Plant Development + Cells + Soil, Nutrient Acquisition, Deficiencies

Laurie Wang

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1 Introduction

Although they're rooted to one place, plants are surprisingly dynamic. Just like humans, they have organs, tissues, and cells, and need nutrients to survive. It is the job of the plant to make sure all of its metabolism and development is supported by making sure it can acquire resources well.

2 Organs

Each section explains the purposes of, types of, and additional information about roots, stems, and leaves, the organs of plants.

2.1 Roots

2.1.1 Purpose

- **Main function**: Absorbs minerals and water from soil
- Anchors the plant in soil
- Sometimes stores carbohydrates and other compounds like secondary metabolites

2.1.2 Types of root systems

Root systems are derived from primary roots and lateral roots. The **primary root** is the first organ to emerge from the seed. **Lateral roots** branch off the primary root, and can branch themselves.

A **taproot system** is usually found in tall, straight plants. They consist of one taproot, usually from the primary root, and lateral roots. Taproot systems take a lot of energy to develop and sustain but the stability they provide is more important to plants that use them. Sometimes, taproot systems can be specialized to store food, as with beets and carrots. Other examples of plants that use a taproot system are dandelions, parsley, and pines.

A **fibrous root system** is usually found in small plants or plants that are easily killed by grazing. They consist of a thick mat of thin roots, each of which can form lateral roots that form more lateral roots. The primary root dies during the development of a fibrous root system. Thus, there is no taproot. There are many small **adventitious** (grown from a non-root part) roots from the stem. An ecological advantage of fibrous root systems is that they hold soil in place, preventing erosion. Most monocots use fibrous root systems. Some examples of plants that use fibrous root systems are grass, corn, and sweet potatoes.

2.1.3 Additional features

- **Root hairs**: Root hairs come from the outermost layer of roots, called **epidermal cells**, and serve to increase the surface area of the roots. This allows for enhanced absorption of water and minerals.
- **Mycorrhizal associations**: These are associations formed between plant roots and fungi. In exchange for energy, fungi help absorb minerals for the plant, especially useful where nutrients are scarce. See "Role of Fungi" for more information.

2.1.4 Special roots

- **Buttress roots**: They are often found in tropical soils, which are nutrient-poor and shallow. Thus, the non-buttress roots are usually shallow as well, which risks the plant tipping over. Buttress roots act as support to stabilize the plant. An example of a tree that uses buttress roots is *Gyranthera caribensis*.

Figure 1: *Gyranthera caribensis*. (Source: Monumental Trees)

- **Prop roots**: They are above-ground and adventitious, usually used to support tall, top-heavy plants. An example is *Zea mays* (maize).

Figure 2: Maize roots. (Source: Wikimedia Commons)

- **Pneumatophores (air roots)**: They are often found in tidal swamps, which are usually muddy. In this environment, they allow roots to get oxygen, as there is not much of it in mud. An example is *Rhizophora mangle* (mangroves).

Figure 3: Mangrove air roots. (Source: GRID-Arendal)

- **"Strangling" aerial roots**: They wrap around a host tree and everything in their way, with shoots growing up to prevent the host tree from getting sunlight, eventually killing it. As such, they are often found in environments that have intense competition for sunlight. An example is the strangler fig.

Figure 4: Strangler fig. (Source: Wikipedia)

- **Storage roots**: Their purpose is to store food and water for the plant. An example is beets.

2.2 Stems

Stems are the part of a plant that has leaves and buds.

2.2.1 Purpose

To get longer and make sure leaves can photosynthesize, elevate reproductive structures, and maybe photosynthesize. Alternative functions include food storage and asexual reproduction.

2.2.2 Anatomy

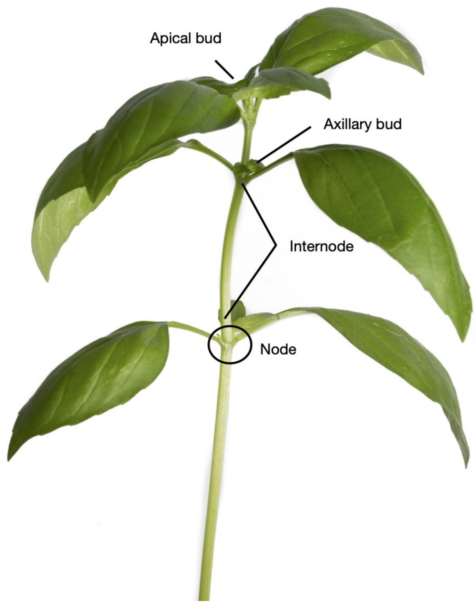


Figure 5: Parts of a stem. (Source: Biology LibreTexts)

- **Node**: Where leaves are attached.
- **Internode**: Stem between nodes.
- **Apical bud**: The growing shoot tip.
- **Axillary bud**: A bud at a leaf-stem junction that can form a branch, thorn, or flower.

2.2.3 Special modified stems

- **Rhizomes**: A rhizome is a horizontal shoot just below the surface of the soil. Vertical shoots emerge from axillary buds on the rhizome. An example of a plant that uses rhizomes is the iris.

Figure 5: *Rhizome.* (Source: House Digest)

- **Stolons**: A stolon is a horizontal shoot along the surface of the soil. It functions in asexual reproduction, as plantlets grow from axillary buds, which eventually become independent. An example of a plant that uses stolons is the strawberry.

Figure 6: Strawberry stolon. (Source: Adobe Stock)

- **Tubers**: A tuber is the enlarged end of a rhizome. The "eyes" found in tubers are clusters of axillary buds. An example of a plant that uses tubers is the potato.

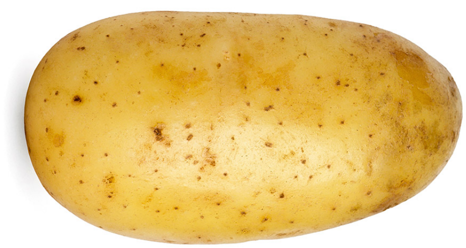


Figure 7: Potato. (Source: Alimentarium)

2.3 Leaves

2.3.1 Purpose

The purpose of leaves is to conduct photosynthesis and gas exchange, dissipate heat, and defend plants from herbivores and pathogens.

2.3.2 Structure

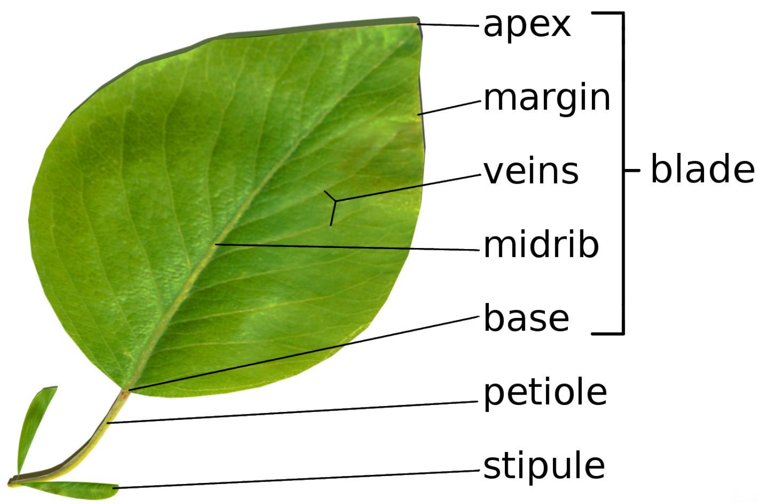


Figure 8: Leaf structure. (Source: ThoughtCo)

- **Blade**: The blade is normally the most noticeable part of the leaf.
- **Petiole** (stalk): Many monocots lack a petiole, with the base of the leaf forming a sheath enveloping the stem instead.
- **Simple** vs. **compound** leaves: Compound leaves have leaflets, which can be identified because they don't have petioles. This structure may be good for confining pathogens to one leaflet as opposed to allowing them to spread through the whole leaf.

