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Recently Updated Pages All living organisms have the need to exchange substances with their surrounding environmentPlants need to take carbon dioxide and nutrients inWaste products generated need to be released The location within an organism where this exchange occurs is described as an exchange siteE.g. roots in plants (water and minerals)Substances are said to not have entered or left an organism until it crosses the cell surface membraneSmall organisms like the single-celled Chlamydomonas are able to exchange substances directly with the environmentThis is due to their large surface area: volume ratioThe diffusion or transport distance in these organisms are also very small so essential nutrients or molecules are able to reach the necessary parts of the cell efficientlySmaller organisms tend to have lower levels of activity and so smaller metabolic demandsLarger organisms require specialised mass transport systems for a number of reasons:Increasing transport distancesSurface area: volume ratioIncreasing levels of activityEvery cell in a plant requires water, glucose and mineral ionsThe roots of a plant take in water and mineral ions while the leaves produce glucose by photosynthesisThese molecules need to be transported to the other parts of the plantGlucose is transported as sucrose in plantsThis large transport distance makes simple diffusion a non-viable method for transporting substances all the way from the exchange site to the rest of the organismDiffusion wouldn't be fast enough to meet the metabolic requirements of cellsSurface area and volume are both very important factors in the exchange of materials in organismsThe surface area refers to the total area of the organism that is exposed to the external environmentThe volume refers to the total internal volume of the organism (total amount of space inside the organism)As the surface area and volume of an organism increase (and therefore the overall 'size' of the organism increases), the surface area: volume ratio decreasesThis is because volume increases much more rapidly than surface area as size increasesSingle-celled organisms have a high SA: V ratio which allows for the exchange of substances to occur via simple diffusionThe large surface area allows for maximum absorption of nutrients and gases and secretion of waste productsThe small volume means the diffusion distance to all organelles is shortAs organisms increase in size their SA: V ratio decreasesThere is less surface area for the absorption of nutrients and gases and secretion of waste productsIn addition, the greater volume results in a longer diffusion distance to the cells and tissues of the organismThere are several adaptations present in plants that help to increase their SA: V ratioPlants have a branching body shapeLeaves are flat and thinRoots have root hairsLarger organisms are not only more physically active but they also contain more cells than smaller organismsA larger number of cells results in a higher level of metabolic activityAs a result, the demand for oxygen and nutrients is greater and more waste is producedPlant cells and tissues have a much lower metabolic rate than animal cellsTherefore their demand for oxygen for aerobic respiration is reducedPlants have evolved specialised mass flow transport systems that enable the efficient transport of nutrients and wasteMass flow is the bulk movement of materials. It is directed movement so involves some source of forceIn mass transport systems there is still some diffusion involved but only at specific exchange sites at the start and end of the route travelled by the substancesThe lungs are the exchange site of the gas exchange systemMass transport systems help to:Bring substances quickly from one exchange site to anotherMaintain the diffusion gradients at exchange sites and between cells and their fluid surroundingsEnsure effective cell activity by keeping the immediate fluid environment of cells within a suitable metabolic rangeFlowering plants have evolved two separate mass transport systems:The xylem transports water and mineral ionsThe phloem transports sucrose and other nutrientsNotably, plants have no specialised transport system for oxygen and carbon dioxideThey do not need one because:They have adaptations that give them a high SA: V ratio for the absorption and diffusion of gasesThe leaves and stems possess chloroplasts which produce oxygen and use up carbon dioxideThere is a low demand for oxygen due to plant tissues having a low metabolic rateDid this page help you? Mechanism of Transportation in Plants: Discover how transportation occurs in plants through xylem and phloem. Learn about the aiding processes, and compare plant and animal transport systems in function and structure. Mechanism of Transportation in Plants Table of Contents Introduction to Mechanism of Transportation in Plants Why Do Plants Need a Transport System? Transport Tissues in Plants Xylem: Transport of Water and Minerals Mechanism of Water Transport in Xylem Phloem: Transport of Food Mechanism of Food Transport in Phloem Differences Between Xylem and Phloem Importance of Transportation in Plants Processes which aid transportation in plants and similarities and differences between transport in animals and plants Conclusion 1. Introduction to Mechanism of Transportation in Plants Unlike animals, plants are stationary, but they still need to move vital substances like water, minerals, and food throughout their bodies. This internal movement is called transportation in plants. Although plants don't have a heart or blood vessels like animals, they possess a highly efficient system made up of specialized tissues that perform transport functions. This blog explains how plants transport water, nutrients, and food from one part to another, ensuring growth, survival, and reproduction. READ ALSO – Differences Between Respiration and Photosynthesis 2. Why Do Plants Need a Transport System? Plants require a transport system for several reasons: Roots absorb water and minerals from the soil, which must reach leaves and other parts. Leaves produce food via photosynthesis that must be transported to all parts of the plant. Hormones and