29b) have large feathered antennae with specialised hair-like sensory receptors to detect pheromones released by a conspecific female moth. The sensory cells on the antennae of male moths can distinguish minute traces of pheromones, even a few molecules, in the presence of many odours. Would you predict that sex attractant pheromones are species specific?

FIGURE 5.29 **(a)** A female moth (*Estigmene acraea*) releases pheromones from brush-like scent organs at the distal tip of her abdomen. **(b)** A male gypsy moth (*Lymantria dispar*) with his feathered antennae that he uses to detect sex pheromones released by a female gypsy moth.

PHEROMONES IN AGRICULTURE

Making use of pheromones

Pheromones are used to reduce insect pests in both glasshouse crops and field crops. Artificial chemicals that mimic particular pest-insect pheromones are used. Insect traps, baited with artificial hormones, attract male pest insects into the traps from which they cannot escape. In a confined space such as a glasshouse (see figure 5.30a), such a strategy allows informed release of other insects for biological control. The insects chosen for the biological control prey on the pest insect but otherwise have no impact on the crop.

In a field crop or for orchards, traps can be used as early warning signals (see figure 5.30b). They indicate that adult insects are emerging and give some idea about the size of the pest population. This enables insecticide to be sprayed only when and where it is needed.

FIGURE 5.30 **(a)** Pheromone traps used in glasshouses detect the presence of pest insects. An appropriate 'non-pest' or 'crop-friendly' species can be used in biological control against the pest insect. **(b)** A pheromone-baited trap in an orchard. The artificial pheromone used here mimics that of the codling moth, *Carpocapsa pomonella*, an important pest of apple and pear orchards.

KEY IDEAS

- Pheromones are chemical signalling molecules for communication between members of one animal species.
- Pheromones convey many different kinds of messages, including alarm signals and territorial signals.
- Pheromones are used in various ways to reduce pest infestation of plant crops.
- Artificial molecules can be made that mimic the effects of natural pheromones.

QUICK CHECK

16 Identify two functionally different kinds of pheromone.
17 What is the difference between a hormone and a pheromone?
18 By what means do male moths detect the pheromone signals produced by females of the same species?
19 What is the flehmen response?

Chemical signals: cytokines

Cytokines are a diverse category of signalling molecules — more than 200 have been identified. Many cytokines are peptides, but some are proteins and some are glycoproteins. The major cells that secrete cytokines are the immune cells (white blood cells) of mammals, but they are also produced by other cell types. Cytokines are '*cell signalling molecules that aid cell-to-cell communication in immune responses and stimulate the movement of cells towards sites of inflammation, infection and trauma*' (Source: News Medical).

Cytokines act as messengers between cells of the immune system, just like the hormones of the endocrine system communicate with various cells throughout the body. Figure 5.31 shows a diagrammatic representation of cytokine-mediated communication between immune cells.

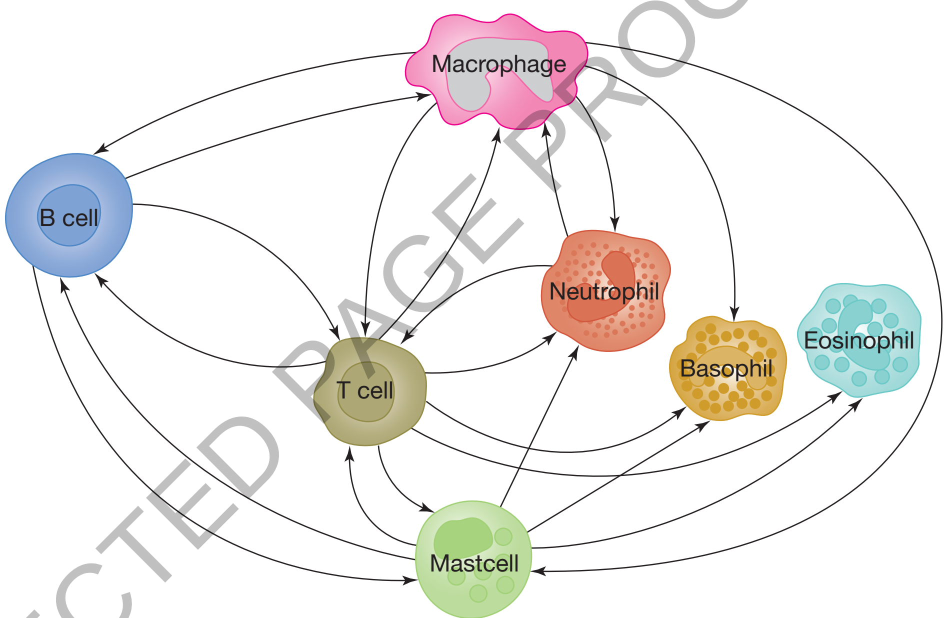


FIGURE 5.31 Diagram showing some of the communication between immune cells that is mediated by cytokine signalling molecules.

ODD FACT

Peptide hormones are important for cell-to-cell communication in plants. One researcher has recently proposed that these peptide hormones in plants be called plant cytokines or phytocytokines

In chapter 7, you will read about some of these various cytokines in action in innate immune responses, including inflammation.

Cytokines have a large number of effects — stimulatory, inhibitory and regulatory — on surrounding cells, with the specific effect depending on the cytokine involved and the target cell. Cytokines are examples of chemical **mediators**, that is, intracellular proteins that enhance and activate the functions of other proteins. So, we can say: 'Cytokines mediate a number of cell processes including immunity, inflammation, and blood cell formation.' Cytokines are also described as **modulators**, that is, molecules that directly influence the effects of other molecules. So, we can say: 'Some cytokines are immune-modulators', meaning that cytokines directly influence immune responses, such as inflammation.

Table 5.3 identifies the major actions of the major subgroups of cytokines. These subgroups are named according to a major function of the subgroup, as, for example, interleukins (*inter* = between; *leuko* = white) are produced by white blood cells and act mainly on other white blood cells.

Cytokines are secreted *by cells* in response to various stimuli, and they usually act briefly, locally, and at very low concentrations. However, cells that produce cytokines do *not* hold stores of pre-formed cytokines. Instead, cytokines must be produced anew in response to a stimulus, such as the presence of a pathogen. Because of this need to synthesise new cytokines, cellular responses to cytokine signals are slow, and may take hours to appear.

TABLE 5.3 Major actions of various subgroups of cytokines.

Subgroup	Major actions
interleukins (IL-1 to IL-35)	• stimulate growth and differentiation of white blood cells • promote inflammation (pro-inflammatory)
interferons (IFRs)	• act as antiviral agents • interfere with replication of viruses
colony-stimulating factors (CSFs)	• signal stem cells in bone marrow to differentiate into various kinds of blood cells (see the box on CSFs in chapter 6)
tumour necrosis factors (TNFs)	• promote inflammation • activate some immune cells • high levels of TNF are seen in cancer patients with wasting disease (cachexia) • induce apoptosis of tumour cells

Once cytokines are produced and released from the signalling cell, the cytokines diffuse to nearby target cells where each binds to a specific cell-surface receptor. The binding of a cytokine to its specific receptor triggers a signal transduction pathway in the cytoplasm. This process involves the production of second messenger molecules (such as cAMP) and enzyme activation. The signal is finally transduced to a specific cell response that is brought about by changes in gene transcription, in which cytokine-related genes are switched 'on' or 'off'.

The cellular responses produced in response to cytokine signalling include promotion of cell growth and differentiation, cell proliferation, cell migration, cell activation, apoptosis, as well as immune responses such as inflammation and phagocytosis.

One cytokine can provide different signals to various cells. Figure 5.32 shows the effects of interleukin-2 (IL-2), a cytokine that is released by one kind of immune cell. IL-2 acts as a signal to other immune cells, but the cellular response to the cytokine signal varies in different kinds of cells.

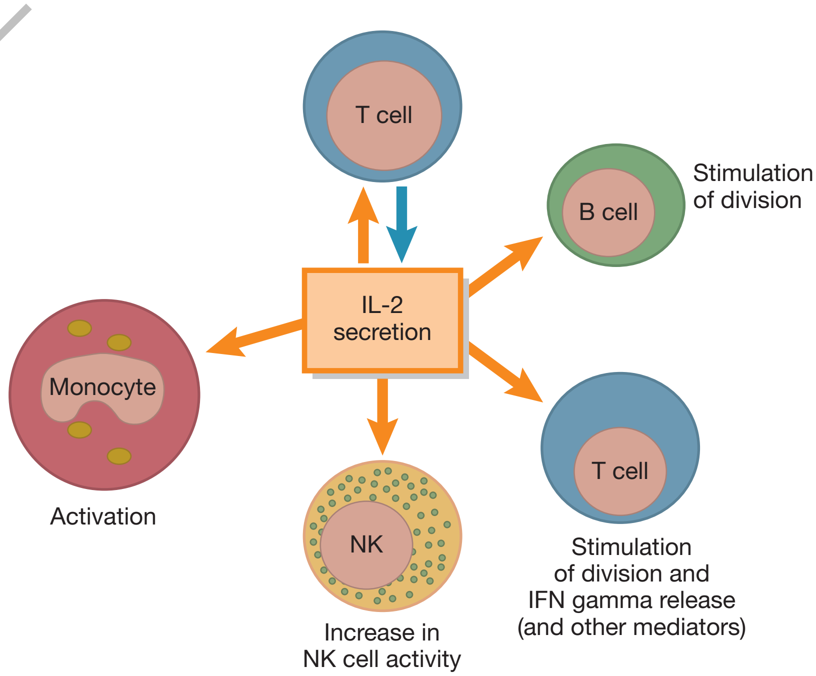


FIGURE 5.32 The same cytokine, interleukin 2 (IL-2), produces different cellular responses in different types of immune cells. Note that one of the actions includes the release of IFN (interferon). What is the cellular response of B cells to the IL-2 signal? (You will meet these and other immune cells in chapters 7 and 8.)

Cytokines in human disease

Several cytokines act as mediators in the normal inflammatory response to infection. For example, one cytokine, tumour necrosis factor (TNF), regulates the production of several other pro-inflammatory molecules, including several interleukins. However, overproduction or overstimulation of pro-inflammatory cytokines can produce undesirable outcomes. For example, pro-inflammatory cytokines appear to be directly linked to the disease process of rheumatoid arthritis and play a role in the joint destruction seen in this disease.

An acute condition, popularly called a 'cytokine storm' is life-threatening. Cytokine-stimulated inflammation is a normal and healthy *localised* response to infection. A cytokine storm refers to the excessive or uncontrolled release of pro-inflammatory cytokines at a *system-wide* level. This involves a positive feedback loop with cytokines stimulating the production of more white blood cells and these cells, in turn, produce more cytokines that attract more cells, and so on.

ODD FACT

The disproportionately high death toll among young people during the 1918 influenza pandemic is thought to have been a result of a cytokine storm in those people.

KEY IDEAS

- Cytokines are important signalling molecules that are involved in communication between immune cells.
- Cytokines are a large and diverse group of proteins and protein derivatives, and their subgroups include interferons and interleukins.
- Cellular responses to cytokine signals vary, including cell growth and differentiation, cell migration, cell apoptosis, as well as immune responses such as inflammation and phagocytosis.
- Cytokines are involved in a number of inflammatory diseases.

QUICK CHECK

20 Briefly describe the function of the following cytokines:
  a interferon
  b colony-stimulating factors.
21 In what way are cytokines like hormones?
22 In what way are cytokines different from hormones?

Chemical signalling in plants

Plant cells, like animal cells, engage in a 'constant chatter' that is carried on through signalling molecules. Intercellular signalling is essential for the coordinated growth, development and reproduction of plants. These signals regulate the development of the undifferentiated mass of cells of a plant embryo into an adult plant with its differentiated organs, including leaves, stems and buds above the ground, and roots below ground. Signalling molecules include messages relating to timing, such as: when seeds should germinate, when dormant buds should sprout, when flowers should bloom, when fruit should ripen, when leaves should drop (see figure 5.33).

Fruits appear on flowering plants and ripen at certain seasons; so, for example, peaches and cherries typically appear for sale in the summer months that follow the ripening season for these fruit. Fruit growth and maturation are just two of many changes that occur during the life cycle of a flowering plant. Changes during the life cycle — from the time of its formation from a germinating seed to the time that the plant matures and itself produces seeds — involve both growth and development. Growth (increase in size) and development (change in form) are seen in many events, such as formation of buds, lengthening of stems, downward growth of roots, expansion of leaves, appearance of flowers, development and ripening of fruits. For each plant species in a particular environment, the events of growth and development occur in a predictable sequence.

Plant growth and development are influenced by both internal and external factors and by interactions between these factors.

- Internal factors include chemical substances known as plant hormones. These hormones are the major signalling molecules that influence germination, growth, development and metabolism in plants.
- External factors include environmental factors such as light intensity, light wavelength, temperature, and day length. For example:
  - Increases in day length and temperature may act as signals to plants to shift resources to sexual reproduction and produce growth in flowers and then in seeds
  - Low light intensity may act as a signal to plants for the stem to elongate (see figure 5.33).

In this chapter, we will explore plant hormones and identify their role as signalling molecules that regulate many aspects of plant life.

study on

Unit 3
AOS 2
Topic 1
Concept 4

See more Plants and hormones

Chemical signals: plant hormones

Plant hormones are chemical messengers or signalling molecules that are produced in one part of a plant and have a physiological effect on cells in a specific target tissue. This target tissue can be both the cells that produce the hormone as well as cells in other parts of the plant.

Plant hormones have many of the same general characteristics as mammalian hormones. Plant hormones are produced by plant cells in small amounts and are active at low concentrations. Plant hormones act as signalling molecules that target various cells in plant tissues and produce specific effects. Both mammalian hormones and plant hormones act as signalling molecules. Hormone signalling in plants is similar to that occurring in animals. The hormone signal binds to a specific receptor, and once received, the signal is transmitted via a signal transduction pathway to the nucleus where a specific cellular response is generated:

1 Reception → 2 Transduction → 3 Response

study on

Unit 3
AOS 2
Topic 1
Concept 4

Plant hormones Summary screen and practice questions

Responses of the plant vary according to the particular signalling molecule involved, its concentration, the region of the plant where the signal is received, and the stage of development. Responses include biochemical and physiological responses ranging from seed germination, shoot and root development, initiation of flowering, ripening of fruit and the regulation of photosynthesis.

Some differences between plant and animal hormones:

Mammalian hormones are produced by discrete endocrine glands. Plant hormones are not produced in glands but are produced mainly in the cells of growing regions (meristems) of shoots and roots, in young leaves, in germinating seeds and in developing fruits. Mammalian tissues are typically transported in the bloodstream, while transport of plant hormones is mainly in the phloem tissue.

The classical plant hormones are:

1. auxins, which are responsible for cell division and growth in cell size
2. cytokinins, which are responsible for an increase in cell division
3. gibberellins, which are responsible for cell division and growth in cell size
4. abscisic acid, which is responsible for dormancy
5. ethylene, which is responsible for ageing (senescence).

