Introduction

New gardeners, and even more experienced ones, tend to learn about gardening by memorizing rules. When do you prune a lilac? Should you pinch out fall asters? When is the best time to move tulips? These all have rules, and once you learn them, they are easy to follow. Prune lilacs after flowering, pinch back asters in midsummer for stockier plants and transplant tulips once the leaves go yellow. But there are thousands of different kinds of plants. You will never learn and remember all the rules for all these plants.

A much better approach is to learn the underlying science—learn how plants grow and develop. Once you understand that, you can skip learning the rules because you don't need them and you will be able to grow just about anything. And that is the main goal of this book: I want you to understand what is really going on inside plants, and how they respond to the environment and your actions in the garden. This book paints a simple, clear picture of the greenery that surrounds you.

Once you have a really good understanding of the basics, you will be able to evaluate any gardening procedure and determine if it makes sense. For example, once you understand how dormant buds respond to pruning, you will have a much better understanding of when and what to cut. Learning about the transfer of water from roots to leaves will explain why some plants wilt at midday and what, if anything, you should do about it.

More importantly, you will be able to evaluate many of the fad techniques and products that are invented every year. Many of these are simply a waste of time and do not improve the health of your plants. This book will make you a more informed consumer.

Introduction to Plant Science

Plants have been studied for a few hundred years and we know a lot about them but with each advancement in our knowledge we realize there is so much more to learn. Plants are complex organisms and we are just starting to appreciate how they really work.

In order to write this book I had to make a lot of choices about what to include and what to leave out. If I'd included everything, this book would be ten times as big, and few people would read it. I have included basic information, like what is a leaf and how does pollination work, to give you a strong foundation of plant science. I then added other topics that are not only interesting but also practical for the home gardener.

For example, it is not critical that you understand mobile and immobile nutrients except that such an understanding helps you decide when foliar fertilization makes sense and why foliar feeding of calcium to prevent blossom end rot in tomatoes does not work. So I decided to include this in the book.

At other times I just included things because they are just cool to know about plants. Did you know plant roots excrete chemicals to attract beneficial microbes which then ward off root pathogens? More about this later.

To complete the book, I also had to leave out a bunch of interesting stuff and in many cases I had to take a complex topic and simplify it. I hope that the book gives you a good grounding of plant science which will allow you to find other more detailed resources as your knowledge and interests expand.

Organization of the Book

I've dissected plants into logical components including roots, stems, leaves and flowers, and each of these is discussed in individual chapters. This provides a basic background that is then used to discuss the whole plant as a single organism.

The focus of most of the book is on herbaceous plants such as grasses and perennials but a lot of the discussion also applies to woody plants. I have also added a special chapter to discuss topics that are specific to trees and shrubs. The book ends with a couple of chapters on propagation that will be very useful to gardeners and will provide better insight into specific topics that are not covered in other sections.

Numerous sidebars have been added throughout the book to discuss garden myths, which is a particular passion of mine. My blog, called gardenmyths.com, has had over 14 million visitors and discusses hundreds more garden myths.

Terms Used in This Book

Science is very precise about the terms it uses, but these are not always used in the same way by the general public, which leads to misunderstandings. One of my challenges is to use terms that are both useful to the gardener and still reflect the accuracy of the science. To ensure that we are all on the same page, it is important that we agree on some basic definitions.

Organic Matter

Organic matter is essentially dead organisms. These could be dead plants or animals, which have reached a certain degree of decomposition. Common forms of organic matter include compost, leaf mold and humus. This type of material and its role in soil is fully explored in my other book, *Soil Science for Gardeners*.

Fertilizer

The term fertilizer can have many definitions. Gardeners often think that the term only refers to synthetic chemical fertilizers, but that is not a correct usage since there are many organic fertilizers that are not synthetic.

Many jurisdictions use a legal definition for fertilizer that requires that the product contains nitrogen, phosphorus and potassium, and that the amounts of these nutrients are labeled on the package. By this definition, something like Epsom salts would not be a fertilizer even though it provides plants with magnesium. Its NPK value would be 0-0-0, which is not a fertilizer.

I will use the term fertilizer in a more general way to describe any material that is added to soil with the primary purpose of supplying at least one plant nutrient. I will also use the term synthetic fertilizer to refer to man-made chemical products and organic fertilizer for natural products.

Nutrients

When talking about plants, nutrients are the basic minerals and nonminerals they require, including things like nitrogen, potassium, phosphorus, calcium, magnesium, etc.

Herbaceous

The term herbaceous refers to plants that are herbs in the botanical sense and not in the culinary sense. It is also not used exclusively to refer to perennials. A herbaceous plant is any plant that does not form woody structures and includes grasses, perennials and bulbs. They can be annuals, biennials or perennials.