other substances also need to be distributed efficiently. Waste products must be removed or stored safely. Without a proper transport system, plants would be unable to survive, especially the larger ones. Plants use two main types of transport tissues: Xylem: Carries water and minerals from the roots to the rest of the plant. Phloem: Transports food (mainly sugars) produced in the leaves to other parts of the plant. These tissues are found in vascular bundles and extend throughout the roots, stems, and leaves, forming a continuous network. Xylem is a complex tissue made of dead cells that form long tubes. It is responsible for: Transporting water from the roots to the leaves Carrying dissolved minerals absorbed from the soil Xylem vessels are strengthened by lignin, which makes them rigid and helps support the plant. The upward movement of water in plants, also called the ascent of sap, is powered by several mechanisms: Root Pressure: As roots absorb water, pressure builds up and pushes water upward. Capillary Action: Water moves up through narrow xylem vessels due to adhesion and cohesion forces. Transpiration Pull: The major force. As water evaporates from the leaves (transpiration), it creates a suction force that pulls water up from the roots. This entire process does not require energy from the plant, making it a passive process. Phloem is a living tissue that carries food from the leaves (where it is made) to all parts of the plant. This movement is known as translocation. Unlike xylem, phloem transports substances in both upward and downward directions depending on the plant's needs. Phloem consists of: Sieve tube elements (transport food) Companion cells (assist in loading and unloading of food) Phloem transport is an active process and requires energy. The steps include: Loading of sugar into sieve tubes by companion cells using energy (ATP). Water enters by osmosis, increasing pressure in the sieve tube. This pressure pushes the sugar solution through the phloem to areas that need it (roots, fruits, etc.). At the sink (storage or growing regions), sugar is unloaded, and water exits, relieving pressure. This pressure-flow mechanism is also called the mass flow hypothesis. FeatureXylemPhloemFunctionTransports water and mineralsTransports food and nutrientsDirection of FlowUpward onlyBoth upward and downwardLiving or Dead CellsMostly dead cellsLiving cellsEnergy RequirementPassive processActive process (requires energy)Cell Types InvolvedVessels, tracheids, fibersSieve tubes, companion cells The transport system in plants is crucial for: Delivering water and minerals to leaves for photosynthesis Distributing food to growing parts, storage organs, and roots Maintaining internal balance and turgor pressure Supporting metabolic processes and reproduction Without efficient transportation, plants would not be able to sustain themselves, especially those with large structures like trees. Several natural processes assist the movement of substances in plants. These processes ensure efficient transport from one part of the plant to another. 1. Osmosis This is the movement of water molecules through a semi-permeable membrane from a region of lower solute concentration to a region of higher solute concentration. Osmosis plays a critical role in water absorption by root hairs and helps maintain turgor pressure in cells. 2. Diffusion Diffusion is the movement of particles from an area of higher concentration to an area of lower concentration. It is essential in gas exchange (carbon dioxide and oxygen) in leaves and also helps minerals move into the roots. 3. Root Pressure This is the pressure created by the active uptake of minerals and water into the roots. It helps push water up through the xylem, especially during the night when transpiration is low. 4. Capillarity (Capillary Action) This is the ability of water to rise through narrow tubes due to adhesive and cohesive forces. In plants, capillary action helps water travel upward through the fine xylem vessels. 5. Transpiration Pull Transpiration is defined as the removal of excess water from plants into the atmosphere in form of water vapor. Plant are capable of losing excess water through the stomata in the leaves and this is called stomata transpiration Through the lenticels in the stem and this is called plenticular transpiration Through the cuticle of the leaf surface in what is called cuticular transpiration. This is the primary mechanism for upward water movement in tall plants. As water evaporates from the leaf surface, it creates a negative pressure that pulls more water upward through the xylem. 6. Active Transport Involves the movement of ions or molecules across cell membranes using energy. It is essential in loading sugars into the phloem and in mineral absorption from the soil. While plants and animals have different structures, their transport systems share some fundamental similarities. However, key differences also exist due to their contrasting modes of life. Similarities Both use specialized transport systems: Plants use xylem and phloem; animals use the circulatory and lymphatic systems. Both transport essential substances: Such as water, nutrients, and gases. Both involve active and passive processes: Like diffusion, osmosis, and active transport. Both systems are vital for survival and function: Ensuring cells get what they need and wastes are removed. Differences FeaturePlantsAnimalsMain Transport MediumXylem sap (water/minerals), phloem sapBlood and lymphTransport TissuesXylem and phloemArteries, veins, capillaries, lymph vesselsPumping OrganNoneHeartFlow DirectionXylem is unidirectional; phloem is bidirectionalBlood circulates in closed loopsEnergy RequirementXylem is passive; phloem is activeRequires energy for circulationMobilityStationary organismsMobile organismsWaste TransportLimited—stored in leaves or vacuolesEfficient excretory systems like kidneys 1. What are the two main transport tissues in plants and what do they carry?Answer: Xylem carries water and minerals from the roots to the leaves. Phloem carries food (mainly sugars) from the leaves to other parts of the plant. 