Figure 5.33 shows some of the actions of these classical hormones in a plant.

study on

Unit 3 | AOS 2 | Topic 1 | Concept 4

Do more
Hormone production in plants

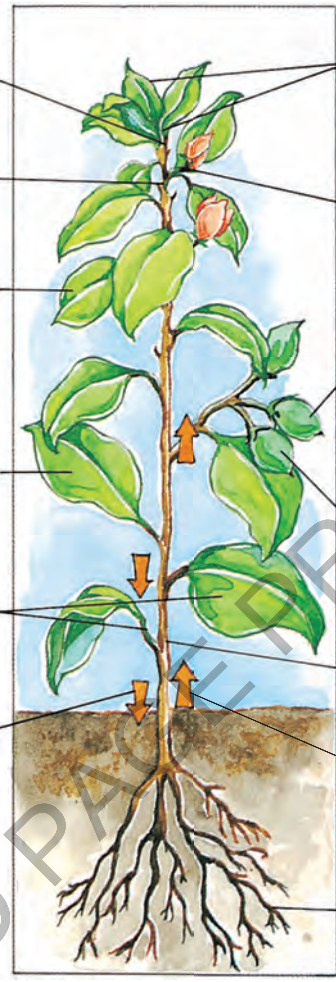
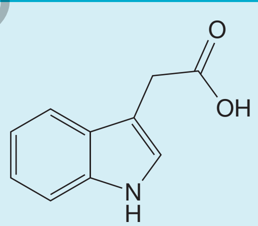


FIGURE 5.33 Plant hormones regulate many aspects of growth and development in flowering plants. Some typical hormone actions are shown in this figure.

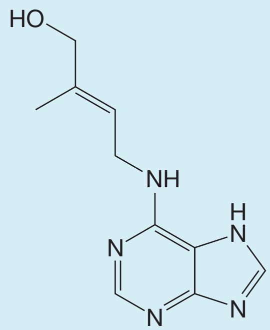
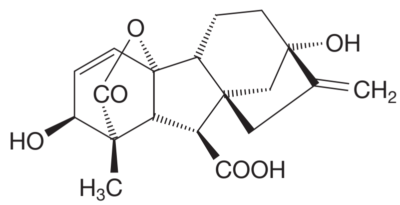
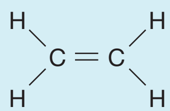
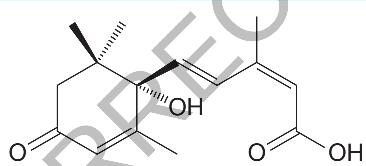
Table 5.4 summarises the main features of the classical plant hormones.

TABLE 5.4 A summary of major actions of the classical plant hormones. In column 2, the chemical structure of a major hormone or the only hormone in a group is shown.

Hormone	Structure	Where found	Major actions include
AUXINS include IAA a growth hormone	 indole acetic acid (IAA)	in meristems at: apical buds (growing tips) in developing seeds in leaf primordia	regulate embryonic growth and form promote flowering and fruit development promote stem and coleoptile elongation produce trophic responses to light and gravity induce formation of xylem and phloem induce formation of adventitious roots prevent leaf drop (abscission)

(continued)

TABLE 5.4 *(continued)*

Hormone	Structure	Where found	Major actions include
CYTOKININS growth hormones	 zeatin	found in actively dividing meristematic regions of stems, roots and leaves believed to be synthesised in roots	promote cell division regulate growth and form (with auxin) promote root growth delay senescence (ageing) stimulate leaf expansion stimulate growth of lateral buds regulate development and activity of chloroplasts
GIBBERELLINS growth hormones	 gibberellic acid	produced by roots, young leaves and seeds	promote rapid stem elongation ('bolting') stimulate shoot growth break dormancy of some seeds and promote germination mobilise food stores in seeds promote flowering, fruit and leaf growth stimulate production of seedless fruits
ETHYLENE the gaseous hormone	 ethylene	produced by most parts of a plant, with highest concentrations during senescence, leaf abscission and fruit ripening	stimulates shoot and root growth promotes flower opening and fruit ripening promotes abscission of leaves and fruit stimulates leaf and flower senescence
ABSCISIC ACID (ABA) the 'stress' hormone	 abscisic acid	produced in roots and terminal buds	inhibits growth of shoots blocks seed germination promotes dormancy promotes synthesis of storage proteins in seeds promotes stomatal closure (in times of water stress)

It should be noted that:

- The same hormone may induce different responses in different tissues of a plant, such as promoting growth in one region (such as the stem) while inhibiting growth in another region (such as the roots).
- The action of a hormone may depend on the concentration of the hormone, with different concentrations producing different responses by a plant.

Further, plant hormones do not act in isolation — one hormone may influence the action of another hormone.

Let's look at the classical plant hormones.

'Adventitious root' refers to any root that develops in an unusual place, such as roots that grow from stems. 'Lateral root' refers to a root that branches out from a main or primary root.

Plant hormones: auxins

The label *auxins* (from the Greek *auxeun* = to grow or increase) refers to several hormones, such as indole acetic acid (IAA), the main naturally occurring auxin in plants. Auxins are essential plant hormones whose signalling

ODD FACT

Bamboos are tropical grasses that grow at rapid rates, with some species growing at rates of up to four centimetres per hour. This growth is due mainly to cell elongation. What class of plant hormone is involved in the control of this growth?

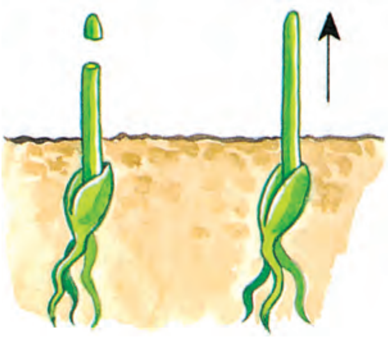


FIGURE 5.34 Experiment demonstrating that the coleoptile tip is the source of a growth factor, later identified as indole acetic acid (IAA), which is an auxin.

influences almost every aspect of plant growth and development. The major roles of auxins are to promote cell growth and cell elongation (expansion), and they are important in root development by inducing the growth of lateral roots and adventitious roots. Auxins also promote the growth of flowers and fruits, and influence the differentiation of unspecialised cells into vascular tissue (xylem and phloem).

Where are auxins produced?

Auxins are produced by meristem cells in the growing tips of plant shoots, and move unidirectionally from shoots to roots in the phloem. The site of production of auxins was first identified in germinating grass seeds from the result of the following experiment:

Experiment 1: **The coleoptile is the outer protective sheath that covers the embryonic shoot of a new grass seedling as it emerges from below ground**. Seeds were allowed to germinate and the tips of the coleoptiles of some seedlings were removed, while other seedlings were left with an intact coleoptile (see Figure 5.34). It was observed that only those seedlings with an intact coleoptile continued to grow, while the seedlings with topless coleoptiles stopped growing. From this observation, it was concluded that the tip of a coleoptile was the source of a growth hormone, which we now know to be the auxin, indole acetic acid (IAA).

Another experiment provided some information about the nature of auxins.

Experiment 2: Tips cut from coleoptiles were placed on agar blocks for several hours. It was observed that, when one of these agar blocks was placed onto a topless coleoptile, normal growth recommenced (see figure 5.35).

From this observation, it was concluded that the substance causing growth was a water-soluble chemical that could diffuse from the coleoptile tip into the agar block and then diffuse downwards from the agar block into the cut end of a topless coleoptile. What is the control in the experiment shown in figure 5.35?

Agar is a firm jelly-like (gelatinous) substance.

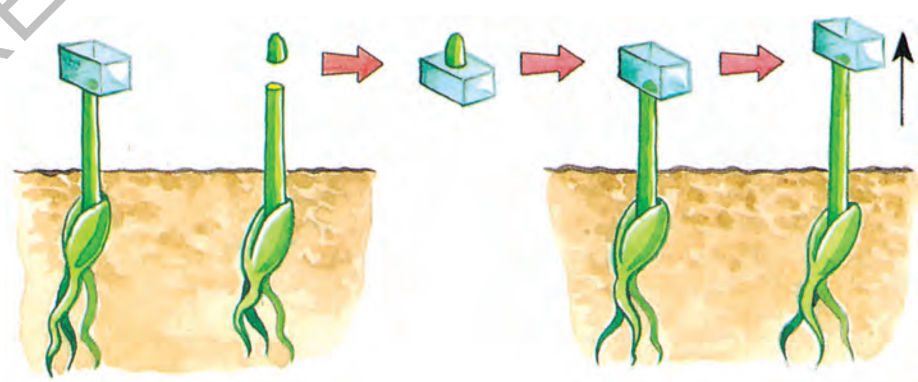


FIGURE 5.35 Experiment demonstrating that auxins are water-soluble chemicals produced in growing coleoptile tips and that auxins promote the elongation of cells in the region below the tip.

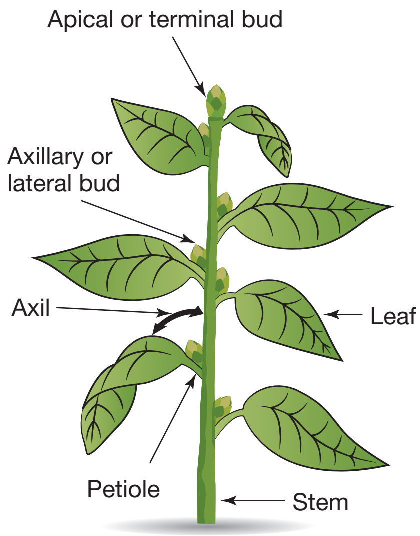


FIGURE 5.36 Diagram showing the types of buds (apical or terminal, and axillary or lateral) and their relative positions on a shoot.

ODD FACT

Apical dominance was one of the first developmental events in plants shown to be regulated by plant hormones. The experimental evidence is described in a classic paper by Thimann and Skoog (1934): *Proc R Soc London Ser B* volume **114**: pages 317–339.

Auxins in action

Let's now look at some specific actions of auxins in:

- apical dominance
- phototropism
- promotion of cell growth:
  - strawberries
  - adventitious roots.

Auxins and apical dominance:

Apical dominance is the control exerted by the shoot tip on the outgrowth of axillary buds. Figure 5.36 shows the positions and kinds of buds on a shoot. Apical dominance can be seen when lateral (axillary) buds on a stem close to the apex of a plant do not develop because of the presence of an actively growing terminal (apical) bud at the apex of a plant.

The principal auxin, indole acetic acid (IAA), is responsible for apical dominance. The IAA produced by cells of the terminal bud moves down the stem through the phloem and sends a signal to cells of the lateral buds that inhibits their growth. The auxin signal travels to target cells in the lateral buds. Receipt of this signal initiates a signal transduction pathway that produces a cellular response.

When apical dominance is strong, plants develop few, if any, lateral branches. What would be expected to happen to a plant when the terminal (apical) bud at the apex is removed (see figure 5.37)?

When the terminal bud at the apex is snipped off, the source of IAA is removed and lateral (axillary) buds lower down on the stem begin to develop. Why does this happen? The answer lies in the relative balance between signals from auxins and signals from another group of plant hormones, the cytokinins.

The removal of the terminal bud removes the major source of auxin. This means that the auxin signals ('Stay asleep') that have dominated the chemical communication to the lateral buds stop. Instead, signals from another group of plant hormones, the cytokinins, can now dominate. The cytokinin signals ('Start growing') stimulate the growth of lateral buds. By selectively pruning or removing growing tips with their terminal buds, gardeners can produce more bushy plants because more lateral buds develop into leafy shoots.

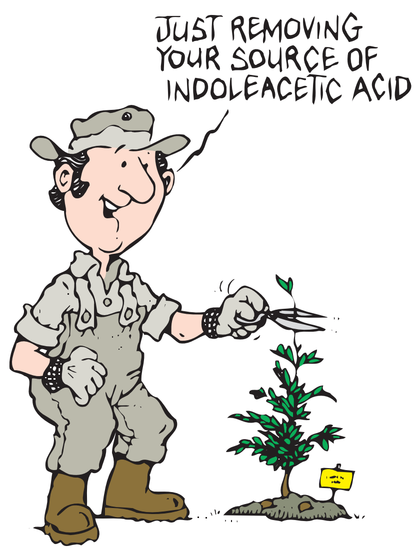


FIGURE 5.37

Auxins and trophic movements:

External factors, such as light, gravity and touch, exert an influence on plant growth and development. The growth of a plant in response to a stimulus such as light or water is called a **tropism**. When a plant grows towards a stimulus, the term *positive tropism* is used. Growing away from the stimulus is called *negative tropism*. Let's look at an example of the signalling that occurs when a plant shoot responds positively to the stimulus of light, an example of positive phototrophism.

In an early investigation of growing seedlings, Charles Darwin (1809–1882) and his son Francis found that they could prevent grass coleoptiles from bending towards the light by covering their growing tips (see figure 5.38). Darwin concluded that the tip of the seedling produced an 'influence' that passed from the tip to the region below the tip where bending occurred.

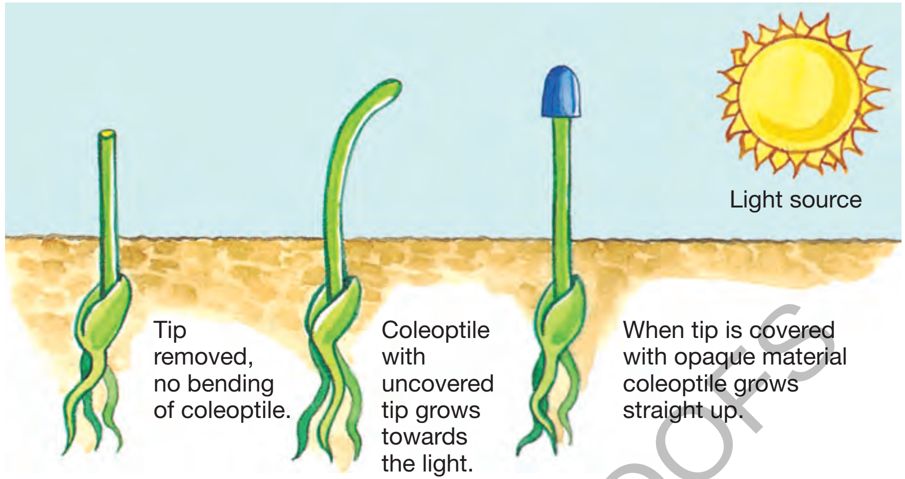


FIGURE 5.38 Growing coleoptiles bend towards a light source. Bending does not occur if the tip is shielded from the light. What conclusion can you draw from the observation that a coleoptile without its tip fails to respond to the light?

We now know that auxin, a plant hormone, is produced in the tip of a coleoptile and causes elongation of cells in the coleoptile. The tip is the site of reception of the light stimulus. Cells of the growing region below the tip are the effector or the target cells.

What causes a plant to bend towards a light? If a coleoptile is evenly illuminated, auxin is evenly distributed throughout the tip and the coleoptile grows straight up.

However, if light is concentrated to one side of a coleoptile, **the auxin moves away from the light source to the darker side and becomes more concentrated in cells in that region**. The increased concentration of auxin in the cells on the darker side causes these cells to elongate to a greater degree than cells nearer the light (see figure 5.39). The uneven growth of cells leads to bending of the coleoptile.

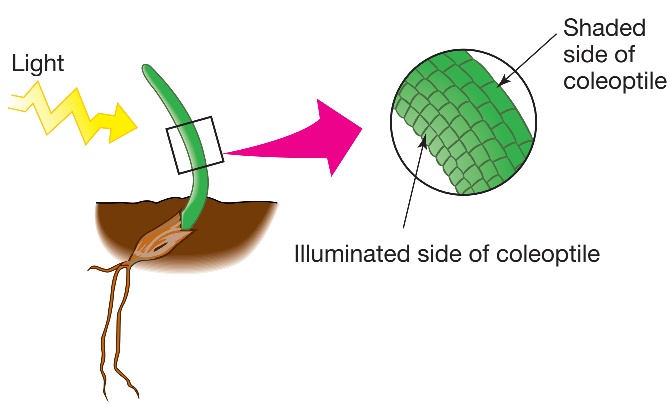


FIGURE 5.39 The distribution of auxin in cells controls the bending of a coleoptile. If light shines from one side, auxin moves to the shaded side and concentrates there. The higher concentration of auxin causes greater elongation of cells in that area (as compared to cells on the lighted side). The different rates of increase in cell size on each side of the shoot result in the bending of the coleoptile towards the source of light.