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Plant Basics

The initial chapters of this book look at different parts of a plant such as roots, stems and leaves, but it is important to understand that none of these parts function in isolation. They are all connected to one another and although they look very different, they also have a lot of similarities. Some of these common elements are discussed in this chapter to provide a foundation for the rest of the book.

Cells

All parts of a plant are made up of cells, and unlike animal cells they have a rigid cell wall. They tend to be square in shape and the cell wall is made up mostly of cellulose, a strong polymer that adds rigidity and strength to the plant. Though cellulose is very resilient, it's also quite flexible and readily takes in water. Paper, including paper towels and toilet paper, is primarily made up of cellulose.

Cells are somewhat similar to boxes and plants can be visualized as stacks of boxes. The rigid cell walls are strong enough to withstand internal pressures and some level of freezing.

The cell wall is not completely solid. Small channels go through the wall and allow water, minerals, sugars and proteins to flow into and out of the cell, allowing material to flow throughout the plant. Water and nutrients flow from roots to the top of the plant, and sugar moves from leaves down the plant to the roots. In this way all cells are connected to one another.

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Visible vascular bundles on a celery stem.

Xylem and Phloem

The xylem and phloem are as vital to plant life as the heart and circulatory system are to animal life. In some ways, both systems play a similar role.

The xylem and phloem are two distinct organs in a plant but they usually occur together in something called the vascular bundle. Note that the term vascular is also used to refer to blood vessels, namely tubes carrying blood.

The vascular bundle is like a super-fast highway where the passengers are various substances needed for plant growth. You can easily see the vascular bundles as small dots in a piece of celery.

Think of the xylem and phloem as hollow tubes, not unlike drinking straws, running through the plant. They are more complicated than this, but the hollow tube analogy is fairly accurate.

Once water or cellular liquid enters the tubes it travels either up or down the tube. I use a simple mnemonic to remember their function. Water and xylem start with letters in the same part of the alphabet and so the xylem transports water, and water always moves up the plant, from roots to leaves.

Xylem

The xylem is responsible for transporting water from the roots to the rest of the plant. Water and dissolved minerals pass through the outer membrane of roots and then flow to the center of the root. There it enters the xylem and starts the journey up the plant.

As water is lost in the leaves it creates a drop in pressure inside the xylem that causes more water to move up the tube.

This system only supports one-way traffic. Spraying water on the leaves does result in a bit being absorbed by the leaves but this water is not moved around the plant. When a plant needs water, it must be absorbed by the roots.

Phloem

The phloem transports carbohydrates, minerals, amino acids, hormones and other chemicals produced by the plant to other areas.

Two-way traffic occurs in the phloem, so molecules in any part of the plant can flow to any other part, using phloem tubes. This system is quite complex and the plant does control the movement of molecules. Some are more easily moved around than others. For example calcium is considered to be "immobile" and it does not easily move around the plant. Other molecules like sugar are "mobile" and are easily moved to any part of the plant.

Photosynthesis

Most of you are familiar with photosynthesis. It is the process plants use to convert carbon dioxide and light into sugars and oxygen. The sugars provide the food energy plants need to grow, and the released oxygen helps us to breathe. This is obviously important for the plant, but it is also critical to life on earth.

Consider this: there were no animals on earth until plants started to grow. Initially they were simple plants like algae, but they soon developed into more sophisticated organisms. You might think that the production of oxygen was the key to animal life and it certainly was important, but plants play a much more important role and that has to do with energy.

All living organisms need energy to live. It takes energy to grow, to reproduce and to move around. It even takes energy to digest food.

Animals can't make their own energy, but plants can. Plants are the source of all our food energy and we get it by either eating plants directly, or by eating other animals that eat plants.

Where do plants get this energy? From the sun, through photosynthesis. Plants capture sunlight and create energy-storing molecules called sugars. Those sugars are then used to keep both themselves and all animals alive. Without photosynthesis, there would be very little life on earth.

A simple formula for the reaction that occurs can be written as:

$$CO_2 + H_2O \rightarrow C_6H_{12}O_6 + O_2$$

Carbon dioxide is combined with water to produce sugar and oxygen.

Plant Myth: Plants Raise the Oxygen Level in Homes

Plants do produce oxygen during photosynthesis and this has led to the belief that they will increase the oxygen level in the home, but that is a myth. The low levels of light in a home reduce photosynthesis which results in less oxygen being produced than outside.

If you had enough plants in a room to use up all of the CO_2 and convert it to oxygen, the oxygen levels would increase from 20.95% to 21%. This increase is difficult to detect and would have no effect on humans. Keep in mind that this increase is the maximum increase possible and assumes plants would use all the CO_2 available. In real life, the increase is much less.