2.3.3 Special modified leaves

- **Tendrils**: Tendrils form a lasso to pull a plant towards its support. Most tendrils are modified leaves but those found on grapevines are modified stems. An example of a plant that uses tendrils is the pea.

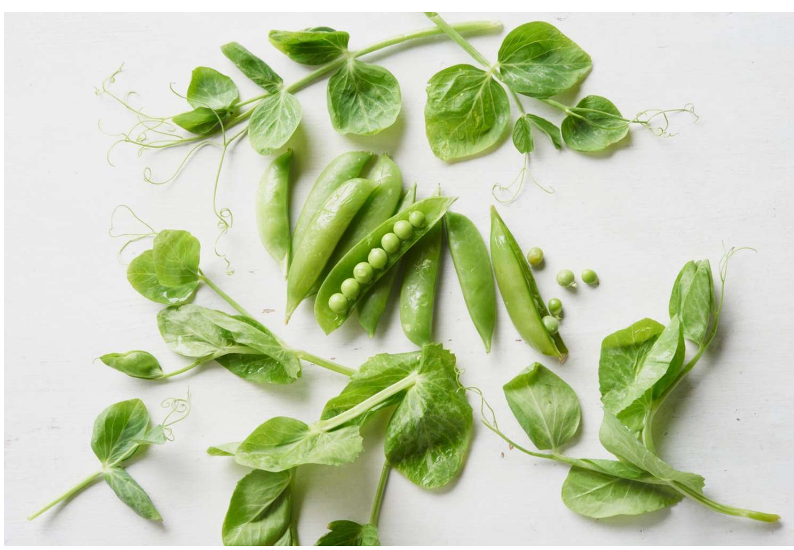


Figure 9: Tendrils on peas. (Source: Allrecipes)

- **Spines**: Spines can help provide protection for a plant from predators, or help reflect sunlight. They are not photosynthetic. An example of a plant that uses spines is the cactus.

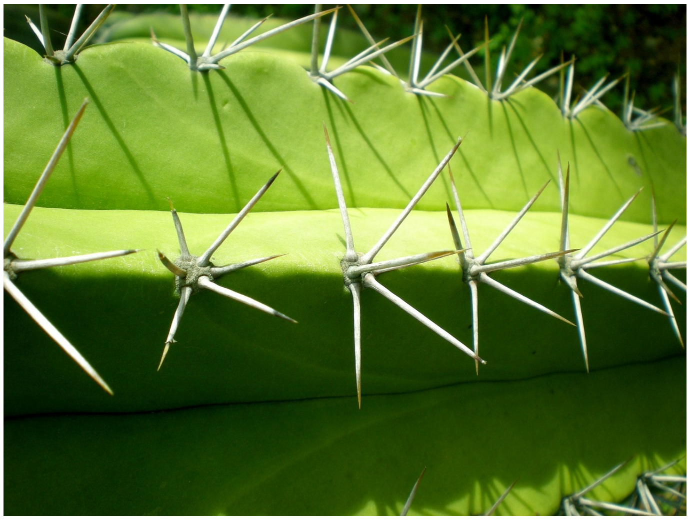


Figure 10: Cactus spines. (Source: Plantsnap)

- **Storage leaves**: Storage leaves are commonly known as bulbs, and serve to store food. An example is the onion.

Figure 11: Onion. (Source: Full Fact)

- **Reproductive leaves**: They are found in some succulents, on which adventitious plantlets fall off and become new plants. An example of a plant that uses reproductive leaves is *Kalanchoe daigremontiana*.

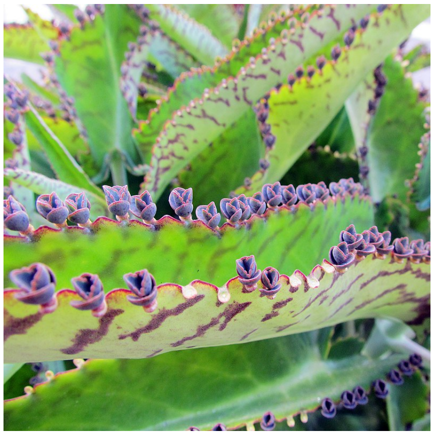


Figure 12: *Kalanchoe daigremontiana.* (Source: Wikipedia)

- **Sporophylls**: These are the carpels and stamens found in flowers.

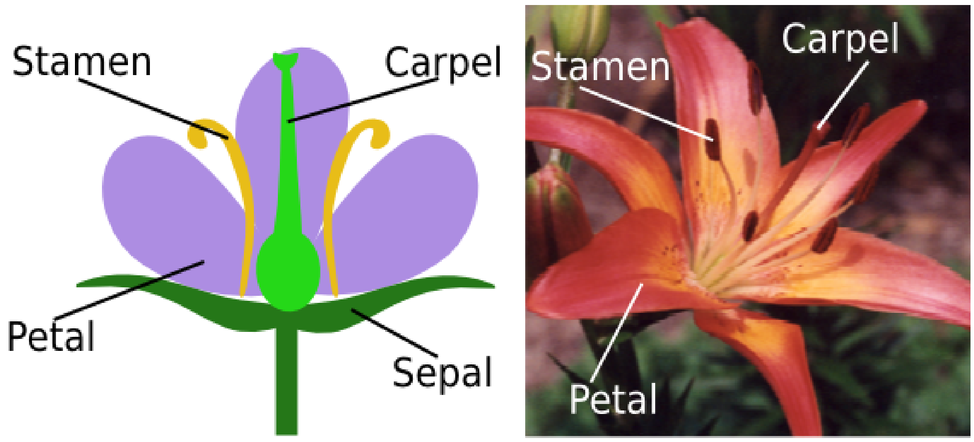


Figure 13: Carpels and Stamens. (Source: Study.com)

3 Tissues

There are 3 fundamental types of tissues in plants. Each type forms a tissue system that connects all organs.

3.1 Dermal Tissue

The purpose of dermal tissue is to defend against physical damage and pathogens.

There are two types of dermal tissue, non-woody and woody. Non-woody epidermis is a single layer of epidermis and a cuticle to prevent water loss. Woody epidermis has a layer called the **periderm** replace the epidermis in older stems and roots.

In roots, water and minerals enter the epidermis, especially in root hairs. In shoots, **guard cells** of the epidermis conduct gas exchange.

Trichomes are sometimes found on dermal tissue. They can reduce water loss and reflect excess light. They can also defend against insects.

3.2 Vascular Tissue

Vascular tissue function in transport within and mechanical support of the plant.

- **Xylem** transports water and dissolved minerals upwards in a plant.
- **Phloem** transports sugars from “sources,” where they are produced, to “sinks,” where they are used up (usually where growth is happening).

The **stele** is the combined vascular tissue of a root or stem. In angiosperms, the stele in the root is called the **vascular cylinder** and in the stems and leaves, where xylem and phloem are separate, the stele is called **vascular bundles**.

3.3 Ground Tissue

Ground tissue is everything that's not dermal or vascular. Ground tissue has specialized cells for storage, photosynthesis, support, transport, and more.

Pith is ground tissue interior to the stele; **cortex** is ground tissue exterior to the stele.