ODD FACT

Auxin activates an enzyme that loosens the structure of the cellulose in the cell wall. The reduced rigidity of the cell walls enables cells to bend more easily.

Auxins and cell growth: *1. Growth of strawberries.*
Figure 5.40 shows strawberries (at left) and a scanning electron micrograph of the surface of a strawberry (at right). Note the large ovoid shields that are commonly referred to as 'seeds'. The flesh of the familiar strawberry that we eat is an enlarged receptacle. The receptacle is part of the strawberry flower on which the 'seeds' form (see figure 5.40c). However, the 'seeds' on a strawberry are not true seeds. Each is a dry fruit, with the botanical name 'achene', and inside each achene is a tiny seed.

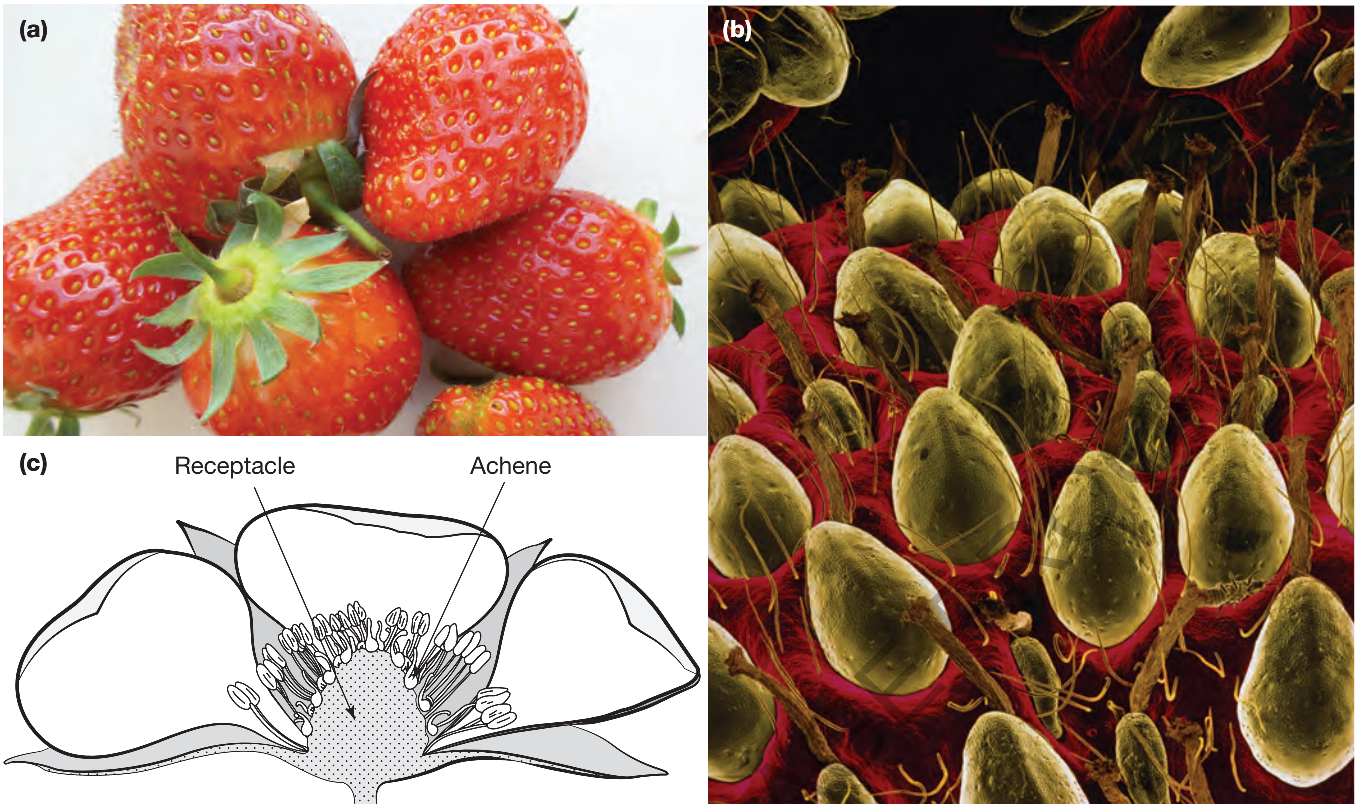


FIGURE 5.40 **(a)** Strawberries. (Image courtesy of Judith Kinnear.) **(b)** Scanning electron micrograph of the part of the surface of a strawberry showing the red flesh of the strawberry and the prominent ovoid-shaped 'seeds' or achenes. The brown tubular structures between the achenes are the styles and stigmas of the female reproductive organs. **(c)** Longitudinal section of a strawberry flower showing the receptacle with developing achenes on its surface.

ODD FACT

One medium-sized strawberry of most varieties has about 200 achenes. So, eat one strawberry and you are eating the strawberry receptacle along with several hundred strawberry fruits.

The achenes are a source of auxins. Refer to figure 5.41 to see the effect of auxin from the achenes on the development of the strawberry receptacle. The receptacle enlarges **only if the achenes are present on its surface and they release auxin signals for cell growth**. The size of a strawberry is directly proportional to the number of achenes on the receptacle.

FIGURE 5.41 Diagram showing the effect of auxin signals on the enlargement of the strawberry. What happens if 'seeds' are removed from the receptacle after flowering? What is the effect if auxins are applied directly to a small 'de-seeded' receptacle?

Auxins and cell growth: *2. Growth of adventitious roots*

Auxins at particular concentrations stimulate the growth of adventitious roots. Commercial rooting powders or solutions are used by gardeners to stimulate root growth in cuttings (see figure 5.42). These products are applied at concentrations of 500–1500 ppm for herbaceous and softwood cuttings, and at higher concentrations (1000–3000 ppm) for cuttings that have more woody tissues.

ppm = parts per million

FIGURE 5.42 A gardener dipping the stems of *Cistus* sp. (rockrose) cuttings into rooting powder prior to planting. Rooting powder contains auxin hormones that promote adventitious root development.

Plant hormones: cytokinins

Cytokinins are another class of growth-promoting hormones that act on shoots, roots and fruits. A common action of this class of hormone is to **promote cell reproduction**. Not surprisingly, high concentrations of cytokinins are found in plant tissues where cell reproduction is occurring at a rapid rate, such as in young, growing fruits.

Along with auxins, cytokinins are a major class of growth-promoting hormones that are important in the organised growth and development of plants. One of the most common cytokinins found in plants is called zeatin. (Zeatin was the first cytokinin to be isolated from plants, and was originally isolated from corn (*Zea mays*) in 1961.) A common action of this class of hormone is to promote cell division. Cytokinins are produced in roots and travel upwards to the shoots. Not surprisingly, high concentrations of cytokinins are found in plant tissues where cell division is occurring at a rapid rate, such as in the meristematic regions of roots, and in young, growing fruits.

Careful! Do not confuse plant cytokinins with mammalian cytokines. Cytokines are discussed earlier in this chapter (see page 183).

Cytokinins and adventitious shoots:

Cytokinins promote the production of adventitious shoots. The term 'adventitious shoot' refers to any shoot that develops in an unusual place, such as shoots that grow from leaves. Some plants, such as *Bryophyllum* sp., have meristematic tissue at notches along the edges of their leaves. This meristematic tissue can divide and give rise to adventitious shoots (see figure 5.43). The signalling molecules that stimulate the production of adventitious shoots are cytokinins that are present in cells at the leaf margins.

Meristematic tissue is located at the tips of stems and roots (= apical meristem), in the sides of stems and roots (= lateral meristem) and at the base of leaves and at internodes (= intercalary meristem).

FIGURE 5.43 A *Bryophyllum* sp. leaf showing the formation of adventitious shoots along its leaf margin, in response to signals from cytokinins.

Evidence of the role of cytokinins in stimulating shoot production came from a study of genetically engineered cytokinin-deficient plants. These plants developed stunted shoots, and their leaf production was just 3–4 per cent of that of normal plants.

Interactions between cytokinins and auxins: Cytokinins typically interact with auxins in plant growth and development. The effects of these two hormones on plant growth is complementary. One effect of cytokinins is to induce shoot formation, while that of auxins is to induce root formation. For example, the small adventitious shoots on the *Bryophyllum* leaf margin are formed in response to cytokinin signals. When these small shoots fall to the soil below, root formation occurs in response to auxin signals.

Another example of the interaction between cytokinins and auxins may be seen in the spread of blackberry bushes (*Rubus fruticosus*). Examine figure 5.44. Note that blackberry plants have long stems, called canes, that grow from the crown of the plant. When a blackberry cane forms an arch that touches the ground, auxins accumulate in the horizontal portion of the cane, and the signals from the auxin promote root development. In turn, the developing roots produce lots of cytokinins, and their signals induce shoot development — hey presto, a new blackberry plant. Daughter plants can be formed at the ends of canes up to 6 m from the crown.

study on

Unit 3	**Cytokines**
AOS 2	Summary screen and practice questions
Topic 1	
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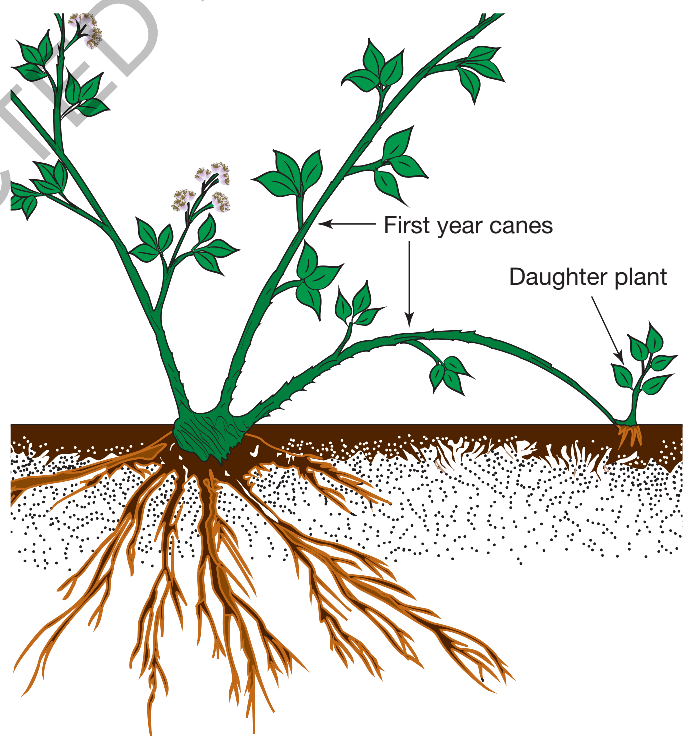


FIGURE 5.44 A blackberry plant can spread when its arching shoots touch the ground, each forming a new daughter plant that is a clone of the parent plant.

ODD FACT

Blackberry is a declared noxious weed in several Australian states, including Victoria.

COMMERCIAL USES OF PLANT HORMONES

Herbicides

Synthetic auxins can be produced in very large quantities in the laboratory. One common auxin, known as 2,4-dichlorophenoxyacetic acid (2,4-D), is used as a selective **herbicide** or weedkiller. This is possible because 2,4-D kills some plant species but not others. Among the susceptible plant species are many of the dicotyledonous noxious weeds. In contrast, monocotyledonous cereals and other grasses show little or no effect from 2,4-D. Crops or pastures where weeds are growing are sprayed, and the herbicide kills the weeds by disrupting normal growth.

Some weeds now have strains that are resistant to 2,4-D, so use of the herbicide in the future may become less effective. In addition, questions are being raised about the possible effects on people and other animals of the long-term use of such herbicides.

Hormones and tissue culture

Whole plants can grow from small cuttings. This is often done by keen home gardeners who take cuttings from favourite plants and propagate them.

When large numbers of plants with a particular genetic make-up or of particular economic importance are required, growth from cuttings or even from a small group of cells is carried out in the laboratory using special techniques. The technique of **tissue culture** or **cloning** (see 'Cloning plants from tissue culture' in *Nature of Biology Book 1 Fourth Edition*) can be used to obtain large numbers of plants in a relatively short time. Cloned plants are genetically identical to the plant from which the original cells were taken and so they have the same valuable genetically determined features present in the parent plant.

When small groups of unspecialised cells are used, they are sterilised and grown on agar in a test tube or other container (see figure 5.45). Each group is called a callus. The hormone cytokinin is added. High levels of cytokinin combined with relatively low levels of auxin result in the growth of shoots. The shoots on each callus are then treated with auxin, leading to a relatively high level of auxin and a relatively low level of cytokinin compared to the level previously. This results in the formation of roots.

Each callus, which started as a small group of cells, gives rise to a complete new plant. By this technique, many genetically identical plants can be quickly produced from the one parent plant.

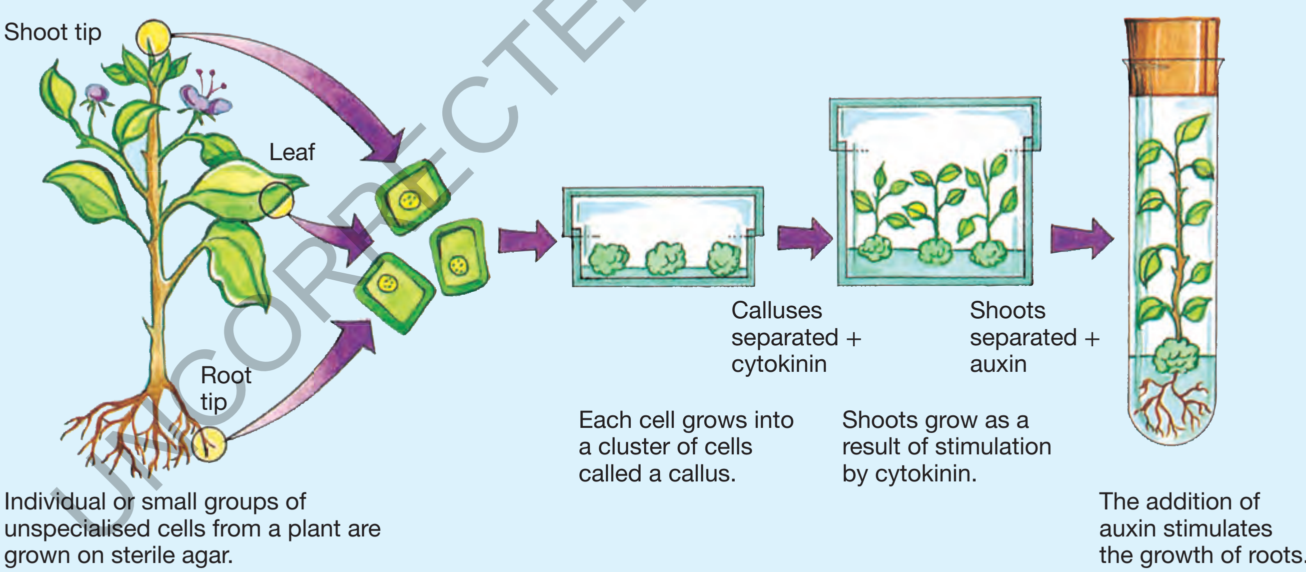


FIGURE 5.45 Plant hormones are used to promote growth when new plants are cloned from unspecialised cells.

