Meet the plants

How plants make a living

A plant's worldview is different from an animal's

Plants form the basis for every ecosystem on Earth exposed to sunlight. We, as animals, depend on them for food, shade, and carbon and nitrogen cycling. As plants evolved from photosynthesising bacteria that appeared over 2 billion years ago, they transformed the early carbon-dioxide-heavy atmosphere into oxygen-rich air.

Plants take a different approach to life from ours. They don't go out looking for anything they need. They make their own food using what they absorb from the air and soil around them and reproduce by spreading their pollen and seeds on the wind and on the bodies of foraging insects and other animals. They've adapted to survive in a single spot (or, in the case of phytoplankton, where the currents take them).

To survive and reproduce, plants invest their resources in three different ways. Some put their energy into outdoing the competition, some into enduring environmental stresses, and some into quickly making and spreading as many seeds as they can.

Within those strategies, there are different tactics. For example, should a plant grow an extra shoot, making room for more leaves to collect light and carbon dioxide, or put more energy into making roots to help it extract more water and nutrients from the soil? It all depends on how much of the things the plant needs are available in its environment.

The secrets of plant cell structure

Chloroplasts and a cellulose cell wall are unique to plants – but plant cells have much in common with fungi, bacteria and animal cells too

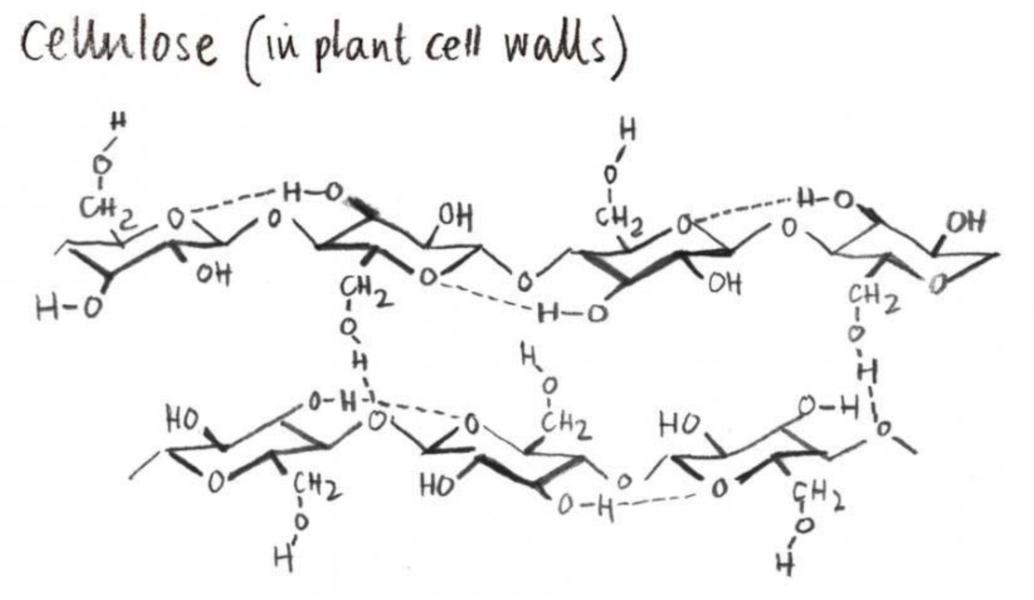
How come plants can make their own food but animals can't? It's all down to the green, pigment-packed chloroplasts that help plants to turn carbon dioxide and water into glucose.

Modern-day chloroplasts were, according to endosymbiotic theory, once independent cells called cyanobacteria, which were incorporated into plant cells.

As they evolved into organelles, many of their genes were transferred into the plant cell genome. So although plants are eukaryotes, like animals, and their cells have many of the characteristics of eukaryotic cells – such as a nucleus containing chromosomes and mitochondria – their chloroplasts gives them an ability to photosynthesise that animal cells don't have.