4 Cells

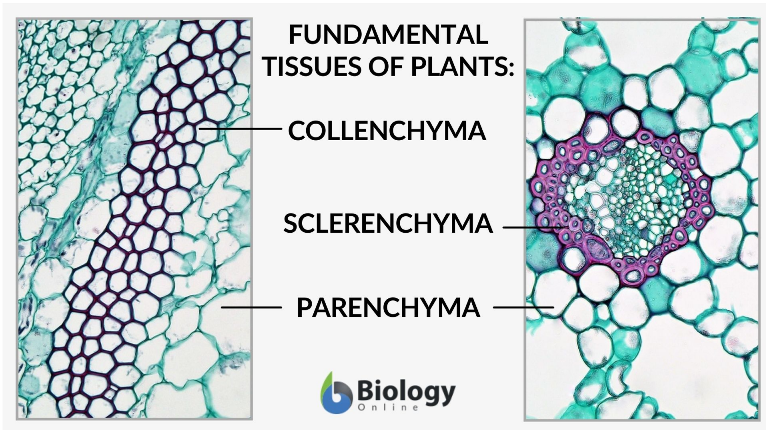


Figure 14: Parenchyma, collenchyma, and sclerenchyma. (Source: Biology Online)

4.1 Parenchyma

Parenchyma usually have thin and flexible primary walls, with mostly no secondary walls. They usually have a large central vacuole and function in metabolism, conducting photosynthesis in leaves, and holding amyloplasts in stems and roots for storage. They form the flesh of fruits. They can differentiate into other types of cells.

4.2 Collenchyma

Collenchyma have thicker but uneven primary walls. They are elongated cells grouped in strands. They usually support young parts of a plant shoot, right below the epidermis. Because they are living, they can elongate with the growing stems and leaves they are supporting.

4.3 Sclerenchyma

Sclerenchyma have a thick secondary cell wall with a lot of lignin. They offer rigid support. They can't elongate, so they are usually in parts of plants that stop growing. Most sclerenchyma are dead.

There are two forms of sclerenchyma, sclereids and fibers. **Sclereids** are boxy and irregular, with very thick and lignified secondary walls. they are found in hard nutshells and cause the grittiness in pears. **Fibers** are usually in strands and are long, slender, and tapered. They allow hemp to be made into rope, and flax to be made into linen.

4.4 Cells of the xylem

Cells of the xylem are tubular and elongated. They are dead at maturity and lignified. The secondary wall of cells in the xylem usually have **pits** where only primary wall is present. Water can migrate laterally through these pits.

There are two types of xylem cells:

- **Tracheids** are found in the xylem of *all* vascular plants. They are long, thin, and tapered at the ends.
- **Vessel elements** are found in most angiosperms, and a few gymnosperms and seedless vascular plants. They are wider, shorter, and less tapered than tracheids, with thinner walls. They are aligned to form vessels. The end walls of vessel elements have **perforation plates** that let water flow freely through vessels.

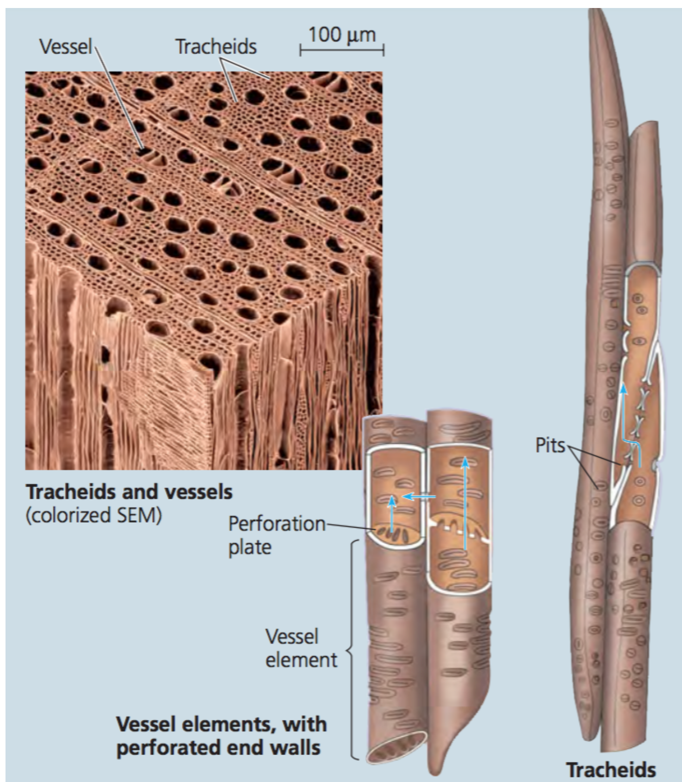


Figure 15: Cells of the xylem. (Source: Campbell Biology)

4.5 Cells of the phloem

All of the cells of the phloem are alive, but they have no nucleus, ribosomes, distinct vacuole, or cytoskeleton. Instead, they are supported by certain cells adjacent to them.

There are two types of cells in phloem:

- **Sieve cells** are found in seedless vascular plants and gymnosperms. They are supported by **albuminous (Strasburger) cells**.
- **Sieve tube elements/members** are found in angiosperms. They contain **sieve plates** on the end walls between sieve-tube elements, which have pores in them to facilitate flow. They are supported by nonconducting **companion cells**, connected to them via plasmodesmata.

5 Seeds and flowers

5.1 Gymnosperms

A **seed** is an embryo and food supply, surrounded by a protective coat. Seed plants are **heterosporous**, meaning that they have two types of spores, a **megaspore** and **microspore**.

The development of a gymnosperm seed is shown below.

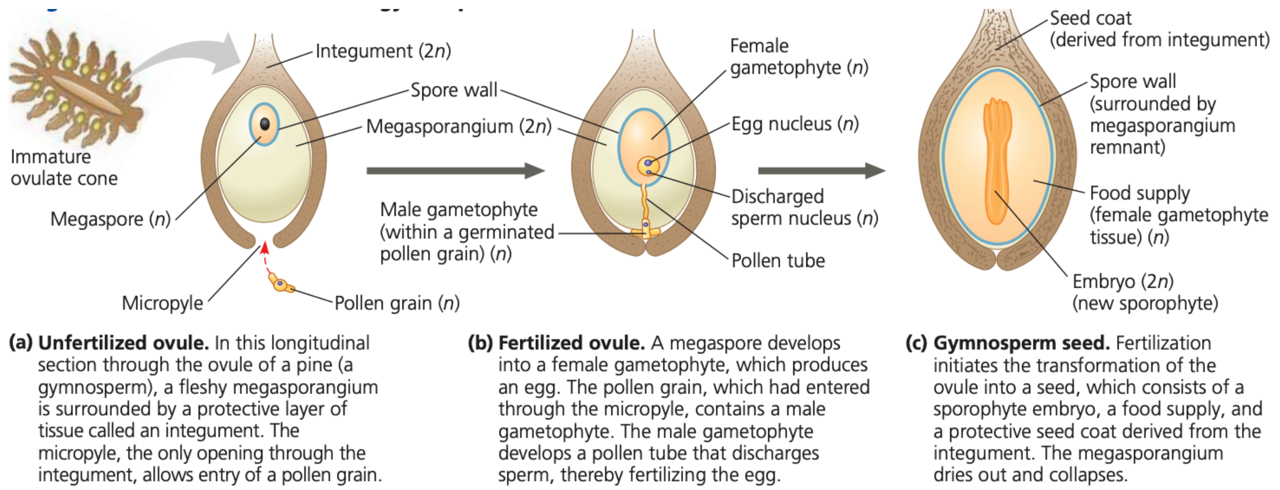


Figure 16: Development of gymnosperm seed. (Source: Campbell Biology)

5.2 Angiosperms

Angiosperms have flowers. Flowering in plants is usually determinate, and producing a flower from a shoot generally stops primary growth.