Plant hormones: gibberellins

In 1926, some plants in rice crops growing in Japan were observed to be diseased. They were thinner and taller than normal and, instead of standing erect, these rice plants tended to fall over. This disease was called the 'foolish seedling' or bakanae disease. These abnormally tall plants had a fungal infection, and the fungus involved was the species *Gibberella fujikuroi*.

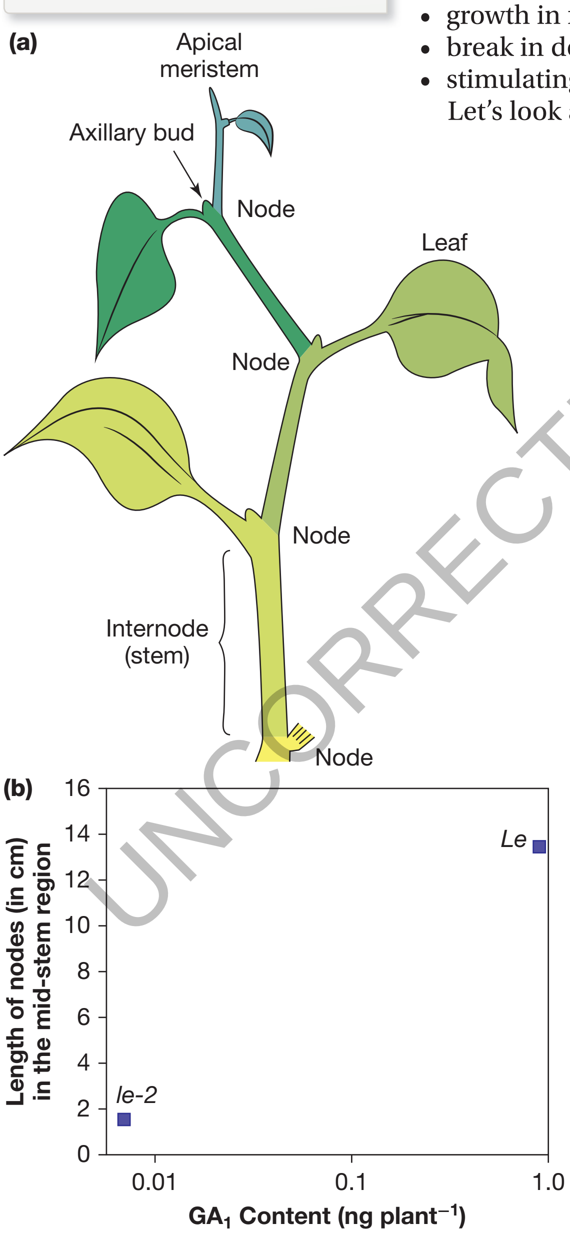
A Japanese scientist extracted many compounds from this fungus and identified one particular compound as the cause of the abnormal growth of the rice plants that made them tall and thin. The compound responsible for the increased height of the rice was named **gibberellin**, after the fungus from which it was isolated. Although the first gibberellin hormone was extracted from a fungus, many naturally occurring gibberellins have now been extracted from many plant species. The best known gibberellin is called **gibberellic acid (GA)**.

Gibberellins are growth hormones, produced by roots and young leaves, that act as signalling molecules for cellular responses including:

- stem growth
- growth in fruit size (in conjunction with auxins)
- break in dormancy of some seeds, promoting seed germination
- stimulating the development of seedless fruits.

Let's look at the results of some of these gibberellin signals.

FIGURE 5.46 **(a)** Diagram showing the nodes along a stem. Nodes are regions from where leaves and axillary buds develop. An internode is the region between two nodes. **(b)** Graph showing internode lengths in the mid-stem region plotted against total GA content of a tall plant (Le) and a dwarf plant (le-2). By what multiple does the GA content of the tall plant differ from that of the dwarf plant?



Gibberellins and stem growth:

1. Mendel's peas:

Gregor Mendel (1822–1884), an Augustinian monk in a monastery at Brno in the present day Czech Republic, is famous for his experiments with pea plants (*Pisum sativum*). One of the traits studied by Mendel was plant height, with pea plants being either tall or dwarf. Pea plants of the tall variety grow to heights of about 180 to 200 centimetres, while plants of the dwarf variety grow to a height of 30 centimetres.

While Mendel solved the mystery of how these traits were inherited, it was not until 1997 that the underlying cause of dwarfness in pea plants was identified. In 1997, scientists demonstrated that the dwarf condition in pea plants was due to a defect in a particular gene. This gene encodes the enzyme needed to convert an inactive precursor of gibberellic acid into active gibberellic acid (GA). GA is the signalling molecule that carries the messages to stem cells in the internode region to divide and to elongate. In the dwarf plant, this enzyme is missing, resulting in the lack of GA signalling to the cells in their stem. The role of GA in stem elongation was confirmed when it was observed that spraying dwarf plants with GA caused them to grow to normal height.

Both tall and dwarf plants have the same number of nodes (and hence internodes) in their stems (see figure 5.46a). The difference between them is that the internode distance (distance between nodes) is much greater in tall plants than in dwarf plants (see figure 5.46b). The increase in internode distance is a result of GA signals to stem cells. These signals carry messages for both cell division and cell elongation of stem cells in the internode region.

Gibberellins and fruit size:

Gibberellins have several uses in agriculture. One example is the treatment of developing clusters of seedless grapes with gibberellic acid (GA). Treatment with GA typically involves spraying when the grape diameter is 3 to 5 mm. This treatment increases the size of individual grapes by a factor of two or three (see figure 5.47) by stimulating the division and the enlargement of individual cells, producing an overall increase in grape size. Interestingly, GA has little or no effect on seed-containing grapes.

FIGURE 5.47 Clusters of seedless crimson table grapes. The cluster at the left was sprayed with gibberellic acid (GA) while the cluster at the right was not treated. Note the difference between the sizes of individual grapes in the two bunches. (Image courtesy of Stephen Vasquez and Matthew Fidelibus, UC Cooperative.)

ODD FACT

Botanically speaking, a grape is a berry. Breeding programs have selected grape plants that naturally produce large berries. This means that many newer cultivars require less GA to attain optimal berry size as compared to older cultivars.

Gibberellins and leaf shape:

Some species of plants, including *Eucalyptus* species, have two leaf forms — juvenile leaves and adult leaves. These two types of leaf have distinctly different shapes (see figure 5.48).

A gibberellin signal promotes the development of branches with juvenile-type leaves; these branches cannot produce flowers. In the absence of gibberellins, branches with adult leaves form, and these branches are able to produce flowers. What would you predict would happen if buds on an adult branch were sprayed with gibberellic acid?

FIGURE 5.48 Distinctly different adult (right-hand side) and juvenile leaves (left-hand side) on the same species of *Eucalyptus*. The presence of gibberellins promotes the development of branches with juvenile-type leaves. Branches with adult leaves form on the same tree in the absence of gibberellins. (Image courtesy of Judith Kinnear.)

Gibberellins in seed germination:

Germination is the growth of a plant that is enclosed within a seed. Enclosed within the seed coat are the plant embryo and its energy store, the endosperm (see figure 5.49). In the seeds of cereals, such as wheat, oats and rice, this energy store is predominantly in form of starch — for example, starch comprises about 60–70 per cent of the whole grain. In addition to starch, the seeds of some plants also have significant oil stores in their endosperm.

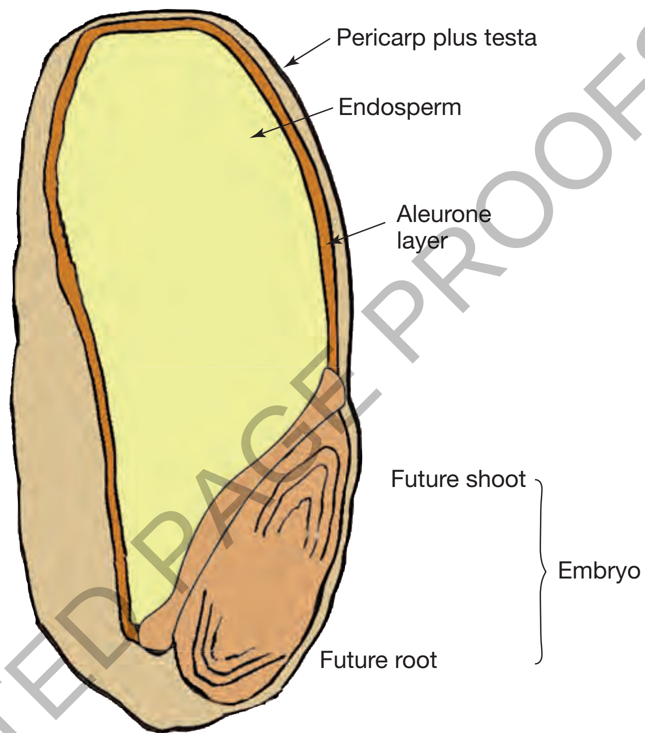


FIGURE 5.49 Diagram showing a longitudinal section through a grain of wheat (*Triticum aestivum*). Note the embryo in the lower right-hand corner and the endosperm, which is an energy reserve mainly in the form of starch. The outer seed coats form wheat bran, and the embryo is wheat germ.

ODD FACT

The oil content of small grains, such as wheat seeds, is around one per cent, while that of oil seeds ranges from about 20 per cent for soybeans to more than 40 per cent for the seeds of sunflower and canola.

At the cellular level, plant hormones produce signal transduction pathways in much the same way as that occurring in animal cells. For example, consider the germination of a grain of wheat (figure 5.50).

- When water enters a seed, cells of the plant embryo release gibberellic acid (GA), which diffuses to the aleurone, the layer of cells that surrounds the starchy endosperm.
- The GA binds to a specific receptor on the plasma membrane of aleurone cells; this is a G protein coupled receptor.
- The binding of GA to the receptor starts the signal transduction pathway.
- The end result of the signal transduction pathway is the activation of a gene that encodes the instructions for the enzyme α-amylase. α-amylase is an enzyme that breaks down starch.
- α-amylase is secreted from the aleurone cells into the endosperm where it catalyses the breakdown of starch molecules into their glucose sub-units. The glucose molecules then diffuse to the embryo and provide it with an energy source for the initial stages of growth of a new plant.

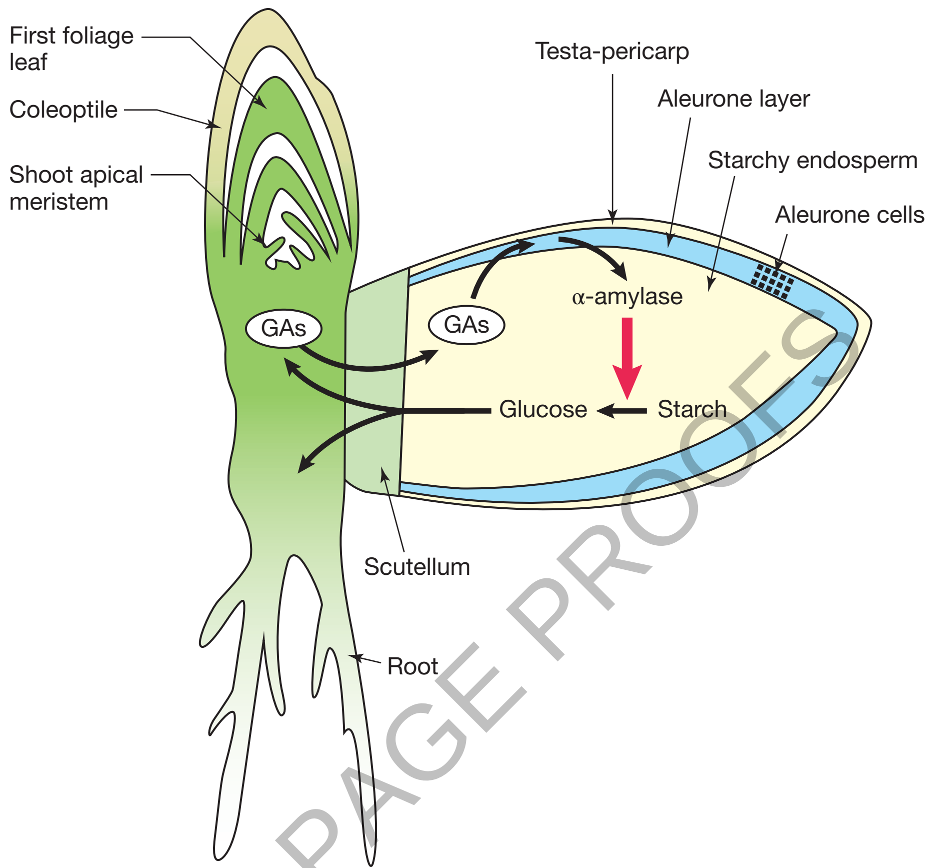


FIGURE 5.50 Diagram of a longitudinal section (LS) through a grain of wheat (at right-hand side) with an LS of an enlarged embryo (at left-hand side). Normally the embryo occupies the lower portion of the seed as shown by the light-green shading. The stimulus to start the release of gibberellins (GAs) from embryonic tissue is the entry of water into the seed.

ODD FACT

Ethylene is produced by many fruits, including apples, pears, bananas, avocados, and tomatoes as they ripen, but not by cherries, grapes or citrus fruit.

Plant hormones: ethylene

In the mid-nineteenth century, unusual changes were observed in plants growing near street gas lamps. These changes, such as the thickening and twisting of stems and premature leaf loss, were not seen in the same kind of plants growing in areas away from the gas lamps. Further investigation showed that the gas lamps concerned were leaking gas, and this suggested that something in the gas was causing the changes in the plants. In 1901, the active component of the gas was identified as ethylene.

However, it was not until 1934 that the first evidence was produced that plants could synthesise ethylene. It is now known that ethylene is produced from the amino acid methionine in almost all the tissues of higher plants.

Ethylene interacts with other hormones to influence special events in the life cycle of a plant, including the ripening of fruit and the autumn drop of leaves. Let’s look at these two events.

Ethylene and fruit ripening

Young bananas are green. If left on the plant, they eventually ripen and turn yellow. The ripening of bananas is stimulated by a signal from ethylene that **increases the rate of respiration** of the banana cells (see figure 5.51).

Under natural conditions, bananas in the same bunch can be at different stages of ripening. However, if some are over-ripe while others are still unripe, this reduces their commercial value.

FIGURE 5.51

A hand of bananas comprises a few bananas joined together. A bunch of bananas consists of many hands of bananas.

For marketing purposes, the ripening of bananas is controlled and synchronised. Bananas are picked while still green but sufficiently mature to ripen after they have been picked. If picked too young, bananas remain green and are generally unpleasant to taste. After picking, mature green bananas are kept under conditions of controlled humidity and temperature and in an atmosphere to which ethylene gas is added at a concentration of 100 μL/L. Under these conditions, uniform ripening of the fruit occurs and bananas in the same bunch ripen synchronously (at the same time).

After they are picked, bananas sometimes need to be kept for some time. How should they be stored? For maximum storage life, bananas are vacuum packed in plastic bags containing material that absorbs ethylene. This method of storage extends the life of the bananas because any ethylene gas produced by the bananas is absorbed and is unavailable to cause ripening of the fruit. In addition, the plastic used for these bags has a low permeability to oxygen. As a result, oxygen is not freely available for the living cells of the fruit and the cellular respiration rates are low.

Through controlled atmosphere storage methods, some fruits that are naturally available only during certain seasons can be made available over longer periods of the year. Are you aware of other fruits that are stored under controlled atmosphere conditions? Can you suggest what the label on a box of 'Controlled atmosphere apples' means?