Plants do share one important feature with bacteria and fungi: a cell wall. Plant, bacteria and fungi cell walls have different compositions, but in plants, the wall is mostly made of **cellulose**. This long-chain molecule is made up of beta-glucose molecules covalently linked by glycosidic bonds that are difficult to hydrolyse (break down with the addition of water), providing strength and structure to the cell. Cellulose is thought to be the most abundant macromolecule on Earth.

In fungi, by contrast, the cell wall is made up of a mixture of long-chain molecules, including chitin (which also forms the exoskeletons of crabs), whereas in bacteria it is largely peptidoglycan-based.



Big Picture: Plants (2016)

Photosynthesis

Plants make their own food – glucose – through photosynthesis, using water, light energy from the sun, and carbon dioxide from the air. That glucose is used to build cellulose, starch, fats and oils – and to power the complementary process of respiration.

At the cellular level, photosynthesis begins in clusters of molecules called photosystems in the inner membranes of chloroplasts . Sunlight kickstarts the light-dependent reactions of the process, by transferring energy to chlorophyll pigments in reaction centres, setting up a chain of further reactions. The second part of the process, the light-independent reactions produces chemical energy in the form of glucose. This is the key feature of photosynthesis: the ability to convert light energy into chemical energy. Plants are capable of making millions of molecules of this sugar every single second. Our poster shows the biochemical details.

The light energy that plants harness accounts for almost all of the energy entering Earth's ecosystems, the exception being ecosystems based on chemosynthetic bacteria like those around deep-sea vents.
Plants' carbon-fixing capabilities also make them the starting-point for the carbon cycle, while the ability of bean-family plants like peas and clover to absorb nitrogen from the air spaces in soil gives them a vital role in the nitrogen cycle.

(Don't forget to view and download our poster on photosynthesis.)

Growth Factors

All sorts of chemicals play a role in plant development

In plants, like in animals, hormones are chemical messengers that carry information from one part of the organism to another.

Some of the most important hormones in plants are often called growth factors or growth substances, because of the specialised role they play in development. Auxins, which control cell growth, enable a plant on a window ledge to lean towards the sun by causing the cells on the shaded side to elongate, extending the stem on that side. This phenomenon is known as phototropism – movement or growth in response to light. Other tropisms include gravitropism (in response to gravity) and thigmotropism (in response to touch or contact).

There are another four major types of plant growth factors: gibberellins, cytokinins, ethene (or ethylene) and abscisic acid. Sometimes these chemicals work together, while at other times they may work against, or antagonise, each other. Auxins keep leaves on the plant, while ethene makes them fall off.

Our table below summarises their purpose and where they are found.

Plant growth factor	What they are responsible for	Where they are found
Auxins – including indole acetic acid (IAA)	Cell elongation and expansion; prioritisation of stem tip growth over side shoot growth (apical dominance); responses to light, gravity and water (tropisms); keeping leaves on plants	Made in growing points called meristems, but present all over the plant, especially shoots, tips and roots
Gibberellins	Stem elongation between leaves; seed germination; fruit growth	Mostly in seeds, roots and stems
Cytokinins	Cell division; generation of new roots and side shoots (lateral buds)	Produced in roots and embryos and travel up via water-transporting xylem, also produced in fruits
Ethene (ethylene)	Ripening, rotting and leaves falling; many growth and development processes	Produced in almost all parts of the plant but mostly in locations where cell division takes place
Abscisic acid	Drought signalling, causing stomata to close to save water; seed dormancy (opposing seed germination promoted by gibberellins)	Made in parched leaves, roots and developing seeds