5.2.1 Flower Structure

Plant flowers generally look like this:

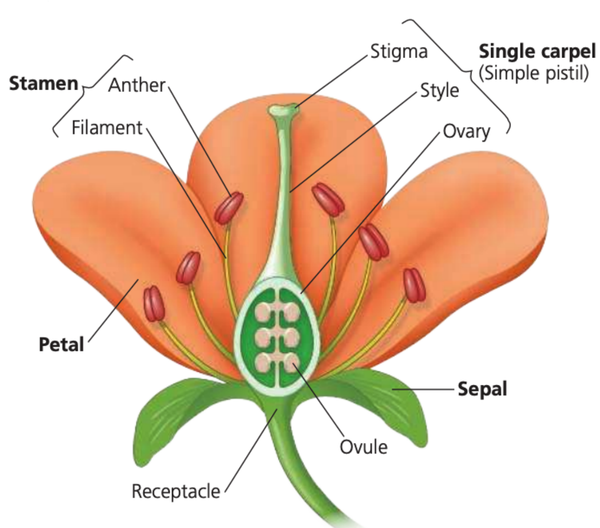


Figure 17: Idealized flower. (Source: Campbell Biology)

Stamens are the microsporophylls, which produce microspores, which become pollen that contains the male gametophytes. Pollen is produced in the **anther**.

Carpels are megasporophylls, which produce megaspores that make female gametophytes. Each carpel is composed of three parts. The **stigma** is the sticky end that "catches" pollen, the **style** is the slender tube that brings that pollen to the ovary, and the ovary contains the ovules. The ovary will become the **fruit**, and the ovules within become the **seeds**. A **pistil** is a single carpel or multiple fused carpels.

5.2.2 Flower Formation

The **ABC hypothesis** is used to describe the three genes (A, B, and C) that determine flower formation. Flowers come in 4 **whorls** (a whorl is basically a radial arrangement of leaves), whose formation is determined by the genes present. From outermost to innermost they are:

- **Sepals** = A only

  These are the green leaves on the edge of the flower. The whorl of sepals is called the **calyx**.

- **Petals** = A + B

  These are the pretty colored leaves we associate with flowers. The whorl of petals is called the **corolla**.

- **Stamens** = B + C

  The whorl of stamens is called the androceium.

- **Carpels** = C only

  The whorl of carpels is called the gynoceium.

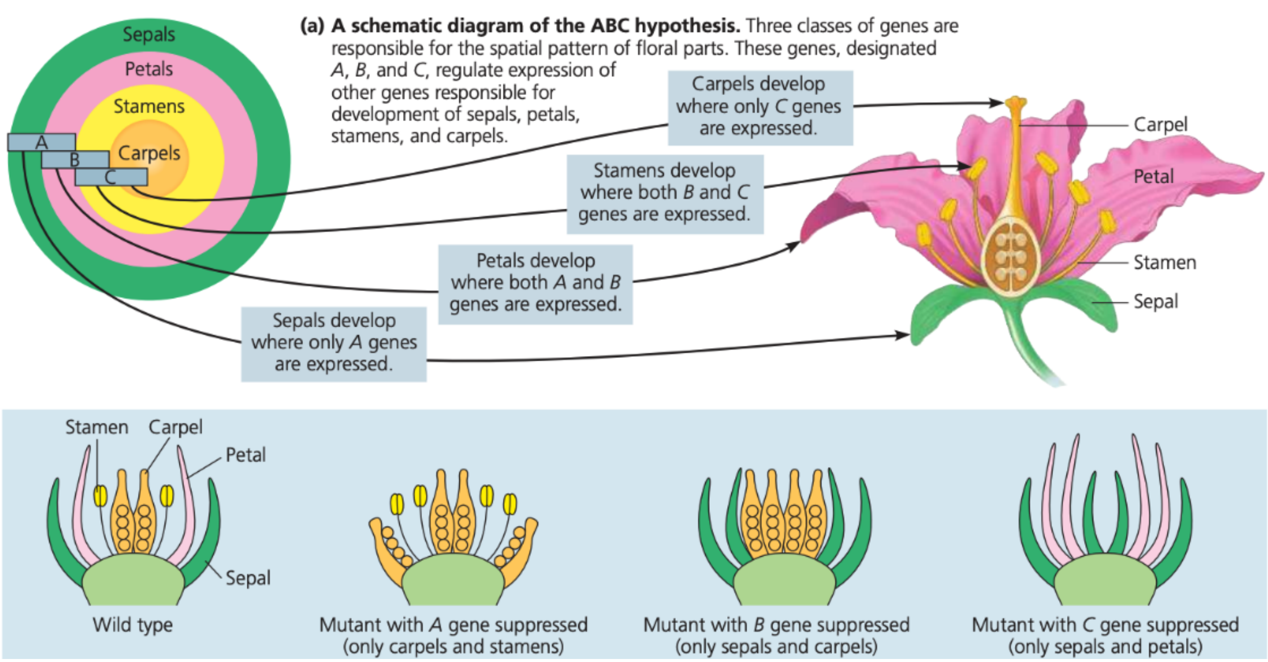


Figure 18: ABC hypothesis. (Source: Campbell Biology)

In some mutants, certain genes are no longer expressed. You should be able to predict what a flower will look like when certain genes are deactivated.

- When B is deactivated, you just ignore it. So the order of whorls becomes sepal, sepal, carpel, carpel.
- When A is deactivated, you replace it with C (carpel, stamen, stamen, carpel) and vice versa.

The current theory is actually the ABCDE hypothesis, as two new crucial genes were discovered:

- D is necessary for the formation of ovules
- E is present in all whorls

5.2.3 Double Fertilization

The following figure shows the life cycle of an angiosperm, from seed to flower.