Ethylene and leaf drop

In September 2008, the scientific journal *PNAS* included a paper titled: 'Regulation of floral organ abscission in *Arabidopsis thaliana*'. Not an attention-grabbing title! However, a summary of this research appeared in a prominent UK newspaper, *The Telegraph*, under the snappier headline: *'Why leaves fall off trees is discovered.'* This research paper was of great interest because it correctly identified ethylene as the plant hormone with a major role in regulating the fall of leaves (see figure 5.52). Previously, this role had been assigned to the plant hormone abscisic acid.

FIGURE 5.52 The fall of leaves from deciduous trees in autumn is regulated by signals from the plant hormone, ethylene.

The separation of a part of a plant, such as a leaf or a flower or fruit from its parent plant, is called **abscission**. Autumn is a time of the year when deciduous trees lose all of their leaves. Before a leaf falls, a special zone called the **abscission zone** forms at the base of the leaf stalk (petiole). **Fruits and flowers have similar abscission zones** in their petioles (see figure 5.53).

Figure 5.54 below shows the abscission zone in a leaf petiole. Note that the abscission zone contains two layers of cells:

1. The separation layer: this multi-layer of cells across the base of the leaf stalk (petiole) marks the end point of the leaf that will fall, either when blown off by the wind or under the influence of gravity. The cells of the separation layer have thin cell walls weakened by the action of cellulase, an enzyme produced in response to an ethylene signal. A split in the separation layer spreads until finally the leaf is either blown away or falls.
2. The protective layer: these cells form a seal that protects the plant against the entry of microbes and against water loss. The cell walls in the protective layer contain suberin, a waxy waterproof substance. Expansion of the protective layer produces a tear in the weakened cells of the separation zone so that this layer splits and separates from the plant.

FIGURE 5.53 Isaac Newton assigned the fall of the apple to gravity. Gravity, yes, but with a little assistance from the plant hormone ethylene.

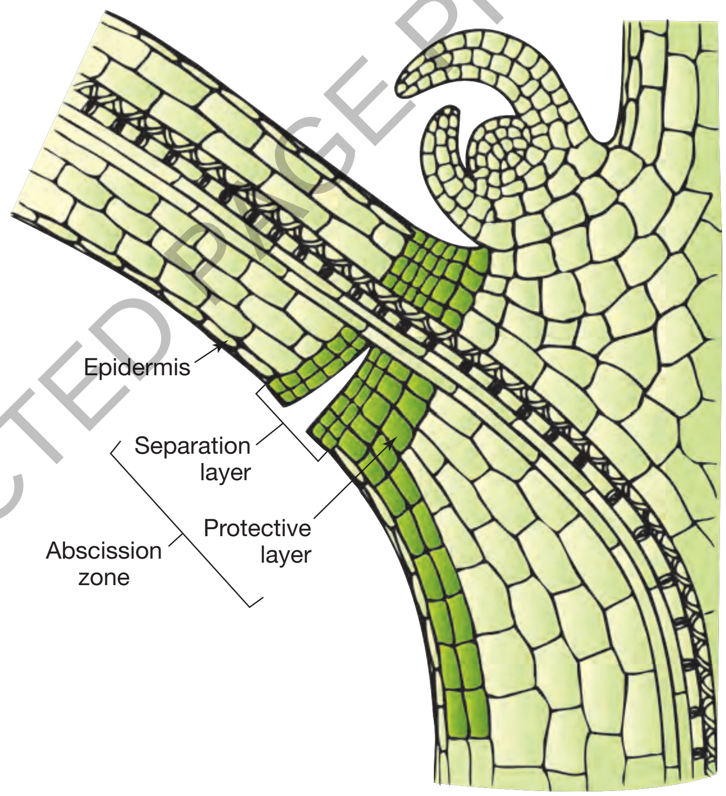


FIGURE 5.54 Abscission zone in a leaf stalk (petiole). Separation of a leaf from the plant occurs across the abscission zone at the base of the leaf stalk or petiole. What is the function of the protective layer? Can you identify the curved structure above the abscission zone?

Abscission is important for plants because it provides a means by which a plant can discard non-functional organs, such as leaves in autumn, or infected organs. In addition, abscission of fruit assists in the dispersal of the seeds, which are the next generation of the plant.

Ethylene and flower senescence

A flower on a plant may be dying at the same time as another flower is forming on the same plant. A flower dies because the petals die. Studies on picked carnations show that petals die because there is an increase in ethylene produced by the plant (see figure 5.55). What is the level of ethylene production by a carnation flower three days after it is cut? What is the level six days after it is cut?

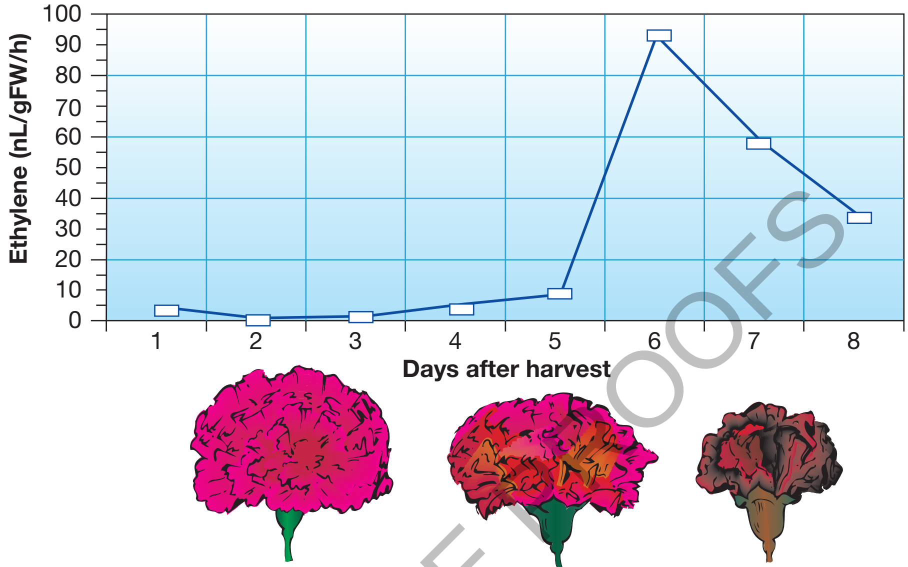


FIGURE 5.55 Ethylene production by harvested carnation flowers. Initially, a cut carnation flower produces very little ethylene. As the amount of ethylene produced increases, the petals begin to curl and die. By about the eighth day after being cut, the flower is in an advanced stage of death.

The less ethylene produced by a carnation, the longer the cut flower lives. Genetic engineering experiments have produced a carnation in which the production of ethylene is blocked. This delays the death of flower petals and increases the life of the cut flower. This reduces the need to use environmentally hostile chemicals to extend the life of cut flowers.

Plant hormones: abscisic acid (ABA)

Abscisic acid (ABA) is sometimes called the stress hormone. When conditions become unfavourable, as in freezing conditions or in drought, animals may migrate to more favourable conditions. This is not an option for plants, which, instead, must depend on other strategies to survive. For plants, the hormone ABA is a key mediator in plant responses to unfavourable conditions. Let's look at two examples of ABA in action.

ODD FACT

Abscisic acid (ABA) has this name because scientists originally thought that ABA was the signal for the abscission (fall) of leaves and fruit. It is now known that the hormone ethylene is the main signalling molecule for abscission, but the abscisic acid name was retained.

ABA: Inducing dormancy

Signals from abscisic acid (ABA) inhibit growth and induce dormancy in leaf buds and seeds during periods of short day length and low temperatures. Abscisic acid signals are important in preventing the growth of leaves and the germination of seeds during periods when the delicate tissues of new leaves and seedlings would be at risk of being killed by freezing conditions. When days lengthen and temperatures rise, ABA concentrations fall and ABA signals decrease. At the same time, gibberellic acid concentrations rise and GA signals increase. As a result, dormant buds sprout, producing new leaves, and dormant seeds begin to germinate.

ABA: Closing stomata

Plants lose most of the water taken up by their roots through their **stomata** (singular = stoma). Each stoma consists of two guard cells. If the guard cells are flaccid, the stomata are closed; if the guard cells are turgid and swollen, the stomata are open and water will be lost from a plant (see figure 5.56).

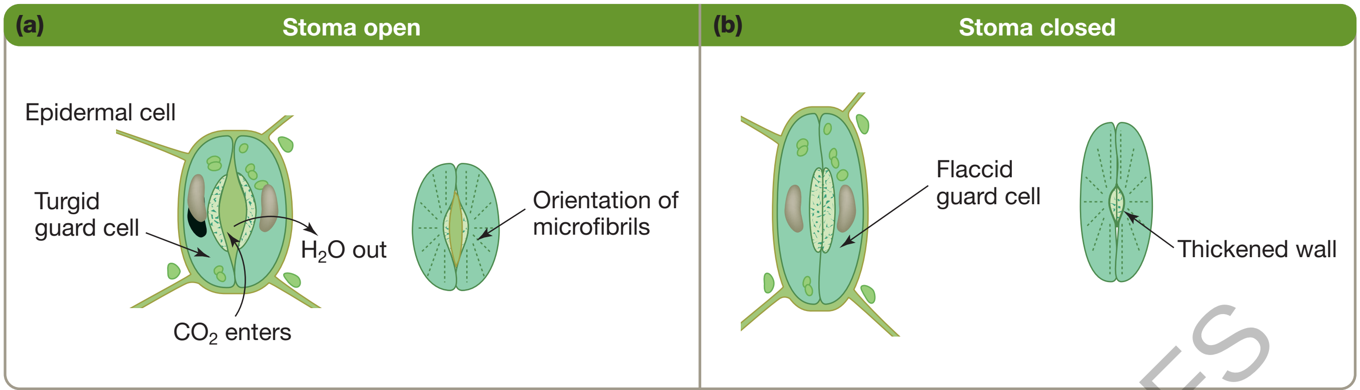


FIGURE 5.56 Diagram showing stomata. **(a)** Open stoma with turgid guard cells that allow water loss through the central pore. **(b)** Closed stoma with flaccid guard cells prevent water loss.

In drought conditions, survival of a plant depends on stopping this water loss. Under drought conditions, plants produce and accumulate abscisic acid (ABA) in their leaves. Signals from ABA lead to the closing of stomata, so preventing the major source of water loss from a plant.

The signal pathway by which ABA leads to closing of stomata may be summarised in simple terms as follows:

ABA molecules bind to receptors at the surface of the plasma membrane of the guard cells.

This sets up a signal transduction pathway that leads to a net loss of ions from the guard cells.

The loss of these solutes from the cytosol of the guard cells reduces the osmotic pressure inside those cells, with the result that the cytosol no longer exerts an outward pressure on the cell walls of the guard cells because the guard cells are no longer turgid (swollen) and the stomata close.

Other plant hormones

The first plant hormones to be recognised were the auxins. In addition to the classical plant hormones, other plant hormones have been identified, including some plant hormones that act as signalling molecules when plants come under attack by herbivores. Herbivore attack may come from sap-sucking or leaf-eating insects at their larval or adult stages, or from the leaf-eating activities of grazing or browsing mammals (see figure 5.57).

FIGURE 5.57 **(a)** Damage to leaves by the feeding activities of insect larvae can be extensive. Here we see the damage to a leaf from the eating activities of caterpillars. **(b)** A gerenuk or Waller's gazelle (*Litocranius walleri*) feeding on leaves of an acacia tree in shrubland in Kenya.

Jasmonates: defence against herbivores

One group of plant hormones known as **jasmonates (JAs)** plays a key role in plant defence against herbivores. JAs, such as methyl jasmonate, are produced by a plant in response to wounding or attack by herbivorous animals and build up in damaged areas of the plant. When JA molecules bind to their specific receptors, this starts a signal transduction pathway leading to the expression of response genes that encode production of a range of defensive chemicals.

These defensive chemicals include enzymes that interfere with leaf digestion. For example, tomato plants that come under insect attack produce a proteinase inhibitor that interferes with the insects' digestive processes. This interference presumably discourages these insects from eating that type of plant again.

Other examples include defence chemicals that attract predators or parasites of the attacking insects, as for example:

- Lima bean plants are often attacked by spider mites. When under attack from spider mites, lima bean plants produce a chemical that attracts a predator that preys on spider mites.
- Corn plants, when attacked by caterpillars, produce a volatile chemical that attracts a parasitoid wasp that lays its eggs in the caterpillar.

Some JAs are volatile compounds that readily evaporate into vapour form. Remarkably, these volatile compounds act as signalling molecules *not only* for the plant that produces them *but also* for other plants of the same species. JA vapours can spread downwind through the air from insect-damaged plants to neighbouring unharmed plants. The JA vapours enter leaf cells of neighbouring plants, either through the stomata or by diffusion. JAs enable communication between plants so that unharmed plants are primed in advance for defence against a herbivore attack.

KEY IDEAS

- Plant hormones are signalling molecules involved in all processes of plant growth and development.
- Signals from plant hormones are transmitted through signal transduction pathways to the nucleus.
- The classic plant hormones are auxins, cyokinins, gibberellins, ethylene and abscisic acid.
- Plant hormones result in signal transduction pathways in plant cells in much the same way as mammalian hormones in mammalian cells.
- Each plant hormone has different target cells and induces one or more specific cellular responses.

QUICK CHECK

23 Identify the plant hormone that is a major signalling molecule in:
  a the fall of leaves
  b the growth of adventitious roots
  c the closing of leaf stomata in drought conditions
  d the growth of lateral buds
  e apical dominance
  f bending response to light.

24 Check back on the signal transduction pathway in wheat seeds (figure 5.50).
  a What is the signalling molecule?
  b Where is the receptor for this signalling molecule located?
  c Name the protein produced by the cellular response to this pathway.
  d What is the function of this protein?

25 What is a key difference between the members of the following pairs:
  a the separation layer and the protection layer in the abscission zone of a leaf
  b an apical and an axillary bud?
26 What plant hormone signal is absent in dwarf pea plants?
27 List the cascade of signal transduction events when gibberellins are activated in a wheat seed.

ODD FACT

An adult loses an estimated 30 000 epidermal skin cells every minute. Don't panic. These lost cells are replaced at the same rate by new skin cells.

ODD FACT

The term *apoptosis* was introduced in 1972 and comes from the Greek *apo* = from, and *ptosis* = falling, which refers to the process of leaves falling from trees or petals from flowers.

Apoptosis: programmed cell death

At any time, the cells in many organs and tissues of our bodies are in a state of turnover — old cells are dying and new cells are being formed. This turnover is happening, for example, in cells that form the lining of the gut, in cells of the epidermis of the skin, in cells of hair follicles, in cells of bone and in cells of the blood. In adults, the rates of the two processes are closely related so that, normally, a balance exists between the rate of new cell production and the rate of cell loss; that is: **rate of cell renewal = rate of cell death**. This balance keeps the number of cells relatively constant in adults. What would you predict about the situation in a growing child?

