

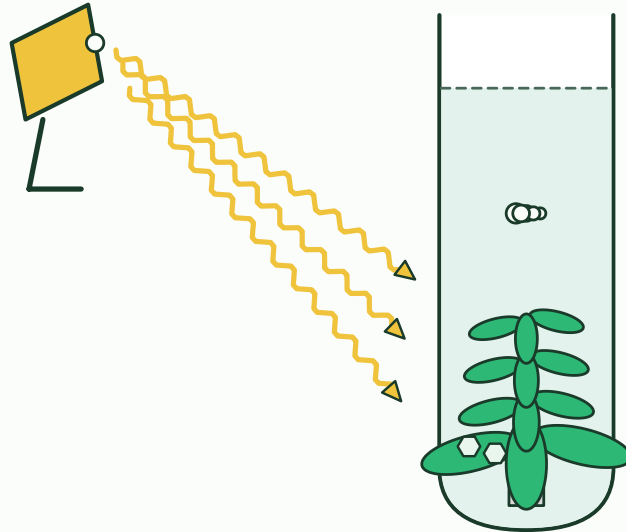
REVISION GUIDE

Light into *sugar*

Photosynthesis

Almost every meal you eat, and every breath of oxygen you take, starts with a leaf catching light. Here is how a plant splits water, pulls carbon out of the air and builds sugar from it, what slows it down, and how you can measure it on a bench.

Sugar made



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By the end you can

- ☐ Explain how photosynthesis turns light energy into the chemical energy of carbon compounds, and why ecosystems depend on it C1.3.1
- ☐ Write the word equation, say where each atom of glucose comes from, and explain why the oxygen given off comes from water C1.3.2, C1.3.3
- ☐ Separate leaf pigments by chromatography, work out Rf values and identify each pigment by colour and Rf C1.3.4
- ☐ Explain why pigments absorb only some wavelengths, and read and sketch an absorption spectrum with wavelengths and colours C1.3.5
- ☐ Compare absorption and action spectra, and plot an action spectrum from oxygen or carbon dioxide data C1.3.6
- ☐ Suggest and test hypotheses about light, carbon dioxide and temperature as limiting factors, naming the variables C1.3.7
- ☐ Compare greenhouse and FACE experiments as ways of predicting how plants will grow in tomorrow's air C1.3.8
- ☐ Describe a photosystem and explain why pigments work only as an array round a reaction centre C1.3.9, C1.3.10
- ☐ Explain how photolysis at photosystem II supplies electrons and protons, and what its waste oxygen did to the Earth C1.3.11
- ☐ Explain how a proton gradient and ATP synthase make ATP in the thylakoid, by cyclic and non-cyclic photophosphorylation C1.3.12
- ☐ Explain how photosystem I reduces NADP, and where in a thylakoid each light-dependent step happens C1.3.13, C1.3.14
- ☐ Explain how Rubisco fixes carbon dioxide onto RuBP, and why the stroma needs so much of it C1.3.15
- ☐ Follow the carbon through the Calvin cycle: GP reduced to TP, and five TP in six remade into RuBP C1.3.16, C1.3.17
- ☐ Explain how every carbon compound in a plant is made from the Calvin cycle's products with mineral nutrients C1.3.18
- ☐ Explain why the light-dependent and light-independent reactions stop without each other C1.3.19

Tick each one when you can do it without the book.

01

C1.3.1 LIGHT ENERGY TO CHEMICAL ENERGY

Sunlight in, *chemical* energy out

Photosynthesis transforms **light energy** into **chemical energy**. In a leaf, pigments absorb light, and that energy ends up in the bonds of **carbon compounds** the plant builds: first sugars, then everything else it is made of. Light is not stored. It is changed into a different form, an **energy transformation**.

That chemical energy runs nearly every food chain. Plants, algae and cyanobacteria are **producers**. A rabbit eating grass, and a fox eating the rabbit, are living on energy the grass caught from the Sun. A few ecosystems, round deep-sea vents, run on chemical energy from the vent instead (C4.2 returns to this), but almost all the others depend on photosynthesis.