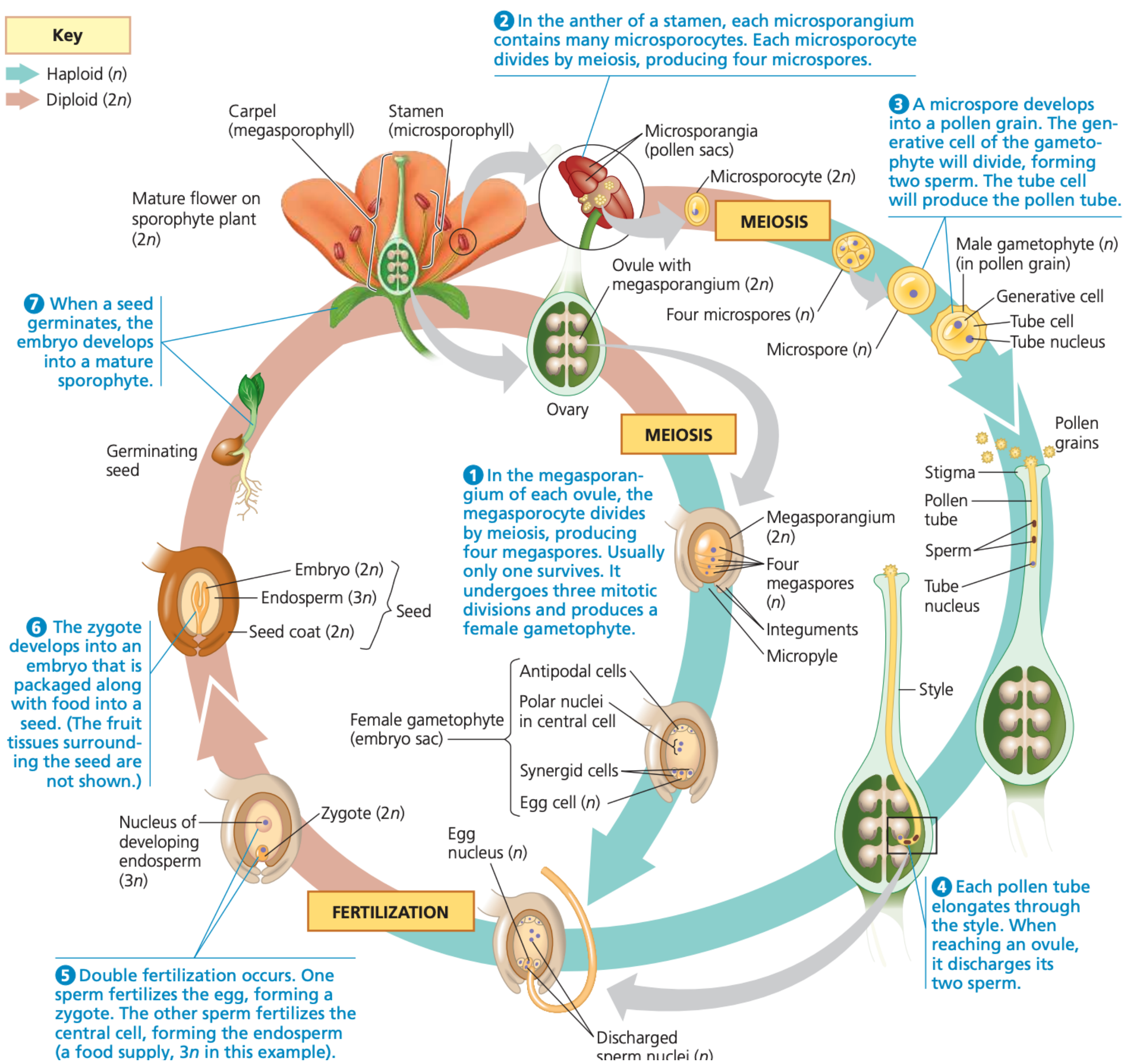


Figure 19: Angiosperm life cycle. (Source: Campbell Biology)

As can be seen in the diagram above, the megaspore in the seed divides to form 8 cells:

- **3 Antipodal cells (n):** Located on the opposite side of the **micropyle** (the opening in the seed that sperm comes through), and can help in providing nutrition or directional information to the embyro.
- **2 Synergids (n):** Located next to the micropyle, guiding the pollen tube.
- **1 Egg cell (n):** Fuses with sperm to become the zygote.
- **1 Polar nuclei (2n):** Fuses with sperm to become the endosperm.

Double fertilization is a process unique to angiosperms. Each pollen grain has 2 sperm (n), one of which fertilizes the 2n polar nuclei, resulting in what becomes 3n **endosperm** (provides nutrients to the embryo), and the other fertilizes the egg cell (n) to create the 2n zygote.

6 Soil and nutrients

6.1 Soil

Soil texture depends on the size of particles, with coarse sand being the largest, to silt in the middle, and clay being the finest. Soil is created through weathering, such as ice in crevices cracking a rock apart, weak acids wearing down rocks, or organisms fracturing rocks. **Loams** are the best soil, with equal parts sand, silt and clay. Good soils are typically half water half air to allow for good aeration, drainage, and water storage.

Topsoil, or the A horizon, is created by a mixture of mineral particles and **humus** (organic matter). Since most soil particles are anions, nitrate, phosphate, and sulfate are commonly lost to leaching, whereas potassium, calcium, and magnesium ions are better retained. Roots absorb cations from the soil solution through cation exchange, where cations are displaced from soil particles by other cations, H+ in particular. The organic components of topsoil are humus, formed by the decomposition of dead organisms, and living organisms, as many as 5 million per teaspoon of soil.

6.2 Essential Elements

Essential elements are required for plants to complete their life cycle and reproduce. Advances in hydroponics determined 17 elements to be essential. **Macronutrients** are needed in large amounts, with nitrogen being in the highest demand. Other necessary macronutrients are C, H, O, N, P, S, K, Ca, and Mg. **Micronutrients** are needed in smaller quantities. They are Cl, Fe, Mn, B, Zn, Cu, Ni, Mb, and Na. they are mainly enzyme cofactors.

The following table gives more information about essential elements.

Element (Form Primarily Absorbed by Plants)	% Mass in Dry Tissue	Major Function(s)	Early Visual Symptom(s) of Nutrient Deficiencies
Macronutrients			
Carbon (CO_2)	45%	Major component of organic compounds	Poor growth
Oxygen (CO_2)	45%	Major component of organic compounds	Poor growth
Hydrogen (H_2O)	6%	Major component of organic compounds	Wilting, poor growth
Nitrogen (NO_3^-, NH_4^+)	1.5%	Component of nucleic acids, proteins, and chlorophyll	Chlorosis at tips of older leaves (common in heavily cultivated soils or soils low in organic material)
Potassium (K^+)	1.0%	Enzyme cofactor; major solute functioning in water balance; operation of stomata	Mottling of older leaves, drying of leaf edges; weak stems; roots poorly developed (common in acidic or sandy soils)
Calcium (Ca^{2+})	0.5%	Important component of middle lamella and cell walls; maintains membrane function; signal transduction	Crinkling of young leaves; death of terminal buds (common in acidic or sandy soils)
Magnesium (Mg^{2+})	0.2%	Component of chlorophyll; cofactor of many enzymes	Chlorosis between veins, found in older leaves (common in acidic or sandy soils)
Phosphorus ($H_2PO_4^-$, HPO_4^{2-})	0.2%	Component of nucleic acids, phospholipids, ATP	Healthy appearance but very slow development; thin stems; purpling of veins; poor flowering and fruiting (common in acidic, wet, or cold soils)
Sulfur (SO_4^{2-})	0.1%	Component of proteins	General chlorosis in young leaves (common in sandy or very wet soils)
Micronutrients			
Chlorine (Cl^-)	0.01%	Photosynthesis (water-splitting); functions in water balance	Wilting; stubby roots; leaf mottling (uncommon)
Iron (Fe^{3+}, Fe^{2+})	0.01%	Respiration; photosynthesis: chlorophyll synthesis; N_2 fixation	Chlorosis between veins, found in young leaves (common in basic soils)
Manganese (Mn^{2+})	0.005%	Active in formation of amino acids; activates some enzymes; required for water-splitting step of photosynthesis	Chlorosis between veins, found in young leaves (common in basic soils rich in humus)
Boron ($H_2BO_3^-$)	0.002%	Cofactor in chlorophyll synthesis; role in cell wall function; pollen tube growth	Death of meristems; thick, leathery, and discolored leaves (occurs in any soil; most common micronutrient deficiency)
Zinc (Zn^{2+})	0.002%	Active in formation of chlorophyll; cofactor of some enzymes; needed for DNA transcription	Reduced internode length; crinkled leaves (common in some geographic regions)
Copper (Cu^+, Cu^{2+})	0.001%	Component of many redox and lignin-biosynthetic enzymes	Light green color throughout young leaves, with drying of leaf tips; roots stunted and excessively branched (common in some geographic regions)
Nickel (Ni^{2+})	0.001%	Nitrogen metabolism	General chlorosis in all leaves; death of leaf tips (common in acidic or sandy soils)
Molybdenum (MoO_4^{2-})	0.0001%	Nitrogen metabolism	Death of root and shoot tips; chlorosis in older leaves (common in acidic soils in some geographic areas)

Figure 20: Essential elements. (Source: Campbell Biology)

The failure to obtain essential elements is called a **mineral deficiency**. Many mineral deficiencies result in **chlorosis**, the yellowing of leaves due to damage to the chlorophyll synthesis pathway. The symptoms of mineral deficiency depend on nutrient mobility. If the nutrient is mobile (P, K, Mg, N, S), symptoms of deficiency appear first in older organs, and if it is immobile, the young organs are affected first. Additionally, mineral needs depend on the age of the plant, as young seedlings usually have most of the essential elements in their seed reserves.