2. Which process is responsible for the upward movement of water in plants, especially during the day? Answer:Transpiration pull, which occurs as water evaporates from the leaves and pulls more water up through the xylem. 3. How does the phloem differ from the xylem in terms of structure and function?Answer:Phloem is made of living cells and transports food in both directions, while xylem is made of dead cells and transports water only upward. 4. What is translocation in plants?Answer:Translocation is the movement of food substances (mainly sugars) through the phloem from source (leaves) to sink (roots, fruits, growing regions). 5. Name three processes that aid transportation in plants.Answer: Osmosis Transpiration pull Capillary action 6. Why is active transport important in phloem function?Answer:Because it is used to load sugars into the phloem sieve tubes using energy (ATP), initiating the flow of food. 7. Compare the direction of flow in xylem and phloem.Answer: Xylem: Unidirectional (roots to leaves) Phloem: Bidirectional (leaves to other parts and vice versa) 8. What is root pressure and when is it most active?Answer:Root pressure is the force created by water entering root cells, pushing water upward. It is most active at night or when transpiration is low. 9. Mention two similarities between transportation in plants and animals.Answer: Both use specialized transport systems (xylem/phloem in plants; blood vessels in animals). Both involve active and passive processes like diffusion and osmosis. 10. List two key differences between plant and animal transport systems.Answer: Plants lack a pumping organ like the heart. Animal transport systems are typically closed and powered by circulation, while plant transport relies on passive processes and pressure gradients. READ ALSO – Mechanism of Transportation in Higher Animals Conclusion on the mechanism of transportation in plants The mechanism of transportation in plants is a remarkable system of internal movement that supports life without the need for a circulatory organ. Xylem carries water and minerals passively from the roots upward, while phloem actively distributes food throughout the plant. These two transport systems work in harmony, helping plants grow, survive, and thrive in various environments. Understanding plant transport helps us appreciate how even non-moving organisms perform complex life functions efficiently. In this article, we are going to learn about the transportation in plant and how plants transport water and nutrients to all parts to grow and survive. We already know that the leaves produce food by using water, sunlight, and carbon dioxide through a process known as photosynthesis. Have you ever wondered how plants transport food and water to other parts of the plant? The transportation system of a plant is like a human's circulatory system—just without all the blood. Instead of the blood, the transportation system helps distribute water and nutrients. Plants have a transport system:To carry water and minerals absorbed by the roots up to the leaves, andTo carry food (sugar and amino acids) from the leaves to all parts of the plant.In simple words, plants have a transport system to carry water and nutrients to all parts of the plant.Transportation in plants is made up of two vascular tissues. They are called the xylem, which transports water and minerals, and the phloem, which is responsible for food distribution. Let's have a deeper look into both of the vascular tissues.A tissue is a group of cells that perform specialized functions in an organism. Xylem is a tissue in vascular plants that transports water and dissolved minerals from the roots to the leaves through the stem and branches. Xylem transports water in only one direction: upwards.Now you may wonder, Why do plants even need a xylem? They can just absorb water from their leaves, right? Well, the answer is that they can't. Plants don't have the ability to absorb water from the environment. They can only get it from the roots.So plants use the xylem vessels to transport water from the roots to the leaves to produce food through the process of photosynthesis. Again, you may wonder, How do plants defy gravity? Do they have a pump like us humans do, or is it something else? The answer to this question is evaporation. In a plant, water is constantly being evaporated. The tiny pores of leaves, called stomata, open up for gas exchange, and while they have opened up, evaporation occurs. This process is called transpiration. The evaporation of the water causes a suction-like force, also known as transpiration pull. This, in turn, helps the xylem pull water in an upward direction and transport it to the other parts of the plant. Transpiration is similar to when you drink something with a straw—there is a suction force that helps you drink it. Xylem consists of four types of cells: xylem parenchyma xylem fibres xylem tracheids xylem vessels All the elements of xylem tissue are dead except the parenchyma, which are living cells with thin walls.The xylem tissues have no organelles (mitochondria, nucleus, chloroplast, vacuole, and cytoplasm).Since the conduction of water is the primary job of xylem, it's elements need to form a narrow pipe-like structure so that water can rise in the pipe through capillary action. Phloem is a vascular tissue that transports food from the leaves to all the other parts of the plant, including the roots.The food produced in the leaves during photosynthesis consists of glucose. The phloem vessel transports food to all parts of the plant in the form of glucose solution. The transportation of food in phloem is called translocation.Phloem is known as bi-directional because it carries food in both directions, upward and downward.Phloem is composed of various cells:sieve elements,phloem fibres,phloem parenchyma cells.Unlike xylem, phloem consists of living cells that carry sap. Sieve elements are living cells that contain little cytoplasm and no nucleus.Sap is a liquid that contains water and dissolved substances such as sugars and minerals. Transpiration is the process by which water is lost as water vapor from the upper parts of a plant through the stomata (the tiny pores of leaves). Leaves continuously lose water to the environment by evaporation.Stomata open during the day