Cells need that energy for three kinds of work: building large molecules (anabolism, C1.1), moving substances against their gradients (active transport, B2.1), and movement, from muscle contraction to the pulling apart of chromosomes. Respiration (C1.2) releases the energy from carbon compounds and holds it in ATP, which pays for the work. At every step some energy leaves as heat. Energy flows through an ecosystem and is not recycled; carbon is (C4.2).

KEY POINTS

- Photosynthesis transforms light energy into the chemical energy of carbon compounds.
- Producers make the carbon compounds that every consumer in a food chain depends on.
- Energy flows light, then chemical energy in sugar, then ATP, then work and heat.

KEY TERMS

photosynthesis

The process that turns the energy of light into chemical energy held in the bonds of carbon compounds. It happens in the chloroplasts of plants and algae, and in cyanobacteria.

light energy

Energy carried by light. A pigment absorbs it.

chemical energy

Energy stored in the bonds between atoms, and released when those bonds are rearranged.

carbon compounds

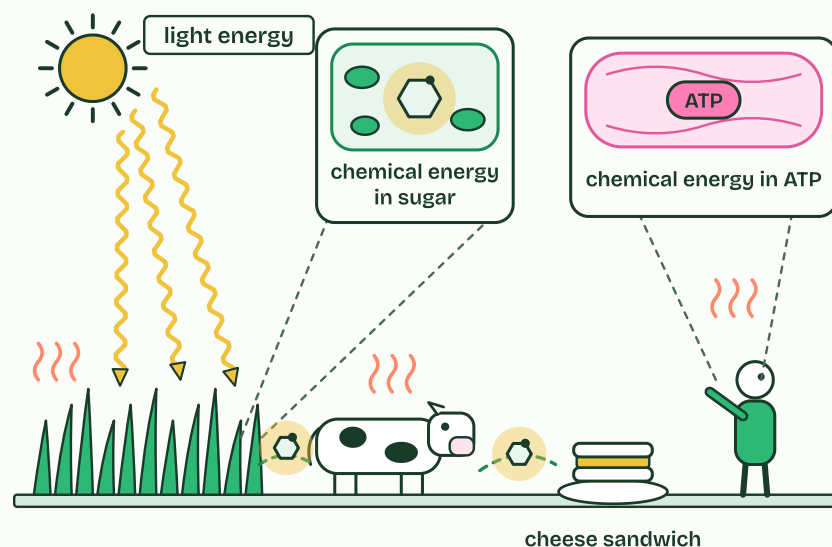
Molecules built on a skeleton of carbon atoms, such as sugars, lipids, proteins and nucleic acids.

energy transformation

A change of energy from one form into another, for example light into chemical energy. Energy is not made or destroyed, and some is lost as heat at every step.

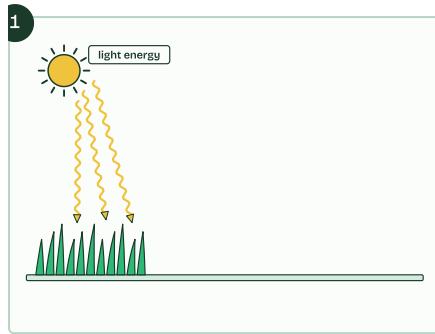
producers

Organisms that make their own carbon compounds from simple inorganic substances, using light energy in photosynthesis.