The following figure shows some common plant deficiencies.

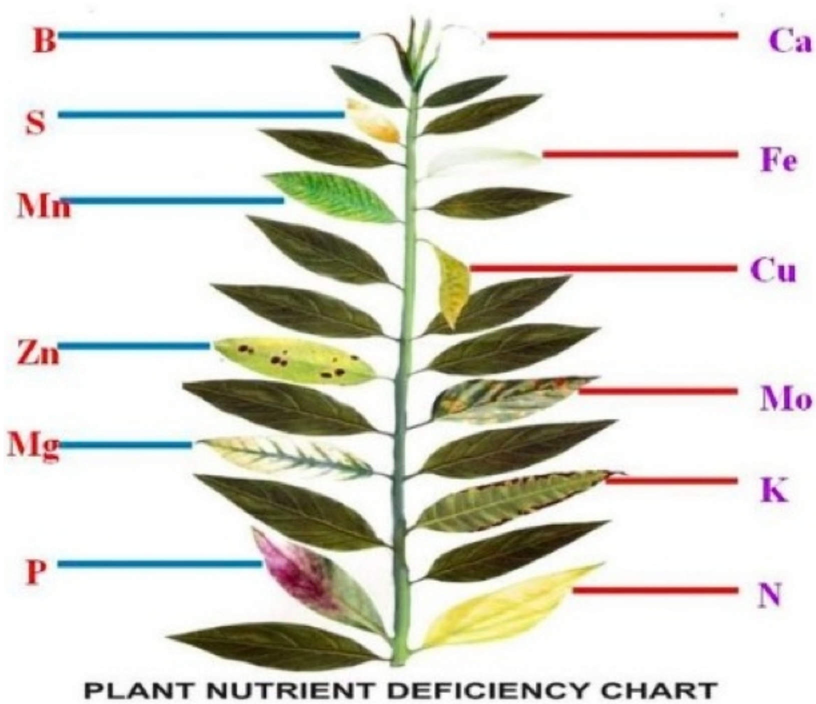


Figure 21: Plant deficiencies. (Source: Direct Compost Solutions)

6.3 Role of Bacteria

Rhizobacteria live in the **rhizosphere**, the soil close to plant roots. They depend on the nutrients secreted by plants, and in return, they produce antibiotics to protect roots, absorb toxic metals, help obtain nutrients, fix nitrogen, and stimulate plant growth. Some of them are free-living, while some are **endophytes**, living between cells within the plant.

Bacteria have an important part in the nitrogen cycle. Plants commonly get nitrogen in the form of nitrate, NO_3^-. **Nitrification** is the process by which other forms of nitrogen are converted to NO_3^-, with ammonia (NH_3) is turned into nitrite NO_2^-, and then into nitrate. **Nitrifying bacteria** mediate these steps, allowing plants to obtain nitrogen. Sometimes, NO_3^- is lost, so **denitrifying bacteria** convert it into N_2, which is diffused into the atmosphere. Plants can also use ammonium (NH_4^+), which can be obtained in 2 processes. In one, **nitrogen-fixing bacteria** convert N_2 into NH_3, which gains an H^+ in the soil. The other is **ammonification**, in which decomposers create NH_4^+ from dead organic matter in the soil.

Bacteria are particularly important in nitrogen fixation, as they are the only organisms that can do so. **Nitrogenase** is used in nitrogen fixation, using up 16 ATP for every $2NH_3$. *Rhizobium* bacteria form close associations with **legume** roots, through "infected" swellings called **nodules**. *Rhizobium* are in a **bacteroid** form in the nodules and generate usable nitrogen for plants.

Nitrogen fixation is incredibly important in agriculture, as it keeps soil fertile for new crops. As such, some farmers use **crop rotation**, alternating between legumes and other plants to replenish the nitrogen in the soil. Artificial nitrogen fertilizers are also used, but are generally harmful to the environment.

6.4 Role of Fungi

Mycorrhizae are the close associations between plant roots and fungi. The plant gives the fungus sugar, while the fungus increases root surface area for water uptake and provides minerals absorbed from the soil. The fungus can also secrete antibiotics and growth factors to help the roots.

There are two types of mycorrizhae, ectomycorrhizae and arbuscular mycorrhizae. **Ectomycorrhizae** forms a mantle of **mycelia** (branching hyphae mass) over a root's surface. The hyphae grow into the root's cortex, but only in the apoplast. They are found in some woody plants, like pines, oaks, birches, and eucalypti. **Arbuscular mycorrhizae** or endomycorrhizae are embedded in the root, entering the cell wall and invaginating the cell membrane. They are present in about 85 percent of plants.

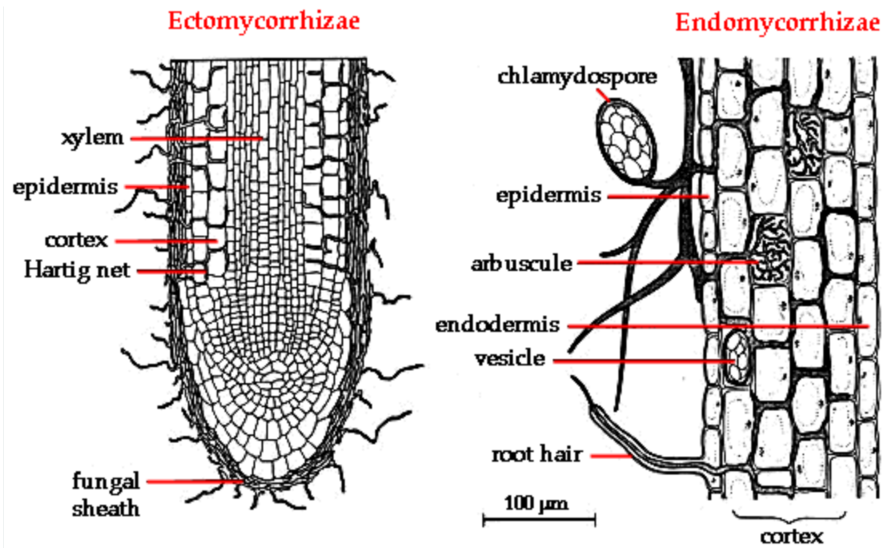


Figure 22: Types of mycorrhizae. (Source: Giordano's)

7 Resource Acquisition

7.1 Vascular Plant Adaptations

Leaf size can be used to optimize light capture. For instance, *Raphia regalis* has giant leaves, but *Crassula connata* has very small ones. Smaller leaves are used where evaporative loss is a issue, but larger ones can capture more light.

Phyllotaxy, the arrangement of leaves on a stem, is another means by which plants can optimize light capture. Phyllotaxy is determined by the arragnement of the shoot apical meristem and comes in a few categories:

- **Alternate**: has 1 leaf per node, alternates between opposing sides at each node
- **Spiral**: also has 1 leaf per node, but spirals around the stem
- **Opposite**: has 2 leaves per node on opposite sides.

- **Decussate**: very similar to opposite, except each pair of leaves is offset 90°. So, if at one node the leaves are north/south, the leaves at the node below will be east/west.
- **Whorled**: has 3 or more leaves per node.