to allow gas exchange and close at night to limit transpiration. The opening and closing of the stomata are due to specialized cells called guard cells. When water enters the guard cells, they become turgid or swollen, and the stoma opens. When the guard cells lose water, they become flaccid and straight, and the stoma closes. The flow of water up to the leaves through the stem is useful for many reasons, including: Supply water for photosynthesis. Creates transpiration pull for transport of water Transports water and minerals from soil to all parts of the plant Removes the excess water. Control the temperature of the plant to keep it cool. The transportation of food from leaves to other parts of the plant is called translocation. A group of xylem and phloem vessels is called a vascular bundle. You can also learn from this. Plants have different tissues that carry water, nutrients and minerals from one part to another. These processes help the plants keep the balance of water and nutrients equal so that the photosynthesis process happens smoothly. In order to maintain the balance of necessary elements in the plants' bodies, they need a transportation system. To ensure "sufficient absorbing surface area", plants need a transportation system. The nature of the "transportation system in plants" is very slow as only two main issues help in the transportation system. Animals and plants both use transportation systems, but the main difference between "plants transportation system" and the "animals transportation system" is that animals "use their blood to transport carbon dioxide and oxygen". On the other hand, plants carry minerals and water to their body for transportation. Definition of Transport system in PlantsIt is a vital system in plants because all the nutrients, minerals, and water needed for survival are carried through the tissues from one part to another. This process is very slow because plants have only two tissues in their body to complete the entire process smoothly. A plant must complete this process multiple times in a day to keep the balance of water and nutrients equal to all the parts of it. Transportation of food also happens in plants, and the entire process is known as "translocation". This process is also completed with the help of one tissue that transports food from one part to another in plants. Importance of Transport system in plantsTransportation plays a vital role in plants because it helps the growth and nourishment by keeping the balance of nutrients, minerals and water equal in all parts of plants. As animals require blood and oxygen to live, similarly, plants also need water, minerals and nutrients for their body to prepare food and to survive. So, transportation is important because it helps survive the plants with the help of water, nutrients and minerals. Different parts of plants require different nutrients, which the transportation system carries in plants' bodies. A plant must complete this process successfully; otherwise, it might lose its immunity power. Types of plants' transport systems Mainly, two types of tissues help in the "transportation system in plants" by carrying water and other nutrients from one part to another. Below are the mentioned issues. These are the two tissues that maintain the flow of water and minerals in the plants' bodies by securing the lives of plants. Suppose a plant cannot complete this process, then the supply of food and water will not be appropriate to all the plant parts. In this case, the plant will not complete the photosynthesis process successfully. As a result, the plant will not grow properly and will not be nourished. Working methods of transport systems in plantsXylem and Phloem are responsible tissues that transport water and food in different plants. Xylem is the vascular tissue that conveys dissolved minerals and water from the roots to other parts of a plant by providing physical support to the plant. Xylem tissue is made of "multiple water-conducting cells" known as treachery elements. These cells help to absorb water and other dissolved minerals and then conveys them to plants' bodies. Phloem is a kind of vascular tissue that conducts foods prepared during photosynthesis in the plants' leaves and then carries the food in different parts of a plant, so the plant gets nourished by getting the nutrition power of the foods. This tissue is composed of "various specialised cells" like "phloem fibres, phloem parenchyma cells" called sieve elements. Conclusion The importance of the "transport system in plants" cannot be defined in one word because this is the process by which plants get their required nutrition and growth by which they can survive in nature. As plants cannot express their pain through words that does not mean that they do not need anything to survive on the earth. They complete their requirements in their way, and every function of plants is equally important as all of them are interrelated. In order to keep plants nourished and healthy, this process needs to be completed successfully among plants. Otherwise, plants will not be able to survive in the nature without the help of transport system. BBC Weather in association with MeteoGroupAll times are British Summer Time (Europe/London, GMT+1) unless otherwise stated. At the end of this chapter you will be able to: Identify the different tissue types in plants Explain how water moves from the roots of a plant up to the leaves Explain how food made by the plant moves from its leaves to the roots for storage Define water potential and explain how it is influenced by solutes, pressure, gravity, and the matric potential Describe how water potential, evapotranspiration, and stomatal regulation influence how water is transported in plants Compare and contrast xylem and phloem Define water potential and explain how it is influenced by solutes and pressure Introduction All living organisms need a way to move nutrients, gasses, water, and waste within their bodies. Some plants and animals are small enough and/or thin enough that they can rely on diffusion for this process; however, larger plants and animals need a more organized system to transport things from one part of their body to another. A common