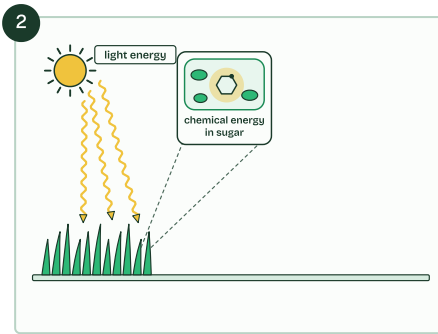


STEP BY STEP

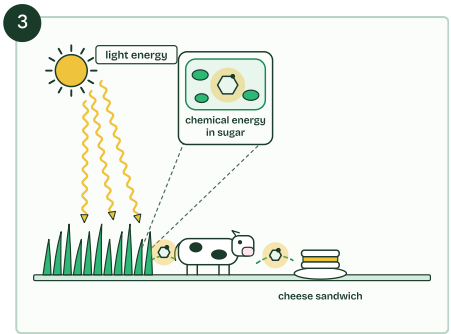
4 STEPS



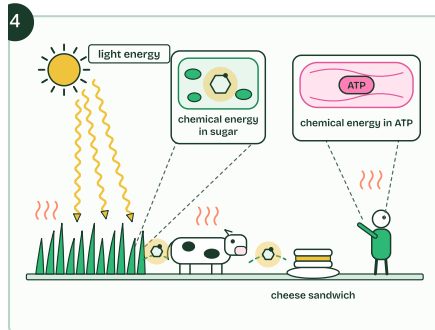
Light energy from the Sun reaches a leaf.



Photosynthesis turns it into **chemical energy** in the bonds of sugar.



The cow lives on that energy, and stores some of it in milk.



You release it in **respiration**, as ATP, and every step loses some as **heat**.

WATCH OUT

Photosynthesis does not make energy; it changes light energy into chemical energy. And plants respire too, in the dark and in the light: they use some of the sugar they make.

PREDICT

The chemical energy in a slice of cheese: where did it first come from?

- (A) Heat made in the cow's own muscles
- (B) Light caught by the grass it ate
- (C) Minerals the grass took from the soil
- (D) Sugars dissolved in the water it drank

Decide before you look. Answer on page 60.

02

C1.3.2

C1.3.3

CARBON DIOXIDE TO GLUCOSE, WITH OXYGEN AS A BY-PRODUCT

Carbon from the air, *hydrogen* from water

The **word equation** for photosynthesis is **carbon dioxide + water → glucose + oxygen**, with light energy and chlorophyll written over the arrow. In symbols it reads $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$, and the product that matters is **glucose**.

Look at the molecules. Carbon dioxide has carbon and oxygen but no hydrogen, and glucose needs plenty. The plant gets its hydrogen from water. It splits water using energy from the light that chlorophyll absorbs, a step called **photolysis**, and the hydrogen is added to carbon dioxide to build glucose. So glucose's carbon and oxygen come from carbon dioxide, and its hydrogen comes from water. Most of a tree's dry mass is carbon and oxygen taken from the air, not from the soil.

The oxygen gas a leaf gives off is a **by-product**. It comes from the water that was split, not from carbon dioxide. Every organism that photosynthesises this way gives off oxygen: plants, **algae** (from single cells to seaweeds) and **cyanobacteria**. Cyanobacteria were the first of them, as chapter 9 shows at higher level.

Adding hydrogen to a molecule is a reduction (C1.2). At higher level, chapters 8 to 13 follow the hydrogen from water to carbon dioxide, as electrons and protons carried by NADP.

KEY POINTS

- Carbon dioxide + water → glucose + oxygen, with light energy and chlorophyll over the arrow.
- Glucose's carbon and oxygen come from carbon dioxide; its hydrogen comes from water.
- The oxygen given off comes from the water that is split, and is a by-product.