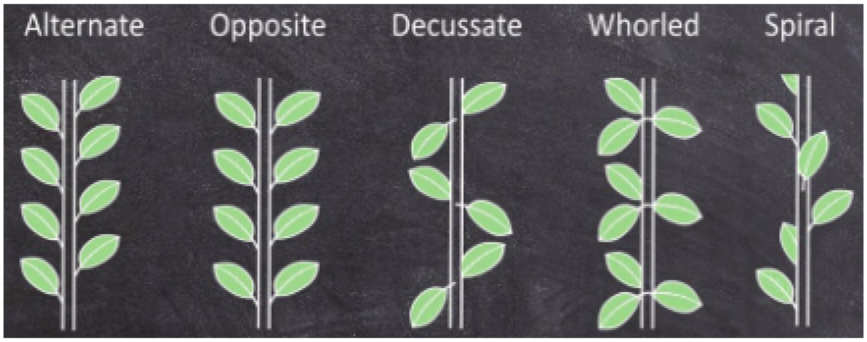


Figure 23: Types of phyllotaxy (Source: sci-ology)

137.5° was determined to be the optimal angle between leaves to minimize shading. Plants also self-prune, removing shaded lower leaves with lower rates of photosynthesis through apoptosis. Leaf orientation also comes into play, as horizontally-oriented leaves capture light better, but may lead to light damage and block lower leaves.

Roots also have adaptations for optimal acquisition of water and minerals. Roots adjust themselves to drive straight through low-nitrate pockets of soil instead of wasting resources branching, and produce more nitrate transport and assimilation proteins in areas with higher nitrate levels. Roots can also distinguish self from nonself, growing less in the presence of its own roots. Mycorrhizae also optimize water and mineral absorption.

7.2 Transport Mechanisms

Plants use different mechanisms over short or long distances.

- **Apoplast and Symplast**

  The **apoplast** is everything outside of the plasma membranes of living cells, including cell walls, extracellular spaces, and the interior of dead cells. The **symplast** is everything that is living, the cytosol, plasmodesmata, and cytoplasmic channels.

  The **apoplastic route** of transport consists of the cell walls and extracellular spaces, the **symplastic route** is entirely through cytosol, crossing plasma membranes and plasmodesmata, and the **transmembrane route** crosses both membranes and cell walls.

- **Short-distance transport of solutes across plasma membranes**

  Plants utilize H^+ pumps to create a membrane potential. Cotransport is conducted with H^+ to take up substances like sucrose and nitrate.

  Gated ion channels are also present in plants to send messages and create responses. For instance, guard cells of the stomata use potassium ions to control opening and closing, and plants use calcium ion-activated ion channels.

- **Short-distance transport of water across plasma membranes**

  The passive transport of water across membranes is called **osmosis**. The direction of osmosis can be found by calculating the **water potential**, or Ψ, measured in MPa. Ψ is equal to = in pure water in open, standard conditions.

$$\Psi = \Psi_s + \Psi_p$$

Ψ_s is the **solute/osmotic potential**. It is directly proportional to molarity.

$$\Psi_s = -\text{iCRT}$$

i = number of ions the solute dissociates into
C = molar concentration of solute
R = pressure
T = temperature, in Kelvin

Ψ_p is the **pressure potential**, which can be positive or negative. In plants, living cells have positive pressure potential as a result of turgor pressure and have a negative pressure potential when dead.

Water flows from areas of high potential to those of low potential.

> **Example 7.1** (USABO Open Exam 2017) In your laboratory, you have *Arabidopsis thaliana* in pot A and pot B. You water the *Arabidopsis* in pot A each day and keep it in very limited sunshine. For the *Arabidopsis* in Pot B, you add salt to the soil and expose it to very strong sunshine with very limited water. You measure the water potential of plants in both pots at the root, stems and the leaves. Select ALL the following statements about the plants that are TRUE.
>
> (A) In the plant in pot B, since there is salt in the soil, the water potential in the root is lower than the water potential in the stem.
> (B) In the plant in pot B, since there is a lot of evaporation in the leaves, the water potential of the leaves is lower than the water potential of the stems.
> (C) Water typically moves from lower potential to higher potential.
> (D) In the plant in pot A, the potential of the leaves is higher than the potential of the stem as there is little evaporation from the sun.

Solution: A is wrong because there is also very strong sunshine, which draws water up. C is incorrect; water moves from high to low potential. D is incorrect because while there is a higher potential in the leaves, the water remaining in the vascular cylinder causes a higher pressure in the roots, balancing the changes out. **B is correct** because evaporation causes the leaves to be drier, and have lower water potential.

- **Bulk Flow (Long-distance)**

  While diffusion can be used over small distances, it would take too long over larger ones. **Bulk flow** is the movement of liquid in response to a pressure gradient, moving from areas of high pressure to those of low pressure. It acts independently of solute concentration. Bulk flow is used within tracheids and vessel elements and sieve-tube elements. Bulk flow cooperates with diffusion and active transport. For instance, the bulk flow of sugar depends on a pressure difference, but active transport of sugars maintains said difference.

7.3 Xylem Transport

Transpiration is what transports water and minerals from the roots to the shoots, through the xylem.

First, root cells absorb water and minerals. Root hairs absorb soil solution (water and dissolved minerals). The solution enters the hydrophilic walls of epidermal cells, passes freely into the root cortex, and active transport allows the cell to accumulate minerals.

Then, the water and minerals are transported into the xylem. The **endodermis** is the last checkpoint for the plant to make sure no toxic substances are being taken in. Minerals that are already in the symplast at this point have been screened by the plasma membrane they went through, and continue through plasmodesmata into the xylem. Minerals in the apoplast reach the **Casparian strip**, made of suberin. This forces them to cross the plasma membrane of an endodermal cell, keeping unneeded substances out and preventing accumulated substances from leaking out. Endodermal cells and cells in the vascular cylinder send minerals from protoplasts into cell walls, using diffusion and active transport.

The xylem then uses bulk flow, powered by transpiration, to transport xylem sap. There are two mechanisms by which xylem sap is sent up the vascular cylinder. **Root pressure** can cause xylem sap to be pushed up the cylinder. At night, there is no transpiration, and lots of ions accumulate in the vascular cylinder, giving it a low water potential. Water then flows into the vascular cylinder from the root cortex, which creates pressure. **Guttation** (different than dew) results, which is when root pressure pushes water out of the leaves. However, the effects of root pressure are very minor. Most movement is by pulling xylem sap up, explained by the **Cohesion-Tension hypothesis**. First, transpirational pull pulls xylem up. Air spaces in leaves are usually moist, saturated with water vapor, whereas air outside leaves is drier, with a low water potential. This creates a pulling force. The following diagram shows the specifics of transpirational pull.