analogy is to consider cells acting as "pipes" for such transport. Before we begin to discuss transport in more detail, we will first need to gain some understanding of plant tissues in general. Plant Tissues Plants are multicellular eukaryotes with tissue systems made of various cell types that carry out specific functions. Plant tissue systems fall into one of two general types: meristematic tissue and permanent (or non-meristematic) tissue. Cells of the meristematic tissue are found in meristems, which are plant regions of continuous cell division and growth. Meristematic tissue cells are either undifferentiated or incompletely differentiated, and they continue to divide and contribute to the growth of the plant. In contrast, permanent tissue consists of plant cells that are no longer actively dividing. Meristematic tissues consist of three types, based on their location in the plant. Apical meristems contain meristematic tissue located at the tips of stems and roots, which enable a plant to extend in length. Lateral meristems facilitate growth in thickness or girth in a maturing plant. Intercalary meristems occur only in monocots, at the bases of leaf blades and at nodes (the areas where leaves attach to a stem). This tissue enables the monocot leaf blade to increase in length from the leaf base; for example, it allows lawn grass leaves to elongate even after repeated mowing. Meristems produce cells that quickly differentiate, or specialize, and become permanent tissue. Such cells take on specific roles and lose their ability to divide further. They differentiate into three main types: dermal, vascular, and ground tissue. Dermal tissue covers and protects the plant, and vascular tissue transports water, minerals, and sugars to different parts of the plant. Ground tissue serves as a site for photosynthesis, provides a supporting matrix for the vascular tissue, and helps to store water and sugars. Secondary tissues are either simple (composed of similar cell types) or complex (composed of different cell types). Dermal tissue, for example, is a simple tissue that covers the outer surface of the plant and controls gas exchange. Vascular tissue is an example of a complex tissue, and is made of two specialized conducting tissues: xylem and phloem. Xylem tissue transports water and nutrients from the roots to different parts of the plant, and includes three different cell types: vessel elements and tracheids (both of which conduct water), and xylem parenchyma. Phloem tissue, which transports organic compounds from the site of photosynthesis to other parts of the plant, consists of four different cell types: sieve cells (which conduct photosynthates), companion cells, phloem parenchyma, and phloem fibers. Unlike xylem conducting cells, phloem conducting cells are alive at maturity. The xylem and phloem always lie adjacent to each other (Fig 1). In stems, the xylem and the phloem form a structure called a vascular bundle; in roots, this is termed the vascular stele or vascular cylinder. Figure 1: This light micrograph shows a cross section of a squash (Curcurbita maxima) stem. Each teardrop-shaped vascular bundle consists of large xylem vessels toward the inside and smaller phloem cells toward the outside. Xylem cells, which transport water and nutrients from the roots to the rest of the plant, are dead at functional maturity. Phloem cells, which transport sugars and other organic compounds from photosynthetic tissue to the rest of the plant, are living. The vascular bundles are encased in ground tissue and surrounded by dermal tissue. (credit: modification of work by "(biophotos)"/Flickr; scale-bar data from Matt Russell) Because it is important to understand plant transport, we will focus more on the vascular tissue of plants: xylem and phloem. These tissues make up the vascular tissue of the stem and are arranged in distinct strands called vascular bundles, which run up and down the length of the stem. When the stem is viewed in cross-section, the vascular bundles of dicot stems are arranged in a ring. In plants with stems that live for more than one year, the individual bundles grow together and produce the characteristic growth rings. In monocot stems, the vascular bundles are randomly scattered throughout the ground tissue (Fig 2). Figure 2: In (a) dicot stems, vascular bundles are arranged around the periphery of the ground tissue. The xylem tissue is located toward the interior of the vascular bundle, and phloem is located toward the exterior. Sclerenchyma fibers cap the vascular bundles. In (b) monocot stems, vascular bundles composed of xylem and phloem tissues are scattered throughout the ground tissue. Xylem tissue has three types of cells: xylem parenchyma, vessel elements (Figs 3 & 4) and tracheids (Fig 5). The latter two types conduct water and are dead at maturity. Tracheids are xylem cells with thick secondary cell walls that are lignified. Water moves from one tracheid to another through regions on the side walls known as pits, where secondary walls are absent. Vessel elements are xylem cells with thinner walls; they are shorter than tracheids. Each vessel element is connected to the next by means of a perforation plate at the end walls of the element. Water moves through the perforation plates to travel up the plant. Figure 3: A cross-section micrograph of large xylem vessel element cells with thick red-stained lignified cell walls. Xylem parenchyma adjacent to the cells have blue green cell walls. Figure 4: Longitudinal section of xylem vessel element cells with annular lignification in two different species of plants: Coleus (left) and Corn (right). Figure 5: Tracheids in tangential section in Quercus (oak). Long cells with oblique end walls and round pits in the walls are tracheids. Small round cells are lines of ray parenchyma with cellulose cell walls Phloem tissue is composed of sieve-tube cells, companion cells (Fig 6), phloem parenchyma, and phloem fibers. A series of sieve-tube cells (also called sieve-tube elements) are arranged end to end to make up a long sieve tube, which transports organic substances such as sugars and amino acids. The sugars flow from one sieve-tube cell to the next through perforated sieve