KEY TERMS

word equation

The chemicals of a reaction written as words: the reactants, an arrow, then the products. For photosynthesis, carbon dioxide + water becomes glucose + oxygen.

glucose

A six-carbon sugar, $\text{C}_6\text{H}_{12}\text{O}_6$. It is the first carbohydrate that photosynthesis is usually said to make, and the fuel that respiration releases energy from.

photolysis

The splitting of water, using energy from light absorbed by chlorophyll. At higher level it is the job of photosystem II.

by-product

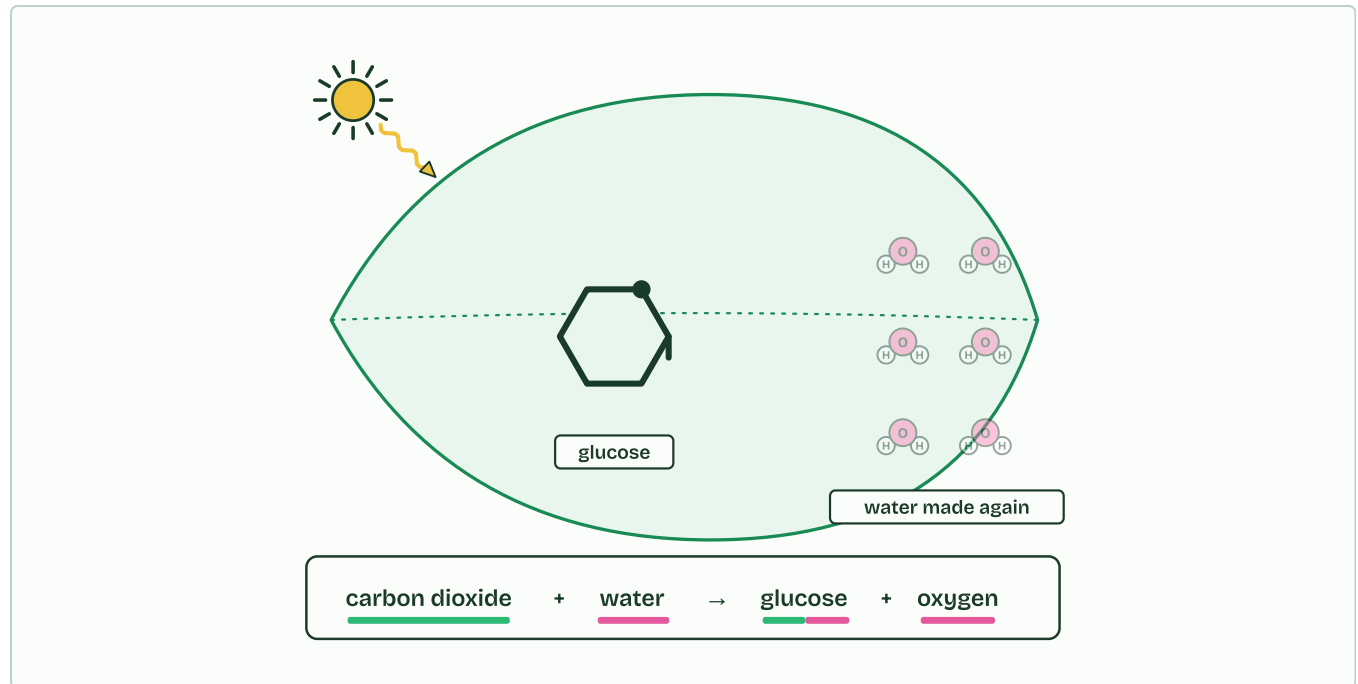
A substance made in a process that is not the aim of it. The oxygen from photosynthesis is a by-product of splitting water: the plant needs the hydrogen, not the oxygen.

algae

Eukaryotic organisms that photosynthesise but are not plants, from single-celled species to the seaweeds.

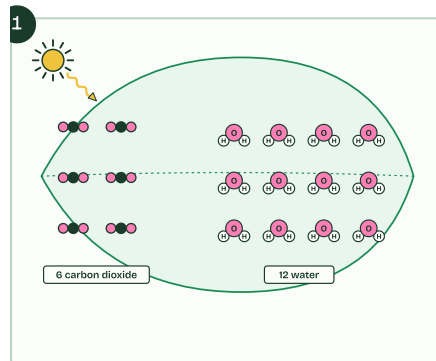
cyanobacteria

Photosynthetic bacteria. They were the first organisms to split water and give off oxygen.