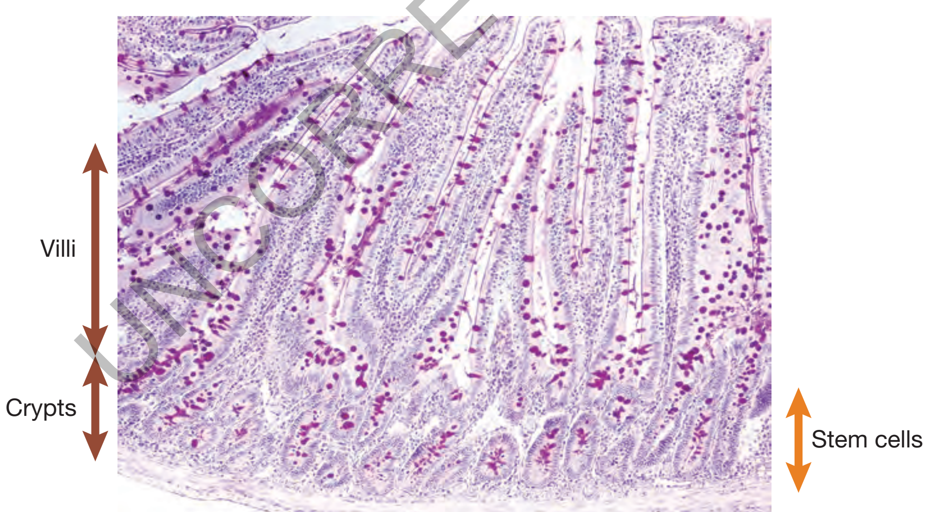
The process known as **apoptosis** or **programmed cell death** is a genetically controlled and highly regulated process of cell self-destruction. Apoptosis plays an essential role in ensuring that a balance exists between cell production and cell loss. It may seem strange at first, but programmed cell death is a normal healthy process in cells.

The rate of cell loss and replacement varies between different tissues. For example, the epithelial lining of the small intestine consists of a single layer of cells that is completely replaced every four to five days. Over this period, an entire layer of cells progressively dies and is replaced by new cells. The replacement of the intestinal lining involves two processes:

(i) the production of new cells deep in infoldings (crypts) of the intestine (see figure 5.58a). Production of these new gut lining cells is by mitotic divisions of stem cells located in the crypts.

(ii) the death of cells at the tips of the intestinal villi by apoptosis or programmed cell death (see figure 5.58b).

(a)



(b)

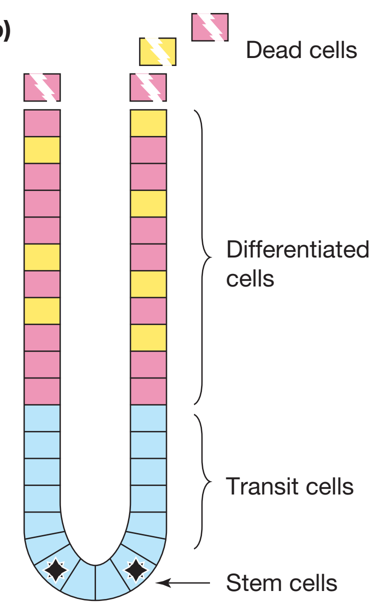


FIGURE 5.58 **(a)** Longitudinal section through the small intestine showing the deep infoldings (crypts) and the upward projecting villi (singular = villus). **(b)** Diagram showing the progression of cells from their production by stem cell mitosis in the crypts, to their death by apoptosis at the tips of the villi.

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Unit 3
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See more
Apoptosis

In apoptosis, the death of cells occurs in a highly regulated sequence in response to specific signals received by the 'condemned' cell. The signal pathway of apoptosis brings about the planned death of various cells including:

- *Cells at the end of their natural life* (such as gut lining cells, as described above, and skin cells)
- *Dysfunctional, damaged or diseased cells*
  - Cells infected with a virus may be eliminated by apoptosis. The programmed death of these cells prevents the virus from replication and spreading to other cells (see chapter 7, page 323).
- *Excessive cells*
  The programmed removal of excessive cells by apoptosis is important in many contexts:
  - Every day, the bone marrow produces millions of new immune cells (white blood cells) and red blood cells. Over the same period, this production of new cells must be balanced by the loss of a similar number of cells. This is achieved in an orderly manner through apoptosis.
  - During embryonic development, the final shaping of organs depends on the programmed cell death of excess cells. This process is seen, for example, in the reshaping of the embryonic limb buds of mammals into digits. Figure 5.59 shows the role of apoptosis in digit formation in a human embryo. This process starts at about week four of embryonic development with the formation of a paddle-shaped limb bud. This is followed by the appearance of five ridges on the limb bud. The cells in the valleys between these ridges are progressively removed by programmed cell death, making the valleys deeper. By week eight, a structure with five distinct digits is clearly visible, the 'webbing' between the digits having been removed by apoptosis.
  - During the body's response to infection, immune cells are produced in larger numbers than required. These excess cells are removed by apoptosis.
  - During the development of the normal brain, enormous numbers of cells are formed, but only those that make the best neural connection are retained. Those cells not selected are culled by apoptosis.

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Unit 3
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Concept 9

Apoptosis
Summary screen and practice questions

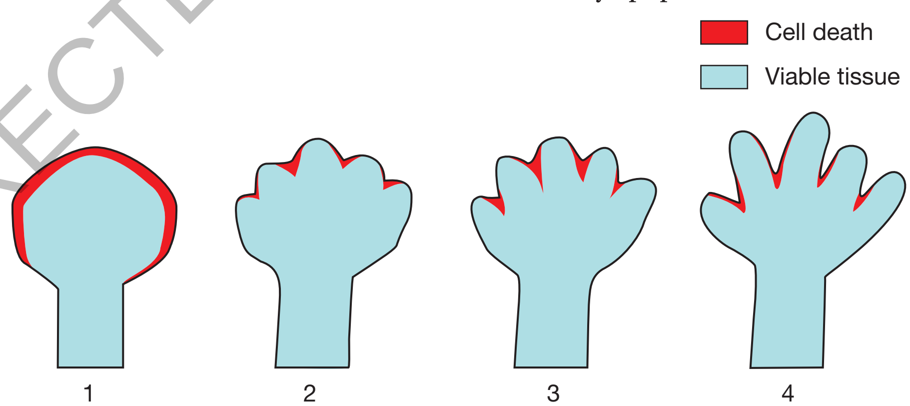

FIGURE 5.59 Diagram showing the development of digits in a human embryo. The process starts with (1) a paddle-like limb bud and (2) the appearance of five ridges on the outer edge of the limb bud. (3) Apoptosis or programmed cell death continues in cells in the valleys (shown in red) so that the valleys become deeper. (4) By the eighth week of embryonic development, the five digits are well separated.

As well as programmed cell death (apoptosis), body cells may die by a process known as necrosis. **Necrosis** is unplanned cell death such as that occurring when cells suffer trauma and die prematurely. Necrotic cell death occurs when cells suffer mechanical damage or chemical trauma, thermal burns, frostbite (such as that occurring when the fluid in cells freezes and crystallises, rupturing their plasma membranes) and oxygen deprivation (such as that occurring in cardiac muscle cells when the flow of oxygen-rich blood is blocked during a heart attack). In uncontrolled necrotic cell death, the dying cells swell, their plasma membranes rupture and their cell contents pour out into the surrounding tissue, causing local inflammation. If an extensive volume of cells undergoes necrotic cell death and the blood supply is cut off, a condition known as gangrene can develop.

Check out figure 5.60, which shows a foot that has suffered frostbite. The blood supply to the ends of the toes has been destroyed and the cells have undergone necrotic cell death, releasing their contents and causing cell damage. Gangrene has developed, as shown by the blackened tissue. This tissue is permanently damaged and will not recover. In cases of severe frostbite, the affected areas may need to be amputated.

FIGURE 5.60 Frostbite of the toes. The blackened tissue has been deprived of its blood supply, and the cells have undergone necrotic cell death.

See figure 5.61 below for a diagrammatic comparison showing the differences in cell death between apoptosis and necrosis.

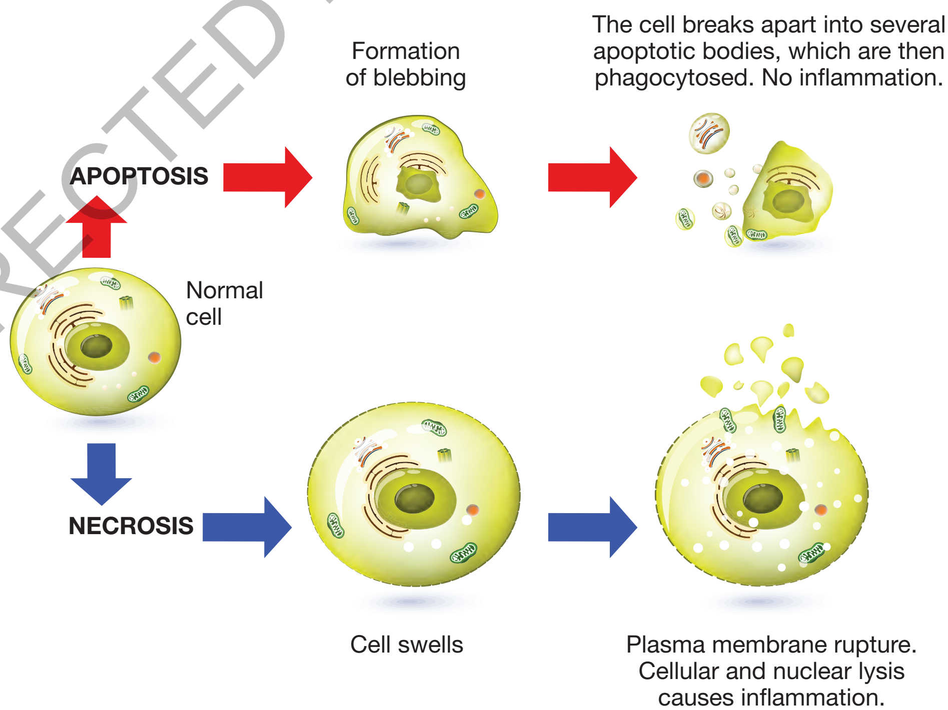

FIGURE 5.61 Diagram showing differences in cell death by apoptosis and by necrosis. Death by apoptosis is an orderly process in which the cell is dismantled into apoptotic bodies that are engulfed by phagocytic cells. In necrosis, the plasma membrane bursts and the cell contents are spilled to the exterior, resulting in inflammation.

Cell changes in apoptosis

An animal cell undergoing apoptosis shows characteristic physical changes: the cell shrinks, its plasma membrane forms bubbles or 'blebs', the nucleus and cytoplasmic organelles condense and fragment, and the cell breaks up and its contents form into parcels called **apoptotic bodies** (see figure 5.62). Apoptotic bodies contain remnants of nuclear and cytoplasmic materials and they are engulfed by nearby phagocytic cells. This process prevents damage to surrounding cells and also enables efficient recycling of macromolecules.

The process of phagocytosis is detailed in chapter 7, page 291.

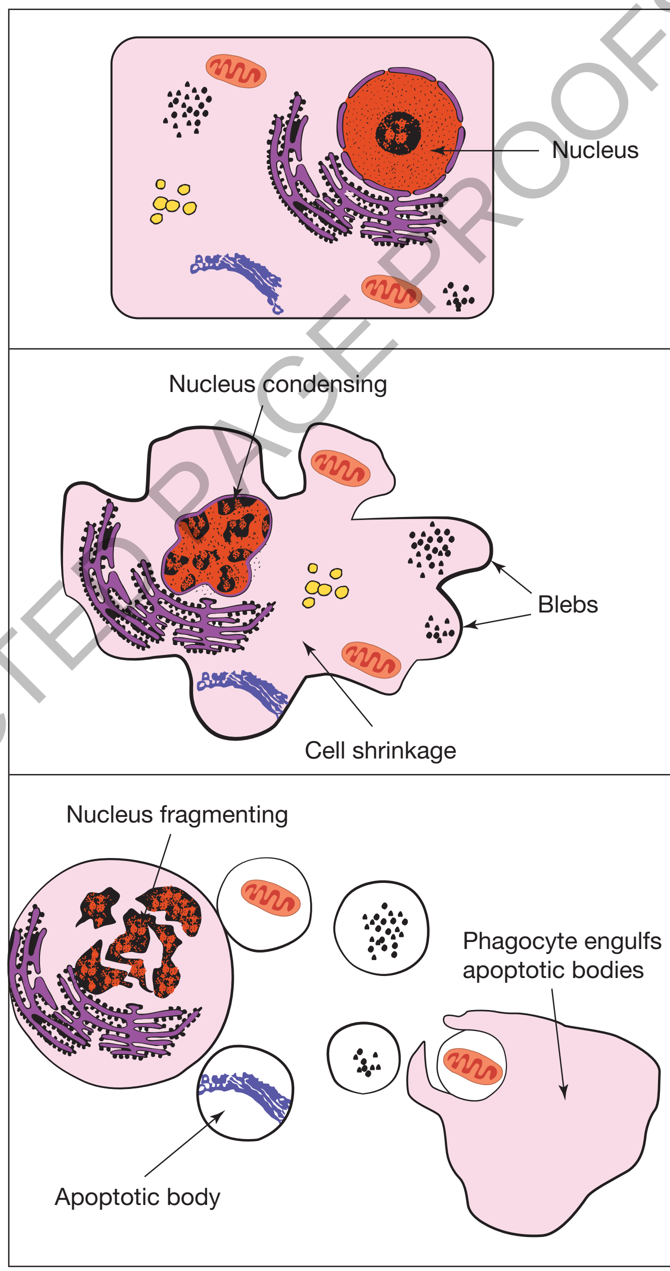

FIGURE 5.62 Programmed cell death or apoptotic cell death. Note how the various cell components are broken down and packaged into apoptotic bodies that are engulfed by phagocytic cells. The removal of dying cells by phagocytes occurs in an orderly manner without producing the inflammatory response that occurs in necrotic cell death.

Figure 5.63 is a scanning electron micrograph (SEM) of lymphocytes (white blood cells) undergoing apoptosis. Note the blebs on the plasma membrane, which are one of the distinctive physical changes that can be seen in cells undergoing apoptosis.

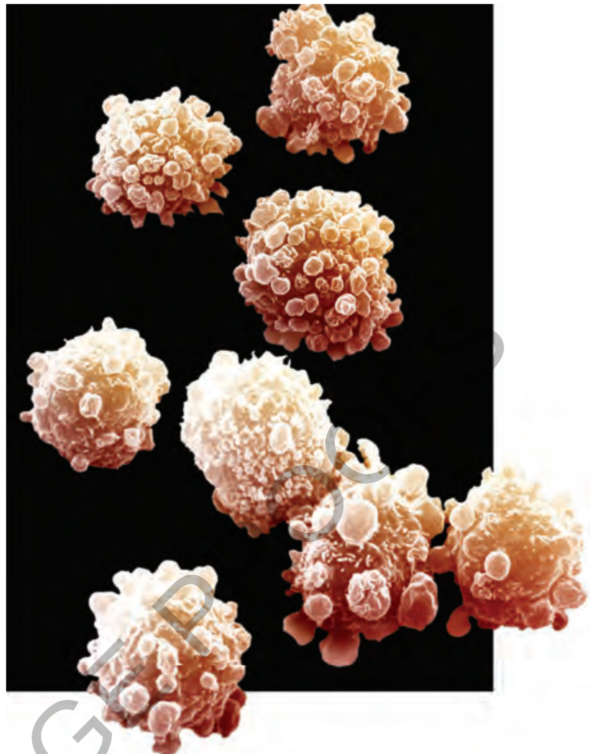

FIGURE 5.63 White blood cells or lymphocytes undergoing apoptosis. The clue that these cells are undergoing programmed cell death is the presence of many blebs on their plasma membranes.

Apoptosis pathways

Apoptosis can be initiated by one of two signal pathways:

1. the intrinsic pathway or mitochondrial pathway, initiated from within a cell
2. the extrinsic (outside-the-cell) pathway or death receptor pathway, initiated by factors external to the cell.