plates, which are found at the end junctions between two cells. Although still alive at maturity, the nucleus and other cell components of the sieve-tube cells have disintegrated. Companion cells are found alongside the sieve-tube cells, providing them with metabolic support. The companion cells contain more ribosomes and mitochondria than the sieve-tube cells, which lack some cellular organelles. Figure 6: Phloem tissue in longitudinal section including sieve cells and companion cells. Roots Another organ of the plant that is important to understand for its part in transport is the root system. The tip of the root is protected by the root cap, a structure exclusive to roots and unlike any other plant structure. The root cap is continuously replaced because it gets damaged easily as the root pushes through soil. The root tip can be divided into three zones: a zone of cell division, a zone of elongation, and a zone of maturation and differentiation. The zone of cell division is closest to the root tip; it is made up of the actively dividing cells of the root meristem. The zone of elongation is where the newly formed cells increase in length, thereby lengthening the root. Beginning at the first root hair is the zone of cell maturation where the root cells begin to differentiate into special cell types. All three zones are in the first centimeter or so of the root tip. The root has an outer layer of cells called the epidermis, which surrounds areas of ground tissue and vascular tissue. The epidermis provides protection and helps in absorption. Root hairs, which are extensions of root epidermal cells, increase the surface area of the root, greatly contributing to the absorption of water and minerals. Inside the root, the ground tissue forms two regions: the cortex and the pith (Fig 7). Compared to stems, roots have lots of cortex and little pith. Both regions include cells that store photosynthetic products. The cortex is between the epidermis and the vascular tissue, whereas the pith lies between the vascular tissue and the center of the root. Figure 7: Staining reveals different cell types in this light micrograph of a wheat (Triticum) root cross section. Sclerenchyma cells of the exodermis and xylem cells stain red, and phloem cells stain blue. Other cell types stain black. The stele, or vascular tissue, is the area inside endodermis (indicated by a green ring). Root hairs are visible outside the epidermis. (credit: scale-bar data from Matt Russell) The vascular tissue in the root is arranged in the inner portion of the root, which is called the stele. A layer of cells known as the endodermis separates the stele from the ground tissue in the outer portion of the root. The endodermis is exclusive to roots and serves as a checkpoint for materials entering the root's vascular system. A waxy substance called suberin is present on the walls of the endodermal cells. This waxy region, known as the Casparian strip, forces water and solutes to cross the plasma membranes of endodermal cells instead of slipping between the cells. This ensures that only materials required by the root pass through the endodermis, while toxic substances and pathogens are generally excluded. The outermost cell layer of the root's vascular tissue is the pericycle, an area that can give rise to lateral roots. In dicot roots, the xylem and phloem of the stele are arranged alternately in an X shape, whereas in monocot roots, the vascular tissue is arranged in a ring around the pith (Fig 8). Figure 8: In (left) typical dicots, the vascular tissue forms an X shape in the center of the root. In (right) typical monocots, the phloem cells and the larger xylem cells form a characteristic ring around the central pith. Transport of Water in Plants Transpiration is the loss of water from the plant through evaporation at the leaf surface. It is the main driver of water movement in the xylem. Transpiration is caused by the evaporation of water at the leaf–atmosphere interface; it creates negative pressure (tension) at the leaf surface. Water from the roots is pulled up by this tension. At night, when stomata, the pores in the leaves of plants, shut and transpiration stops, the water is held in the stem and leaf by the adhesion of water to the cell walls of the xylem vessels and tracheids, and the cohesion of water molecules to each other. This is called the cohesion–tension theory of sap ascent. Inside the leaf at the cellular level, water on the surface of mesophyll cells (general body cells) saturates the cellulose microfibrils of the primary cell wall. The leaf contains many large intercellular air spaces for the exchange of oxygen for carbon dioxide, which is required for photosynthesis. The wet cell wall is exposed to this leaf internal air space, and the water on the surface of the cells evaporates into the air spaces, decreasing the thin film on the surface of the mesophyll cells. This decrease creates a greater tension on the water in the mesophyll cells (Fig 9), thereby increasing the pull on the water in the xylem vessels. The xylem vessels and tracheids are structurally adapted to cope with large changes in pressure. Rings in the vessels maintain their tubular shape, much like the rings on a vacuum cleaner hose keep the hose open while it is under pressure. Small perforations between vessel elements reduce the number and size of gas bubbles that can form via a process called cavitation. The formation of gas bubbles in xylem interrupts the continuous stream of water from the base to the top of the plant, causing a break termed an embolism in the flow of xylem sap. The taller the tree, the greater the tension forces needed to pull water, and the more cavitation events. In larger trees, the resulting embolisms can plug xylem vessels, making them non-functional. Transpiration is a passive process, meaning that metabolic energy in the form of ATP is not required for water movement. The energy driving transpiration is the difference in energy between the water in the soil and the water in the atmosphere. However, transpiration is tightly controlled. Figure 9: The cohesion–tension theory of sap ascent is shown. Evaporation from the mesophyll cells produces a negative water potential