It is also important to remember that plants also respire and produce CO_2, negating in part the oxygen they produce. If you are concerned about this CO_2 and remove plants from a bedroom at night, don't bother. The amount is tiny compared with what humans produce.

Water is collected by the roots and transported to the stems and leaves. Openings in leaves and stems called stomata allow carbon dioxide to enter. Sun is absorbed through the leaves. Chloroplasts, which are special organs in green tissues, combine these ingredients and produce sugars. A waste product of this reaction is oxygen, some of which is used by the plant, but most of it is expelled through the stomata.

What Happens at Night?

What happens to photosynthesis when the sun goes down? Almost immediately, photosynthesis stops. This means that plants need to produce enough sugars during daylight hours to support normal metabolism both during the day and all night long.

During the night, plants are still absorbing water and nutrients at the roots, and growth in various parts of the plant continues. Flowers are forming or being pollinated and leaves are producing various natural pesticides to ward off insect predation. All these processes require energy.

Photosynthesis is efficient enough to provide all the energy needed during the day and night as well as produce some excess that is stored for a rainy day, and I mean that literally.

Sugars, Carbohydrates and Energy

The terms sugars, carbohydrates and energy tend to be used interchangeably in gardening circles. Photosynthesis produces mostly glucose, a sugar, but it also produces other sugars. These sugars are simple carbohydrates and they are used as building blocks to create larger carbohydrates like starch and many other compounds found in plants.

Almost all reactions in a plant require energy and sugars provide that energy.

Each of the above terms are different but can be and are used to refer to something very similar. The glucose produced in photosynthesis can be called a sugar, a carbohydrate or even energy.

A more general term that is used by scientists is "photosynthates"—the compounds that are produced by photosynthesis. This term includes the sugars as well as many other compounds produced in the overall process.

In this book I have mostly used the term sugars and energy to refer to all of these.

Photosynthesis and Climate Change

Once you understand photosynthesis you can start to appreciate how important it is to climate change. We add CO_2 into the atmosphere and plants remove it. At present we are adding much more than plants can remove which increases the level in the air. By adding more plants to earth, we will reduce the CO_2 levels in the air and that is my excuse for buying more plants.

Most of the CO_2 absorbed by plants ends up in the soil and in woody plants. Two-hundred-year-old trees are a great storage system for CO_2. On the other hand, removing old growth forests not only stops the reduction of CO_2 by the living trees, but as the wood rots it releases the CO_2 back into the atmosphere through a process called respiration.

Herbaceous plants are also important for capturing CO_2 and that carbon ends up in soil from either root exudates (chemicals given off by roots) or decomposed plants.

ATP and the Energy Cycle

One of the most important molecules in the plant is something called adenosine triphosphate, or ATP for short. This is a relatively simple molecule that can be thought of as a rechargeable battery. Not much happens inside a plant, or even your body for that matter, without energy. ATP is that energy source.

ATP will combine with water to form another compound called ADP, as well as forming phosphate and free energy. That energy is used by thousands of other reactions to build all of the chemicals found in a plant. For example, it is used to take simple sugar molecules and build them up into large starch molecules. It is also used in the root hairs to actively move nutrient molecules across the root membrane.

ATP + H_2O → ADP + phosphate + free energy

Think of ADP as a discharged battery. It is now time to recharge this battery so it can be used again and that happens during photosynthesis. The light from the sun is used to recharge ADP into an ATP molecule. The ATP battery is now ready to be used somewhere else in the plant to carry out reactions.

ADP + phosphate + sun energy → ATP + H_2O

Note that phosphate plays a big role in this. It is one of the main ways in which plants use this soil nutrient.

The discharged ADP battery can also be charged through a process called respiration.

Respiration

Respiration is a process that happens in both animals and plants. An energy source, the sugars, are reacted with oxygen to produce CO_2, water and free energy. The free energy is stored in ATP.

$C_6H_{12}O_6$ + O_2 → CO_2 + H_2O + ATP (energy)

The ATP molecule is then used as described above to carry out all the other processes taking place in a plant.

Respiration takes place in every part of the plant, including roots, stems, flowers and even in fruits and seeds. The process is not light dependent and happens 24/7. Luckily for plants, the photosynthesis process is more efficient than respiration. A well-grown plant can produce all the energy a plant needs, during daylight hours.

Respiration requires oxygen which is easy to come by in both stems and leaves which have stomata openings that allow oxygen to enter. But what about the roots? Respiration is vital for roots and the only way for them to get oxygen is from the soil. They need to breathe oxygen just like we do.

Ideal soil is about 25% air and this provides the oxygen needed by roots. This value is lower in compacted soil or if the soil is waterlogged. In both of these cases, roots can suffocate and die.