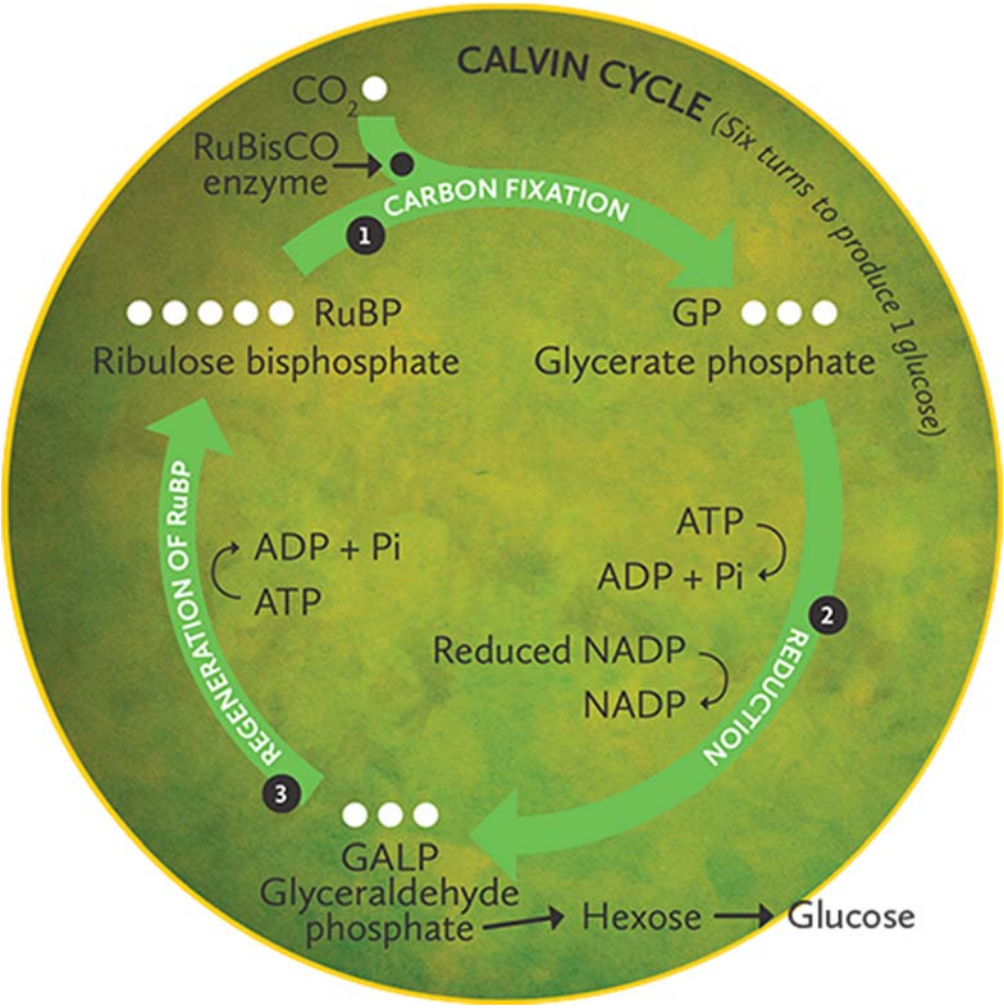
These growth factors allow plants to respond to many of the challenges that life throws at them by changing their structure. Many normal plant cells are totipotent, meaning they can give rise to any type of plant cell and even lead to a fully-grown plant. With the correct chemicals, tiny samples of plant material – sometimes even single cells – cultured in the lab can grow into entire plants. Very few animal cells have this ability; in humans, only the first 16 cells, starting with the zygote, are totipotent.

View the accompanying animation to learn how the function of IAA was scientifically determined.

The great RuBisCO and its amazing carbon fixation

Thanks to its role in photosynthesis, ribulose bisphosphate carboxylase oxidase (RuBisCO) is perhaps the most abundant enzyme in the world.

Dissolved in the stroma of a chloroplast, the plant cell structure responsible for photosynthesis, is the enzyme RuBisCO, which makes up half of the soluble protein of most leaves.



The Calvin cycle, as shown in our photosynthesis poster. CC BY Bret Syfert/'Big Picture: Plants' (2016)

RuBisCO does a very difficult biochemical job. It kick-starts the first stage of the Calvin cycle, taking carbon dioxide dissolved in the leaf water and placing it into sugar molecules to make them bigger. That chemical reaction is called carboxylation – and the overall process is called carbon fixation.

How the enzyme got its name

An enzyme is named in two parts. The first part is its substrate (the chemical it works on); the second part is its action. RuBisCO's substrate is the high-energy five-carbon sugar RuBP, or ribulose bisphosphate. Its primary action is carboxylation, but at most temperatures, RuBisCO also oxidises RuBP – which is why the final two words of the name are 'carboxylase oxidase'.