gradient that causes water to move upwards from the roots through the xylem. The atmosphere to which the leaf is exposed drives transpiration, but also causes massive water loss from the plant. Up to 90 percent of the water taken up by roots may be lost through transpiration. Leaves are covered by a waxy cuticle on the outer surface that prevents the loss of water. Regulation of transpiration, therefore, is achieved primarily through the opening and closing of stomata on the leaf surface. Stomata are surrounded by two specialized cells called guard cells, which open and close in response to environmental cues such as light intensity and quality, leaf water status, and carbon dioxide concentrations (Fig 10). Stomata must open to allow air containing carbon dioxide and oxygen to diffuse into the leaf for photosynthesis and respiration. When stomata are open, however, water vapor is lost to the external environment, increasing the rate of transpiration. Therefore, plants must maintain a balance between efficient photosynthesis and water loss. Figure 10: Opening and Closing of Stoma. As K+ levels increase in the guard cells, the water potential of the guard cells drops, and water enters the guard cells. Ali Zifan, CC BY-SA 4.0 < , via Wikimedia Commons Plants have evolved over time to adapt to their local environment and reduce transpiration. Desert plants (xerophytes) and plants that grow on other plants (epiphytes) have limited access to water. Such plants usually have a much thicker waxy cuticle than those growing in more moderate, well-watered environments (mesophytes). Aquatic plants (hydrophytes) also have their own set of anatomical and morphological leaf adaptations. Xerophytes and epiphytes often have a thick covering of trichomes or of stomata that are sunken below the leaf's surface. Trichomes are specialized hair-like epidermal cells that secrete oils and substances. These adaptations impede air flow across the stomatal pore and reduce transpiration. Multiple epidermal layers are also commonly found in these types of plants. Water & Solute Potential Plants are phenomenal hydraulic engineers. Using only the basic laws of physics and the simple manipulation of potential energy, plants can move water to the top of a 116-meter-tall tree. Plants can also use hydraulics to generate enough force to split rocks and buckle sidewalks. Plants achieve this because of water potential. Water potential is a measure of the potential energy in water. Plant physiologists are not interested in the energy in any one particular aqueous system, but are very interested in water movement between two systems. In practical terms, therefore, water potential is the difference in potential energy between a given water sample and pure water (at atmospheric pressure and ambient temperature). Water potential is denoted by the Greek letter ψ (psi) and is expressed in units of pressure (pressure is a form of energy) called megapascals (MPa). The potential of pure water (Ψwpure H2O) is, by convenience of definition, designated a value of zero (even though pure water contains plenty of potential energy, that energy is ignored). Water potential values for the water in a plant root, stem, or leaf are therefore expressed relative to Ψwpure H2O. The water potential in plant solutions is influenced by solute concentration, pressure, gravity, and factors called matrix effects. Water potential can be broken down into its individual components using the following equation: Ψsystem = Ψtotal = Ψs + Ψp + Ψg + Ψm where Ψs, Ψp, Ψg, and Ψm refer to the solute, pressure, gravity, and matric potentials, respectively. "System" can refer to the water potential of the soil water (Ψsoil), root water (Ψroot), stem water (Ψstem), leaf water (Ψleaf) or the water in the atmosphere (Ψatmosphere): whichever aqueous system is under consideration. As the individual components change, they raise or lower the total water potential of a system. When this happens, water moves to equilibrate, moving from the system or compartment with a higher water potential to the system or compartment with a lower water potential. This brings the difference in water potential between the two systems (ΔΨ) back to zero (ΔΨ = 0). Therefore, for water to move through the plant from the soil to the air (a process called transpiration), Ψsoil must be > Ψroot > Ψstem > Ψleaf > Ψatmosphere. Water only moves in response to ΔΨ, not in response to the individual components. However, because the individual components influence the total Ψsystem, by manipulating the individual components (especially Ψs), a plant can control water movement. Solute potential (Ψs), also called osmotic potential, is negative in a plant cell and zero in distilled water. Typical values for cell cytoplasm are –0.5 to –1.0 MPa. Solutes reduce water potential (resulting in a negative Ψw) by consuming some of the potential energy available in the water. Solute molecules can dissolve in water because water molecules can bind to them via hydrogen bonds; a hydrophobic molecule like oil, which cannot bind to water, cannot go into solution. The energy in the hydrogen bonds between solute molecules and water is no longer available to do work in the system because it is tied up in the bond. In other words, the amount of available potential energy is reduced when solutes are added to an aqueous system. Thus, Ψs decreases with increasing solute concentration. Because Ψs is one of the four components of Ψsystem or Ψtotal, a decrease in Ψs will cause a decrease in Ψtotal. The internal water potential of a plant cell is more negative than pure water because of the cytoplasm's high solute content (Fig 11). Because of this difference in water potential water will move from the soil into a plant's root cells via the process of osmosis. This is why solute potential is sometimes called osmotic potential. Plant cells can metabolically manipulate Ψs, and by extension, Ψtotal by adding or removing solute molecules. Therefore, plants have control over Ψtotal via their ability to exert metabolic control over Ψs. Figure 11: In this example with a semipermeable membrane between two aqueous systems, water will move from a region of higher to lower water potential until