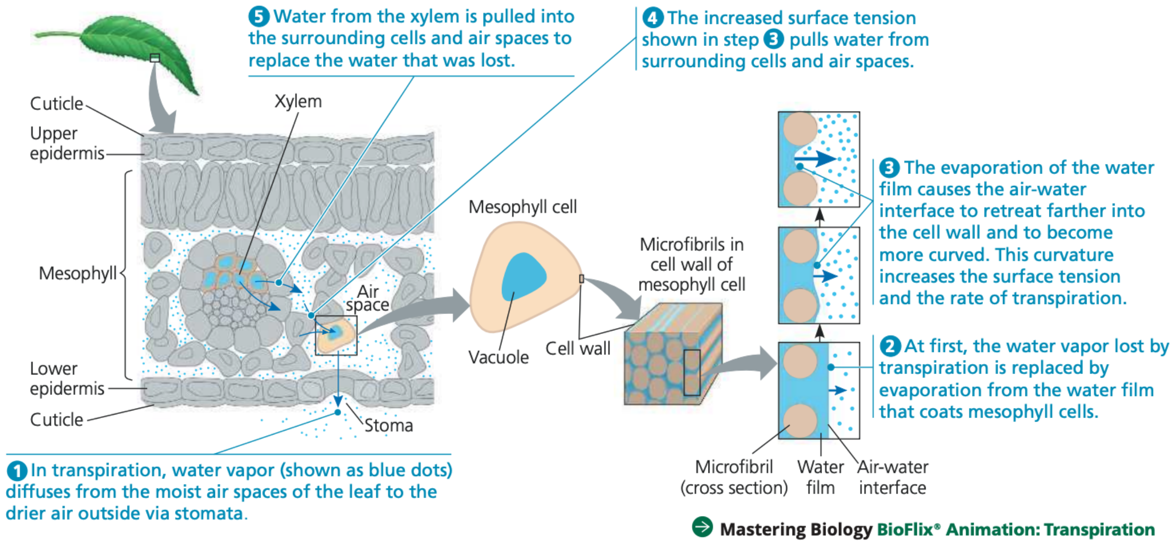


Figure 24: Generation of transpirational pull. (Source: Campbell Biology)

Cohesion and adhesion make this possible. Cohesion makes the xylem sap a column that can be pulled, and adhesion to the walls offsets gravity. There are thicker secondary walls in vessel elements and tracheids to prevent them from collapsing under this pressure.

Cavitation is when a water vapor pocket forms in the xylem, breaking the chain of water molecules. It is more common in vessel elements because they are thicker. They occur during drought stress or the freezing of xylem sap in winter. The air bubbles may expand and block water channels, but detours can be made around the bubbles. Cavitation may also be repaired.

7.4 Stomata and Transpiration

Stomata are pores on leaves whose opening and closing are controlled by 2 **guard cells**. The guard cells themselves are surrounded by **subsidiary cells**, which provide support.

Stomatal density on a leaf is both genetic and environmental. For instance, shade-tolerant species of plants have fewer stomata, as carbon dioxide uptake doesn't limit photosynthesis when there is no sun. If plants have low carbon dioxide levels when developing, they develop higher stomatal density to compensate.

Stomata depend on potassium ions to open and close. Guard cells have thicker walls facing the pore, and having cellulose microfibrils oriented so guard cells bow outward when turgid. When the stomata needs to open, guard cells actively accumulate potassium ions from nearby epidermal cells. K^+ flowing into a guard cell is coupled to proton pumps generating a membrane potential by pumping protons out.

Stomata are open during the day, and closed at night. Light stimulates guard cells to accumulate potassium ions and become turgid, as the illuminating blue-light receptors in the plasma membrane stimulates proton pumps, resulting in more K^+ moving in. CO_2 depletion is also a stimulus for stomata to open, making stomata open during the day when CO_2 decreases. A plant's circadian rhythms can also regulate stomatal opening and closing. Drought stress may cause stomata to close via the production of abscisic acid.

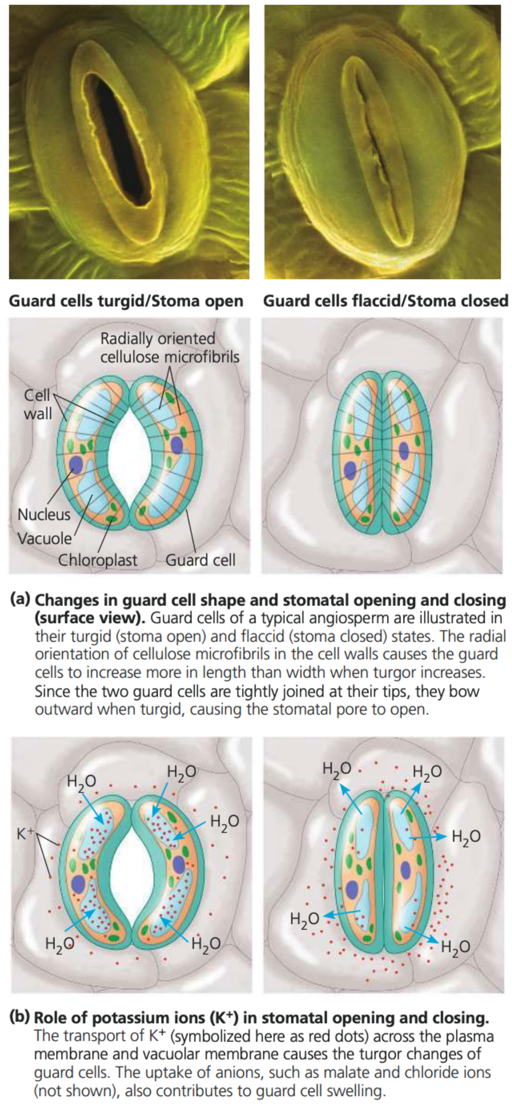
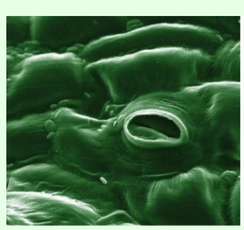


Figure 25: Stomatal opening and closing. (Source: Campbell Biology)

Example 7.2 (USABO Open Exam 2014) The structure in the image on the right is NOT important for which of the following:



(A) Playing an important role of plants movement to land.
(B) Preventing the majority of water loss in the process of transpiration
(C) Providing a major avenue of evaporative loss of water
(D) Recycling the total water content of the atmosphere.
(E) Regulating CO_2 uptake in photosynthesis.

Solution: The picture shows a stoma. All are correct **except for B**, as transpiration by definition is water loss. Stomata often support transpiration if it is beneficial to photosynthesis.

7.5 Phloem Transport

Sugar can move both up and down in the phloem, from sugar source to sugar sink. The transport of photosynthates is called **translocation**.

Phloem sap, a sugary (usually sucrose), syrupy fluid that may also have amino acids, hormones, and minerals, is what flows in the phloem. A sugar source is a plant organ that is a net producer of sugar, usually mature leaves or storage organs in the spring. Sugar sinks are net consumers or depositories of sugar, such as areas that are growing or storage organs during the summer. The transport of sugar from sources to sinks occurs via the **pressure-flow hypothesis**.

Phloem sap is loaded into sieve-tube elements through symplastic or apoplastic pathways. Active transport is required to bring phloem sap into the sieve-tube elements, as sucrose is more concentrated there than in mesophyll. This is done through proton pumps and the H^+/sucrose transporter. Unloading is done passively, as the concentration of sucrose in the sink is always lower than in the phloem. The solutes diffuse out, and water follows by osmosis.

Example 7.3 (USABO Open Exam 2015) Which of the following statements about long distance transport systems in plants are TRUE?

(A) Phloem requires rigid cell walls to prevent implosion.
(B) Phloem transport can be multidirectional.
(C) Phloem transport is dependent upon metabolic activity.
(D) The driving force that moves water in the xylem is ultimately derived from the energy of the sun.
(E) Xylem transport occurs through the living xylem conduits.

Solution: A is wrong because phloem does not have secondary cell walls, and thus, is not rigid. B is correct, as phloem transport can go both up and down. C is correct because the flow of phloem sap is from sugar sources to sugar sinks. D is correct because the pulling force on xylem sap is caused by transporation. E is wrong because xylem cells are dead and lignified. Thus, **BCD**.

8 Conclusion

Plants have been around for a long time and there's a lot more to them than just what meets the eye. As a human needs food and water, plants do too, they simply just source it differently.