How fast does it work?

How fast an enzyme works depends on three things: temperature, substrate and concentration.

Enzyme reactions speed up as temperature increases – up to an optimum point.

The optimum point is the temperature at which the enzyme's active site is best at binding to its substrate. Human enzymes, for instance, have an optimum of 37ºC – our body temperature. Plant enzymes have varying optimums, to match the varying climates the plants grow in. At higher temperatures than its optimum, RuBisCO starts to be better at oxidation than carboxylation. When the rate of carboxylation slows down, so does photosynthesis.

The more substrate there is, the more likely the enzyme's active site is to be full, so the rate of reaction is faster.

RuBisCO's substrate is RuBP, which is regenerated as the Calvin cycle turns (see diagram). But it also requires CO_2 for the process to start. As the level of CO_2 dissolved in the water in the leaf drops, the active site is less likely to be full.

The higher the enzyme concentration, the faster the reaction.

Leaves contain a huge amount of RuBisCO to increase the rate of this vital reaction.

Oxidation vs reduction

Oxidation occurs when chemicals have oxygen added to them or hydrogen taken away. The level of oxidation is indicated numerically (positive numbers for oxidised atoms, negative for reduced ones).

- Carbon dioxide (CO_2) consists of a carbon atom double-bonded to two oxygen atoms. The carbon is highly oxidised, with an oxidation state of +4.
- Methane (CH_4) is a carbon atom with four hydrogen atoms single-bonded to it. The carbon is highly reduced, with an oxidation state of –4.
- Glucose ($C_6H_{12}O_6$) is a carbohydrate. For every individual carbon atom, there is one oxygen atom and two hydrogen atoms. The oxidation state of the carbons in glucose comes out as zero.
- Glycerate phosphate (GP), which is produced during a turn of the Calvin cycle, is also a carbohydrate. It too has an average carbon atom oxidation of zero.

During photosynthesis, the oxidation state of carbon atoms falls from +4 to zero. This requires energy provided by ATP and reduced NADP from the light-dependent reactions. This reduction takes place in just one step: the carboxylation reaction catalysed by RuBisCO. The energy found in the ATP and reduced NADP is used in subsequent reactions to rearrange GP into glucose and RuBP.

When it's hot

As temperatures rise over approximately 35ºC, photosynthesis slows down and becomes far less efficient, with a higher rate of oxidation. During the first carboxylation, RuBisCO takes a carbon dioxide molecule but cannot hold on to it.

Many tropical plants such as maize and sugar cane have an extra biochemical pathway bolted on to the Calvin cycle. Their process is called C4 photosynthesis.

Plants that use C4 photosynthesis can concentrate the carbon dioxide locally – with less competition from oxygen – so carbon is fixed faster. If this fixes carbon faster, why haven't all plants evolved to use C4? The answer is energy: C4 photosynthesis requires more ATP – approximately 30 ATP, compared with 18 ATP for lower-temperature photosynthesis (known as C3) – so at lower temperatures, C4 photosynthesis has no advantage.

QUESTIONS FOR DISCUSSION

- Why is sugar cane (*Saccharum officinarum*) the most important sugar crop in the tropics but sugar beet (Beta vulgaris) the most important sugar crop in Europe?

- Find an explanation of oxidation and reduction in terms of gain and loss of electrons.
- How much a chemical is oxidised or reduced is given a number called the 'oxidation state'. Find the oxidation state of carbon dioxide and glucose and use those figures to explain why photosynthesis is a difficult reaction.
- Ribulose is not much different from glucose or even ribose (from RNA). The formula for glucose is C6H12O6. Find the formula for ribulose.
- Where does the energy come from to make RuBP and drive the Calvin cycle?
- RuBisCO takes carbon dioxide from the leaf water that surrounds it. Explain how this carbon dioxide gets to RuBisCO from the air outside the leaf.
- Go a little deeper: find out how RuBisCO is switched on by light and switched off in the dark.