equilibrium is reached. Solutes (Ψs), pressure (Ψp), and gravity (Ψg) influence total water potential for each side of the tube (Ψtotal right or left), and therefore, the difference between Ψtotal on each side (ΔΨ). (Ψm , the potential due to interaction of water with solid substrates, is ignored in this example because glass is not especially hydrophilic). Water moves in response to the difference in water potential between two systems (the left and right sides of the tube). Pressure potential (Ψp), also called turgor potential, may be positive or negative (Fig 12). Because pressure is an expression of energy, the higher the pressure, the more potential energy in a system, and vice versa. Therefore, a positive Ψp (compression) increases Ψtotal, and a negative Ψp (tension) decreases Ψtotal. Positive pressure inside cells is contained by the cell wall, producing turgor pressure. Pressure potentials are typically around 0.6–0.8 MPa, but can reach as high as 1.5 MPa in a well-watered plant. A Ψp of 1.5 MPa equates to 210 pounds per square inch (1.5 MPa x 140 lb in-2 MPa-1 = 210 lb/in-2). As a comparison, most automobile tires are kept at a pressure of 30–34 psi. An example of the effect of turgor pressure is the wilting of leaves and their restoration after the plant has been watered (Fig 12). Water is lost from the leaves via transpiration (approaching Ψp = 0 MPa at the wilting point) and restored by uptake via the roots. A plant can manipulate Ψp via its ability to manipulate Ψs and by the process of osmosis. If a plant cell increases the cytoplasmic solute concentration, Ψs will decline, Ψtotal will decline, the ΔΨ between the cell and the surrounding tissue will decline, water will move into the cell by osmosis, and Ψp will increase. Ψp is also under indirect plant control via the opening and closing of stomata. Stomatal openings allow water to evaporate from the leaf, reducing Ψp and Ψtotal of the leaf and increasing ii between the water in the leaf and the petiole, thereby allowing water to flow from the petiole into the leaf. Figure 12: When (a) total water potential (Ψtotal) is lower outside the cells than inside, water moves out of the cells and the plant wilts. When (b) the total water potential is higher outside the plant cells than inside, water moves into the cells, resulting in turgor pressure (Ψp) and keeping the plant erect. (credit: modification of work by Victor M. Vicente Selvas) The following video does a nice job reminding you about osmosis and general concepts before reviewing water potential (starting around 7.25 minutes). Transport of Sugars/Photosynthates in Plants Plants need an energy source to grow. In seeds and bulbs, food is stored in polymers (such as starch) that are converted by metabolic processes into sucrose for newly developing plants. Once green shoots and leaves are growing, plants are able to produce their own food by photosynthesizing. The products of photosynthesis are called photosynthates, which are usually in the form of simple sugars such as sucrose. Structures that produce photosynthates for the growing plant are referred to as sources. Sugars produced in sources, such as leaves, need to be delivered to growing parts of the plant via the phloem in a process called translocation. The points of sugar delivery, such as roots, young shoots, and developing seeds, are called sinks. Seeds, tubers, and bulbs can be either a source or a sink, depending on the plant's stage of development and the season. Movement of sugars from the cells into the phloem requires energy/ATP. This means active transport is needed. When the sugars arrive at the sinks, they will passively move into those cells. This means that no ATP energy is required. The dissolved sugars will diffuse from an area of high concentration (in the phloem) to an area of low concentration (in the sink cells). The products from the source are usually translocated to the nearest sink through the phloem. For example, the highest leaves will send photosynthates upward to the growing shoot tip, whereas lower leaves will direct photosynthates downward to the roots. Intermediate leaves will send products in both directions, unlike the flow in the xylem, which is always unidirectional (soil to leaf to atmosphere). The pattern of photosynthate flow changes as the plant grows and develops. Photosynthates are directed primarily to the roots early on, to shoots and leaves during vegetative growth, and to seeds and fruits during reproductive development. They are also directed to tubers for storage. So how does it work in more detail? Photosynthates, such as sucrose, are produced in the mesophyll cells of photosynthesizing leaves. Then ATP energy is used to actively move the excess sugars out of the leaf cells and into the phloem cells. When these sugars arrive, they lower the concentration of water in the phloem. As a result, water diffuses out of the xylem, which is adjacent to the phloem, and moves into the phloem. This osmosis is automatic and passive. That is, when the sugars are loaded into the phloem, water will move from a higher concentration in the xylem to a lower concentration in the phloem (in other words, osmosis occurs). The now dissolved sugars, called phloem sap, are found in a high turgor pressure environment. This fluid will now move toward a sink as a result (Fig 13b), where there is lower turgor pressure. Once at the sink, the sugars will diffuse out of the phloem and into the sink cells. Sucrose concentration in the sink cells is lower than in the phloem because the sink sucrose has been metabolized for growth, or converted to starch for storage or other polymers, such as cellulose, for structural integrity. Unloading at the sink end of the phloem tube occurs by either diffusion or active transport of sucrose molecules from an area of high concentration to one of low concentration. Water diffuses from the phloem by osmosis and is then transpired or recycled via the xylem back into the phloem sap. So the phloem translocates sugars and larger molecules to where they are used or stored. The photosynthates in the leaf cells move through plasmodesmata channels (cytoplasmic channels) to reach specifically the phloem sieve-tube elements (STEs) in the