In both the intrinsic and the extrinsic pathways, a family of protease enzymes, known as **caspases**, drives the apoptotic death process. Caspases are present in cells in an inactive form, called procaspases. When activated by the removal of a small part of their molecular structure, procaspases are converted to caspases that are functional enzymes. Once activation of the first caspases starts, this sets in train a cascade of reactions that produces more caspases. This cascade can neither be stopped nor reversed.

Caspases are a family of cys protease enzymes that can cleave proteins at a particular amino acid residue (asp) near their active sites. The name, caspase, comes from **c**ys and **asp**art**ase**.

The intrinsic apoptosis pathway (or mitochondrial pathway):

The intrinsic apoptosis pathway is also known as the mitochondrial pathway because it depends on factors released from the mitochondria. The mitochondria are important in determining how and when damaged and stressed cells recognise that it's time to die.

On occasion, cells come under stress resulting from factors such as DNA damage, viral infection, hypoxia, ultraviolet radiation, and deprivation of growth factors. Cellular stresses cause the cells concerned to activate the intrinsic (mitochondrial) pathway of apoptosis and kill themselves. For the organism concerned, the decision by its stressed cells to commit suicide by apoptosis is beneficial. Virus-infected cells, for example, remove themselves before the infection worsens and spreads, and this is done without damage to neighbouring cells such as would occur if stressed cells underwent necrotic cell death and released the virus particles.

When the intrinsic apoptosis pathway is activated, pores form in the outer membranes of the mitochondria of the cell concerned. These pores allow the release of cytochrome c from the mitochondria into the cytoplasm. (You may recall from chapter 4 that cytochrome c in mitochondria is an electron acceptor in cellular respiration.) In the cytoplasm, however, cytochrome c forms aggregates with other compounds and this activates caspase-9, the initiator caspase. (Activation chops a fragment from inactive pro-caspase-9 molecules, converting them to active caspase-9 enzymes.)

Active caspase-9 then activates other caspases (caspase-3, -6 and -7) that are the executioners. These executioner caspases then systematically dismantle the cell by fragmenting its DNA, cleaving the proteins of its nuclear envelope, cleaving the proteins of its cytoskeleton and Golgi complex. (What might cause the blebs to appear?) By the end, the executioner caspases have cleaved hundreds of proteins, and the cell contents have been dismantled into packages (apoptotic bodies) that are removed by phagocytic cells.

Figure 5.64 shows a highly simplified diagram of the intrinsic (mitochondrial) apoptosis pathway.

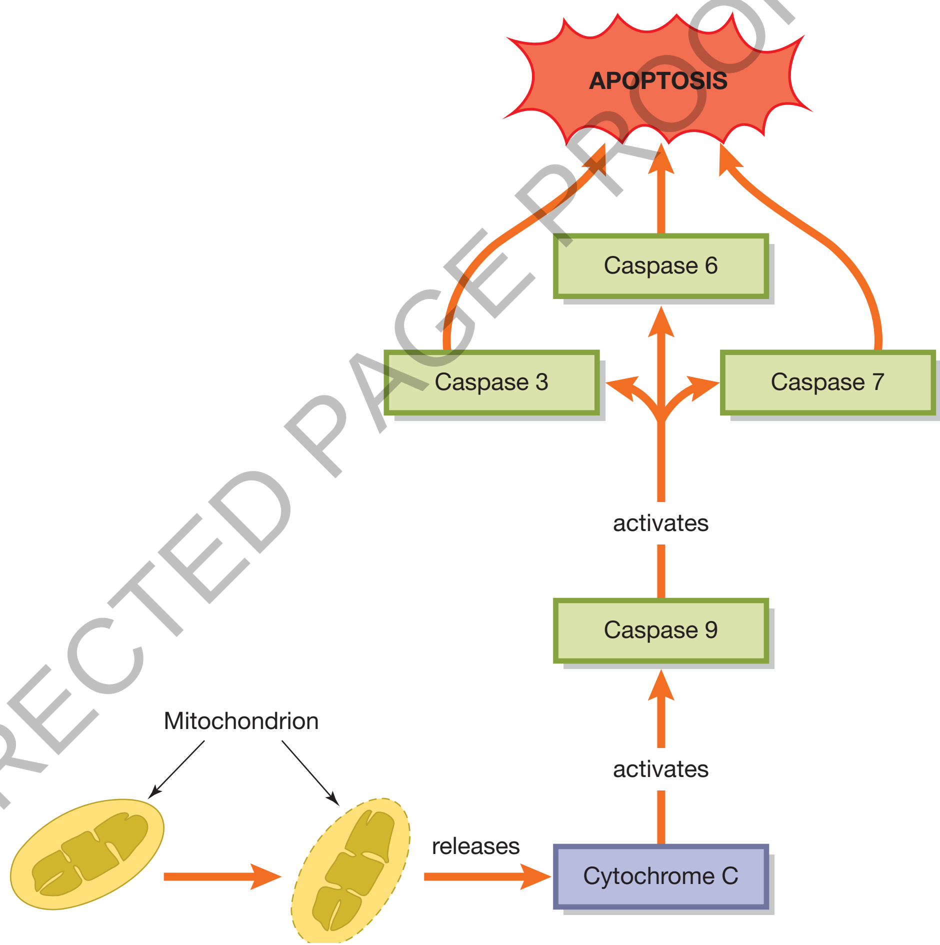

FIGURE 5.64 Diagram showing a simplified representation of the intrinsic or mitochondrial apoptosis pathway. In reality, the process is far more complicated, but this diagram shows the key elements in this process.

The extrinsic pathway (or death receptor pathway) of apoptosis:

The extrinsic or **death receptor pathway** is activated when molecules from *outside* a cell bind to death receptors on the plasma membrane of a cell and signal the cell: 'It's time to die.' Every nucleated cell carries within it the molecules for its own self-destruction. These are the inactive pro-caspases, but they become active caspases when the signal 'It's time to die' is received.

The cells that undergo programmed cell death by the extrinsic pathway are not stressed cells (as is the case for the mitochondrial pathway). Why send an external signal to healthy cells to self-destruct? In some cases, these cells are no longer needed, or they are being replaced by new cells, or they are in excess of current needs. The death of these cells is necessary to maintain the balance between cell production and cell loss.

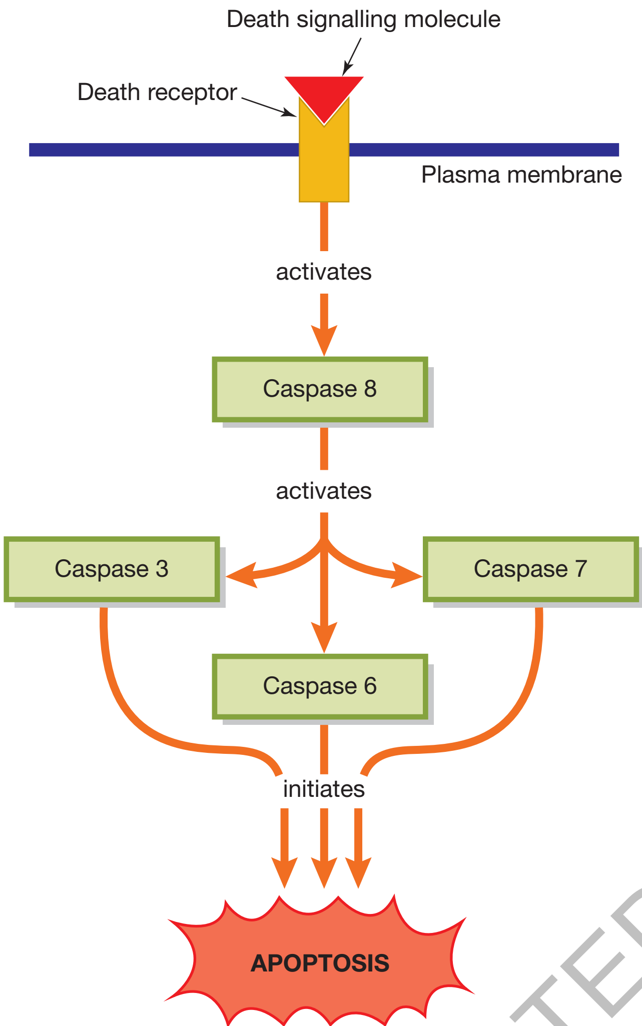

FIGURE 5.65 Diagram showing a simplified version of the extrinsic or death receptor pathway of apoptosis. Note that caspase 8 is the initiate caspase that activates caspases 3, 6 and 7.

The binding of external signalling molecules (ligands) to the death receptors activates these receptors. This starts the extrinsic pathway of apoptosis. The first step is to cleave (cut) inactive pro-caspase-8 molecules in the cell and convert them to active caspase-8, the initiator. Caspase-8 then cleaves and activates the executioner caspases (caspase-3, -6 and -7). The executioner caspases dismantle the cell in an orderly manner and package its various components into apoptotic bodies (see figure 5.65).

In chapter 7 (see page 323), you will meet some immune cells called cytotoxic T cells. On the outer surface of the plasma membranes of these cells is a signalling molecule (ligand) called FasL. The signalling molecules bind to death receptors on target cells and this activates the extrinsic pathway of apoptosis.

What about plants?

So far, the discussion of apoptosis in this chapter has related to mammals. So, what about plants? Since programmed cell death is a normal part of the life of multicellular organisms, it would be expected that apoptosis would play a role in the life of plants by enabling an orderly process of removal of unwanted or damaged cells.

Researchers have shown that plant cells go through an orderly process of cell death when treated with chemicals known to induce apoptosis in animals. Further investigations have revealed that the treatment of plant cells with ethylene induces apoptotic cell death. Further, the treatment of cells with inhibitors of ethylene biosynthesis block this chemically induced cell death. These experimental findings indicate that ethylene is a mediator of programmed cell death in some plant species at least.

Apoptosis and human disease

The caspase proteases in a cell generate benefits when their activity is highly regulated. However, the complex process of apoptosis can malfunction. Many human diseases are now known to be the direct or indirect results of malfunctions of the apoptotic pathway. If the normal operation of apoptosis is disrupted so that apoptosis is reduced to inadequate levels, too little cell loss will occur and, instead, cells will live beyond their 'use-by-date' and accumulate abnormally. On the other hand, if apoptosis increases above normal levels, the excessive cell loss that results can cause disease.

Examples of diseases associated with too little apoptosis and an abnormal accumulation of cells include the following:

- Many cases of cancer appear to be the result of too little apoptosis. Mutations present in cancer cells enable these cells to grow in an uncontrolled fashion, crowding out normal healthy cells, and forming tumours. This situation arises because the cancer cells do not respond to the normal apoptotic signal to self-destruct.
- Autoimmune diseases appear to involve disruption of apoptosis; for example, rheumatoid arthritis is characterised by an excessive proliferation of cells in the synovial tissue of the joints that leads to joint destruction (see figure 5.66). These cells do not respond to the signals of the extrinsic apoptosis pathway so that a situation of too little apoptosis exists.

study on

Unit 3	**Malfunction of apoptosis**
AOS 2	Summary screen and practice questions
Topic 1	
Concept 10	

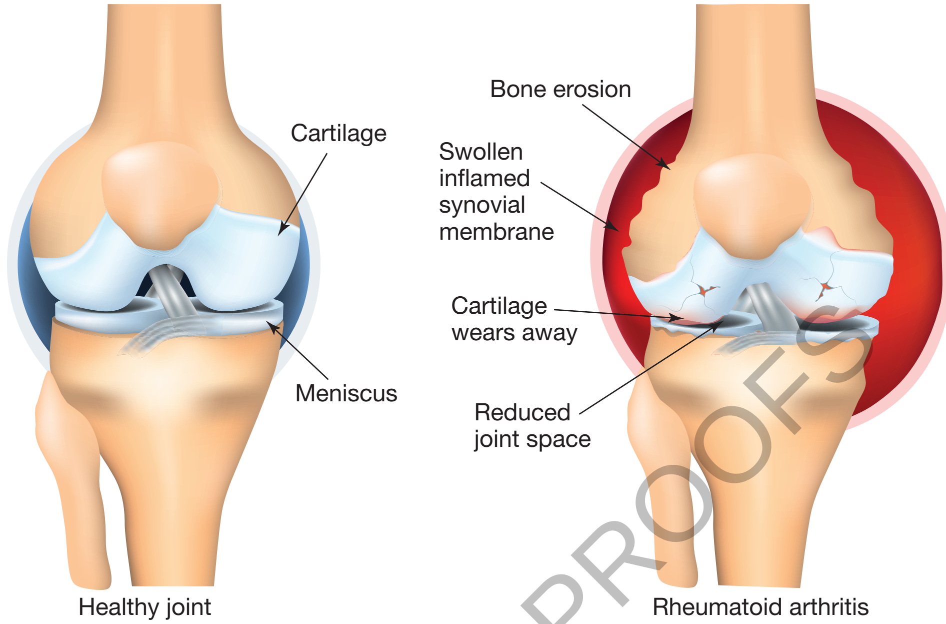

FIGURE 5.66 Rheumatoid arthritis is a chronic inflammatory disease in which the synovial lining becomes inflamed and the adjacent bone and cartilage are destroyed. Alterations in the apoptosis of synovial cells is associated with the pathogenesis of rheumatoid arthritis.

Examples of diseases associated with too much apoptosis and an abnormal loss of cells include the following:

- In neurodegenerative disorders, such as Parkinson's disease and Alzheimer disease, abnormal progressive loss of nerve cells occurs in particular regions of the brain. The loss of nerve cells is associated with unregulated activation of caspases and apoptosis that produces excessive cell death.
- In untreated acquired immune deficiency syndrome (AIDS), excessive unregulated apoptosis leads to the loss of a particular group of immune cells, known as T-helper cells, also known as CD4+ cells.

AIDS is explored further in chapter 8, page 358.

KEY IDEAS

- Apoptosis is a process of programmed cell death.
- Apoptosis can occur by one of two pathways, the mitochondrial pathway and the death receptor pathway.
- In an adult, apoptosis ensures that a balance exists between the rates of cell renewal and cell death.
- Uncontrolled apoptosis appears to be associated directly or indirectly with a number of human disorders.

QUICK CHECK

28 Briefly identify the important balance that is maintained by apoptosis.

29 Identify a key difference between the members of the following pairs:
  a apoptosis and necrosis
  b mitochondrial pathway and death receptor pathway of apoptosis
  c a caspase and a pro-caspase.

30 Which pathway of apoptosis will be undertaken by a cell that is stressed by a viral infection?

31 Give an example of the following:
  a normal apoptosis in human embryonic development
  b normal apoptosis in an adult human
  c unregulated apoptosis associated with a human disorder or disease.

BIOCHALLENGE

1 **Epinephrine signalling pathway:** When the blood glucose levels drop below the normal range, several hormones are released that raise the blood glucose level. These hormones include epinephrine (also known as adrenalin), cortisol, growth hormone and glucagon. Epinephrine is secreted by cells of the adrenal glands and its targets are liver cells.

The pathway from epinephrine to a cellular response in the form of an increase in blood glucose levels is a signal transduction pathway. In this case, the cellular response is the breakdown of glycogen into its glucose sub-units and their release into the blood, returning the blood glucose levels to within the normal range.

Figure 5.67 shows a diagrammatic representation of this signal transduction pathway that involves several steps, but only a few are shown here. (Note that you do not need to know the specific details, just the 'big picture'.)