Meristematic Cells

Plants are quite different from animals in a number of respects but one that is most important is the plant's ability to keep growing. You can cut your lawn and it grows back. You can take a stem cutting and grow a complete plant. Slice a hosta in half and you have two plants. Cut down a mature tree and in no time at all you have suckers growing that will eventually grow into new trees. Try doing that to animals!

This ability to regenerate and grow is a major characteristic of plants and depends on meristematic cells.

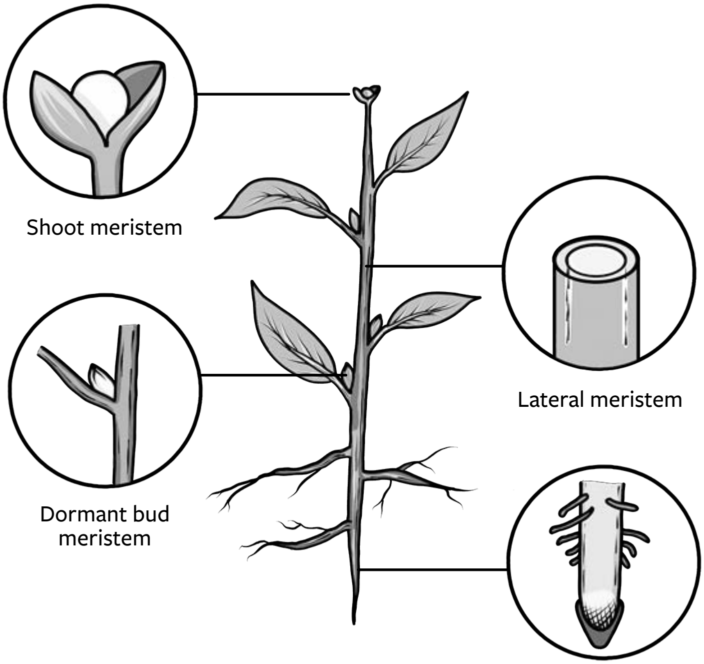
Before we get into that, it is important to understand differentiated and undifferentiated cells. An undifferentiated cell looks like a blob. It is very simple and does not look much like a plant cell. It really can't do much yet. It is a special cell with only one function: to replicate. It divides to make more of itself and it can do this very rapidly.

Plants keep making more undifferentiated cells so that they always have a ready supply of them.

Differentiated cells are ones with a specific defined function. They might be root cells, or leaf cells or any other cell needed by the plant. They take on the physical characteristics needed as well as the biological and chemical functions required. They are mature cells ready to do whatever they were differentiated to do.

Meristematic cells are undifferentiated cells and are similar to animal stem cells which have an analogous behavior and function. They are a pool of cells ready to differentiate into whatever form the plant needs. In the root area, they might become root hair cells, but the same meristematic cell in a bud can become a leaf cell or a flower cell.

The plant keeps meristematic cells in various key locations so that they are ready to develop as needed. Primary spots for these cells include the tip of roots, the tip of shoots and in dormant buds.



Location of meristematic tissue.

As the shoot grows, meristem tissue is also produced at all side branches in something called dormant buds. Some of these dormant buds will become new shoots or flowers the following spring, but many remain dormant for the life of the plant, or until the plant needs them. If the plant is damaged these dormant buds become active to allow the plant to grow. All the suckers produced after cutting a tree are dormant buds that have been activated by the damage.

Stems of woody plants, like trees and shrubs, have a special lateral meristem that allows the stem to grow in width.

Most growth in plants involves meristematic cells.

Unlike animals, plant growth is essentially indeterminate—both roots and shoots continue to grow throughout the life of the plant. It can slow down as the plant gets larger, and it is controlled by environmental factors, but plants never stop growing.

Classification of Plants

Plants can be divided into four main types based on how they grow and how they reproduce.

- Mosses and liverworts: simple plants that do not contain a xylem or phloem.
- Ferns: have a xylem and phloem but they do not make seeds.
- Gymnosperms: includes the evergreens and have needles and cones.
- Angiosperms: flowering plants and include most perennials and deciduous trees.

Monocots and Dicots

The angiosperms can be further separated into two distinct groups called monocots and dicots. At a high level, both groups look fairly similar but when you drill down and look at how their internal systems function you will see differences.

Monocots have a single cotyledon, flower parts are in multiples of three, leaf veins are parallel and they don't have secondary growth. Grains, grasses, lilies, daffodils and bamboo are all monocots.

Dicots have two cotyledons, hence the name dicotyledon. Flowers have four or five parts, stem vascular bundles form a ring and they tend to have secondary growth. This category includes many of the popular garden plants including peas, sunflowers, daisies, mint, marigolds, tomatoes and oaks.

In order to keep things simple, I will talk mostly about dicots and will only mention the monocots in a couple of spots where the difference impacts gardening.