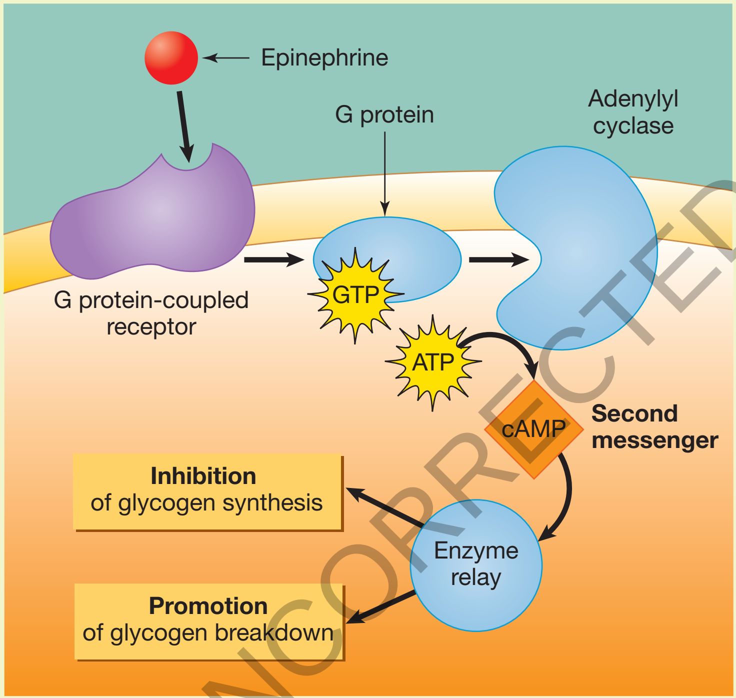

FIGURE 5.67 Diagram showing *some* features of the signal transduction pathway that occurs after an epinephrine signal is received by a G protein linked receptor on the surface of a liver cell.

a Identify the signalling molecule or first messenger in this pathway.
b Where are the receptors that can receive this signal?
c Identify the second messenger in this pathway.
d Why is a second messenger necessary — why not just use the first messenger to continue to carry the message?
e Would you expect that this signal transduction pathway would be continual or would you expect it to stop after a limited time? Explain your choice.
f What is the cellular response to the transduced signal?
g Would you predict that epinephrine is hydrophilic in nature? Explain.

2 An important part of a signal transduction pathway is the amplification of the signal. This is needed because signalling molecules (first messengers) are typically present in very low concentrations. Amplification is achieved through an enzyme relay that is a bit like a chain reaction. The amplification means that a small number of signalling molecules can produce a large cellular response (see figure 5.68).

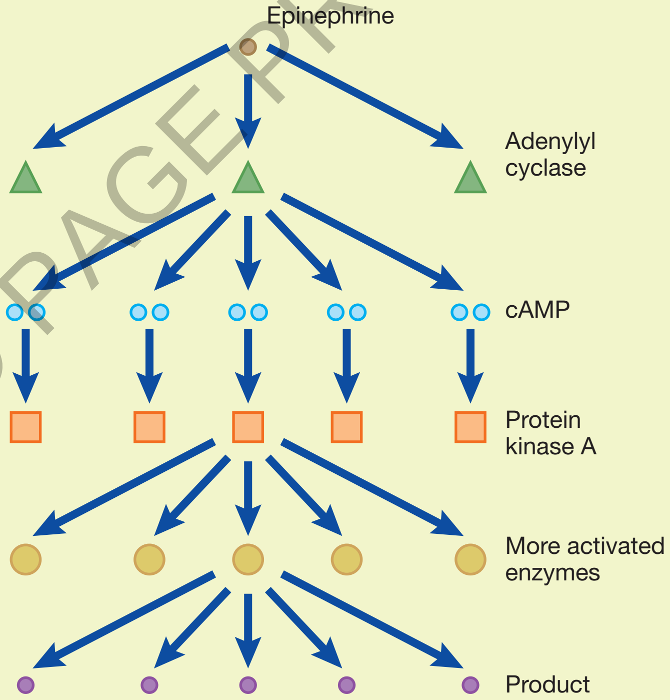

FIGURE 5.68

Amplification occurs at various steps in the signal transduction pathway.

a Reception of one epinephrine molecule sets off a signal transduction pathway that produces a large number of cAMP second messenger molecules. Is this an example of amplification?
b Each cAMP molecule activates one protein kinase A molecule. Is this a further amplification of the signal?

Each protein kinase A enzyme molecule then activates a large number of the enzymes that are the next members of the relay.

c Explain why the action by the various enzymes in the relay can result in amplification of the signal.
d The final product of this pathway is an enzyme called glycogen phosphorylase. Explain how this enzyme produces the cellular response.

Chapter review

studyon
Unit 3 AOS 2 Topic 1
Cellular signals
Practice questions

Key words

abscission
abscission zone
apical dominance
apoptosis
apoptotic bodies
caspases
cell-surface receptors
cloning
cytokine
cytokinin
death receptor pathway
depolarisation
endocrine-disrupting chemicals (EDCs)
first messenger
flehmen
gibberellic acid (GA)
gibberellin
herbicide
hydrophilic
hydrophobic
intracellular receptors
jasmonates (JAs)
ligand
local mediators
mediator
modulator
motor end plate
necrosis
neurotransmitters
pheromone
polar
programmed cell death
rate of cell renewal = rate of cell death
reception
response
resting membrane potential
second messenger
signal transduction
signal-binding domain
stomata
synapse
synaptic clefts
tissue culture
transcription factors
transduction
tropism
vomeronasal organ (VNO)

Questions

1 Making connections between concepts → Use at least eight of the key words from this chapter to construct a concept map relating to cellular communication.

2 Communicating knowledge and understanding → Examine figure 5.69, which shows a cell with two different receptors, S and R.

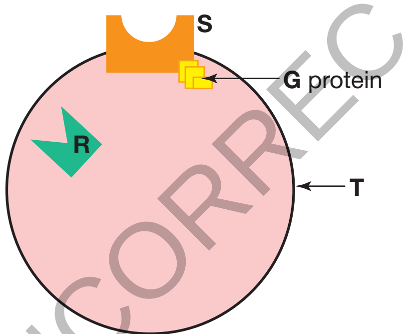

FIGURE 5.69

a Identify structure T.
b Identify two characteristics of the signalling molecule that has receptor R as its target.
c Identify two characteristics of the signalling molecule that has receptor S as its target.
d What name is given to the kind of receptor that is physically associated with a G protein?

3 Applying principles in a new context → Cholera is a bacterial disease caused by *Vibrio cholera*. These bacteria produce an exotoxin that enters particular gut cells and activates a signal transduction pathway, causing it to be to be switched 'on' permanently. This results in the continual activation of the CFTR protein channel that pumps chloride ions (Cl–) out of the gut cells. These negatively charged chloride ions are accompanied by the loss of an equivalent number of positively charged sodium ions (Na^+). This movement of NaCl into the gut drags with it large amounts of water from gut cells.

Suggest the likely effects of this particular malfunction of a signal transduction pathway caused by the cholera toxin.

4 Developing and communicating explanations → Examine figure 5.70 and suggest a carefully argued explanation for the cause of this condition of fused digits, which is known as syndactyly.

FIGURE 5.70 Photo of the hand of a young child showing fusion of digits 3 and 4.

5 Demonstrating knowledge and understanding → Consider each of the following statements and identify whether each is true or false. Where you judge a statement to be false, (i) give a reason for your decision and (ii) rewrite the statement so that it would be judged to be true.

- **a** One type of receptor can receive signals from many different kinds of signalling molecule.
- **b** A signalling molecule must cross the plasma membrane in order to be received.
- **c** Only some body cells respond to a given signalling molecule.
- **d** Communication between two neurons can occur in both directions across a synapse.
- **e** A given signalling molecule that is received by several different kinds of cell will produce the same cellular response in those cells.
- **f** Signalling molecules must be small enough so that they can reach the cell interior.

6 Communicating knowledge and understanding → Examine figure 5.71 and tell the story that it communicates.

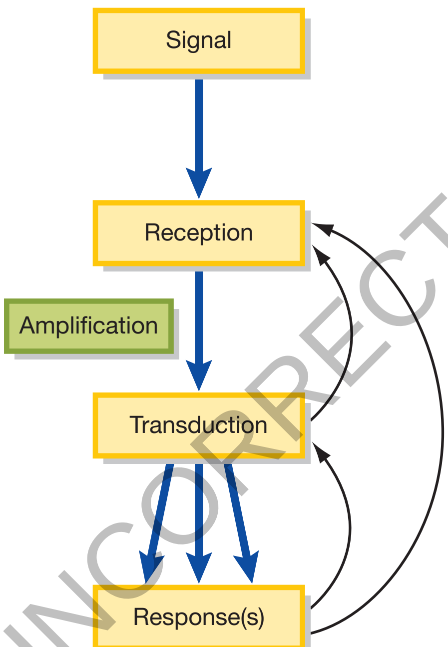

FIGURE 5.71

7 Developing and communicating explanations → Suggest an explanation in biological terms for each of the following observations:

- **a** Caspase-9-deficient mice suffer from large brain outgrowths characterised by excessive neurons.
- **b** Pruning the shoots of a newly planted tree slows root regeneration.
- **c** The direction of travel of a nerve impulse along a nerve pathway is always one-way.
- **d** Hormones reach all cells of the body, but only particular cells respond to their signals.
- **e** Cytokines are sometimes called the 'messengers' of the immune system.

8 Demonstrating understanding of biological terminology →

- **a** Identify an essential difference between the members of the following pairs:
  - i pheromone and hormone
  - ii hydrophilic and hydrophobic signalling molecules
  - iii signal reception and signal transduction
  - iv an interferon and an interleukin
  - v a hormone and a local mediator
  - vi the intrinsic apoptosis pathway and the extrinsic apoptosis pathway.
- **b** For each pair, identify one feature that they have in common.

9 Developing valid biological explanations → Give an explanation in biological terms for each of the following observations:

- **a** Grapes ripen more quickly if they are placed near bananas.
- **b** Some receptors for signalling molecules are located on cell surfaces while other receptors are intracellular.
- **c** Cytokine production as part of a localised response to infection is normal, but a system-wide production can be fatal.
- **d** Loss of nerve tissue occurs in neurodegenerative diseases such as Parkinson's disease.

10 Applying understanding to familiar and new contexts → The drug tamoxifen is an anti-estrogen compound and is an example of a hormone blocker. This drug is used in the treatment of forms of breast cancer that have high levels of estrogen receptors. These cancers are said to be ER-positive, and their growth is enhanced by estrogen.

- **a** Where would these receptors be located in the breast cancer cells? Give a reason for your answer.
- **b** Identify a possible rationale for the use of tamoxifen in the treatment of ER-positive breast cancers?

11 Making predictions → In 1926, the Dutch biologist Fritz Went (1903–1990) carried out experiments in total darkness in which he placed blocks of agar containing auxin in offset positions on the cut tops of the coleoptiles of grass seedlings (see figure 5.72). He also prepared some control coleoptiles.

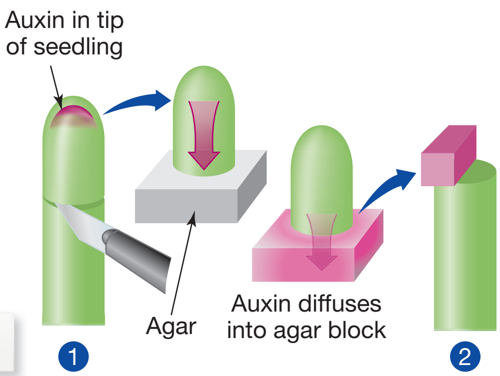

FIGURE 5.72

a Predict what would be expected to happen to the coleoptile (2) and give an explanation in biological terms for your decision.
b What control would be expected to be part of this experiment?
c What valid conclusion may be drawn from the results of this experiment?

12 Applying knowledge in a new situation ➔ Patients with rheumatoid arthritis (RA) were treated with an anti-tumour necrosis factor (anti-TNF).
a To which group of signalling molecules does tumour necrosis factor (TNF) belong?
b Identify three characteristics of this group of molecules.
c Identify a possible rationale for use of anti-TNF in treatment of patients with RA.
d What effect, if any, would you predict that treatment with anti-TNF might have on patients with RA?

13 Communicating information and ideas effectively ➔ Explain how pheromones could be useful:
a in reducing the use of insecticides in crop farming
b as control agents of insect pests in glasshouses.

14 Interpreting data ➔ Figure 5.73 shows how the various responses to the plant hormones auxin and cytokinin depend on the relative concentrations of these hormones. Note that the term 'callus' refers to a mass of unorganised plant tissue consisting of cells of one kind.

Small shoots of a particular plant species were treated with solutions as follows:

Solution A: High concentration of auxins and low concentration of cytokinins

Solution B: High concentration of cytokinins and low concentration of auxins.
a Identify the growth response that would be expected on shoots treated with solution A.
b Identify the growth response that would be expected on shoots treated with solution B.
c At what relative concentrations of the two hormones did callus formation occur?
d What solution would have been used in this experiment to serve as the control?

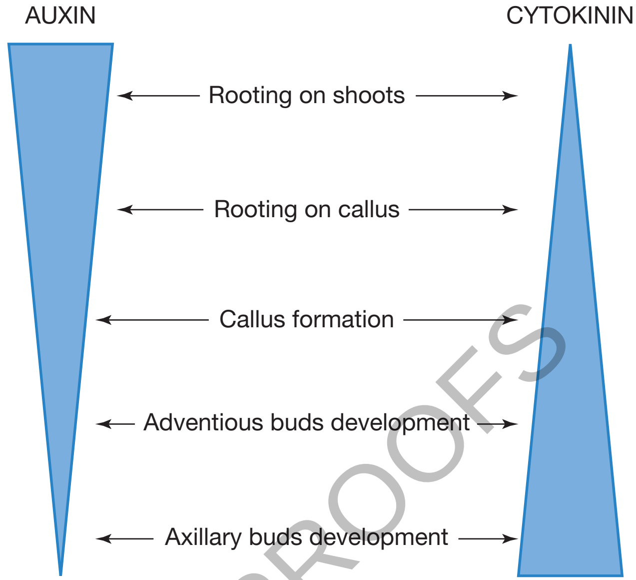

FIGURE 5.73 Various plant responses to different relative concentrations of the plant hormones auxin and cytokinin.

15 Discussion question ➔ Some synthetic chemicals can bind to the receptors that are normally sites where natural hormones bind. These synthetic chemicals include DDT (dichloro-diphenyl-trichloroethane), bisphenols used in the manufacture of plastics, dioxin, and some PCBs (polychlorinated biphenyls). In the main, these synthetic compounds are lipophilic (hydrophobic) and persist in the environment. Some natural compounds including phytoestrogens from fungi and plants can also bind to hormone receptors on mammalian cells.

These chemicals, termed **endocrine-disrupting chemicals (EDCs)**, can interfere with the function of the normal hormones. Any system in the body controlled by hormones can be affected by EDCs. In a 2015 publication, the Endocrine Society identified evidence from several sources, including animal experimentation, for an association between endocrine disruption and conditions such as obesity, diabetes, abnormal puberty, female reproductive impairments, testicular dysgenesis, hormone-sensitive cancers in females, prostate cancer, and disorders of the thyroid, as well as neurodevelopment and neuroendocrine systems.
a Do a search on the web and find an example of an animal population in the wild that shows some reproductive abnormalities associated with EDCs.
b Suggest how an EDC might produce a particular disorder, such as precocious puberty in girls.