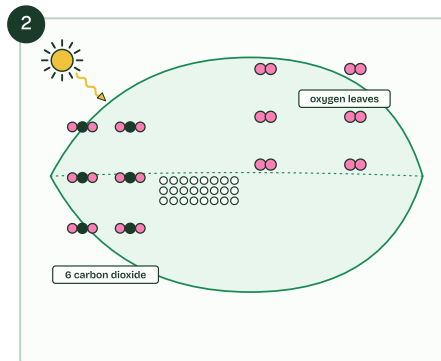


STEP BY STEP

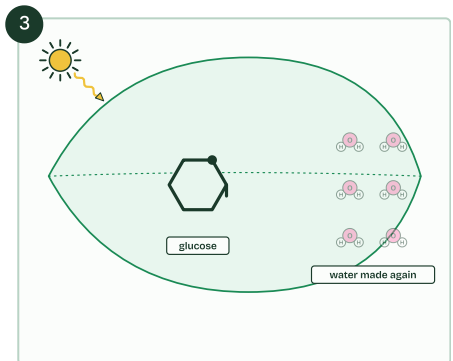
4 STEPS



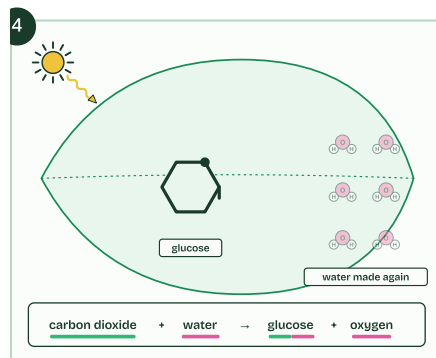
What goes in: **carbon dioxide** from the air, **water** from the soil.



Light energy **splits water**. The oxygen leaves as a by-product.

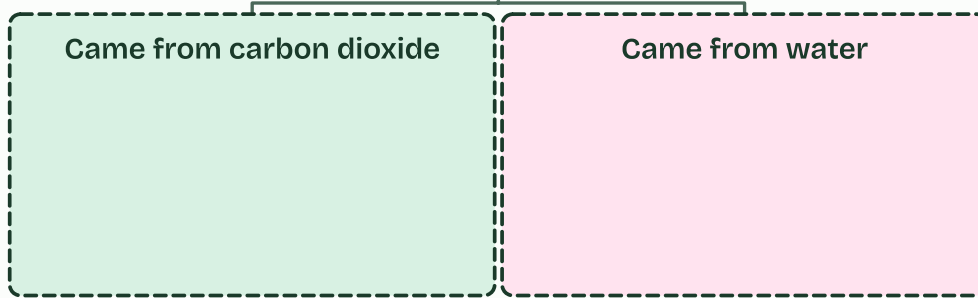


The **hydrogen** is added to carbon dioxide, building **glucose**.

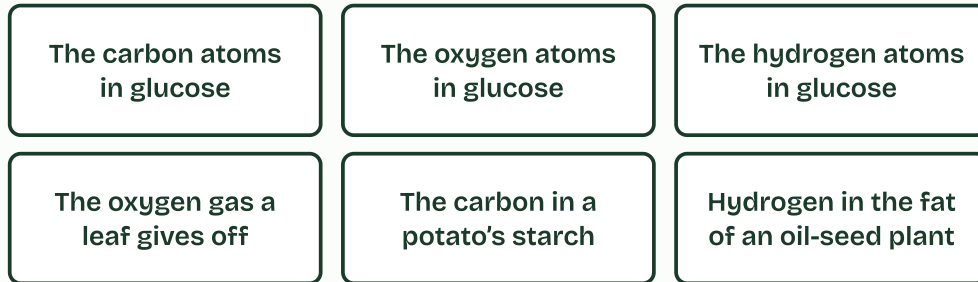


carbon dioxide + water → glucose + oxygen.
The bars show where each atom came from:
green, carbon dioxide; pink, water.

Where did it come from?



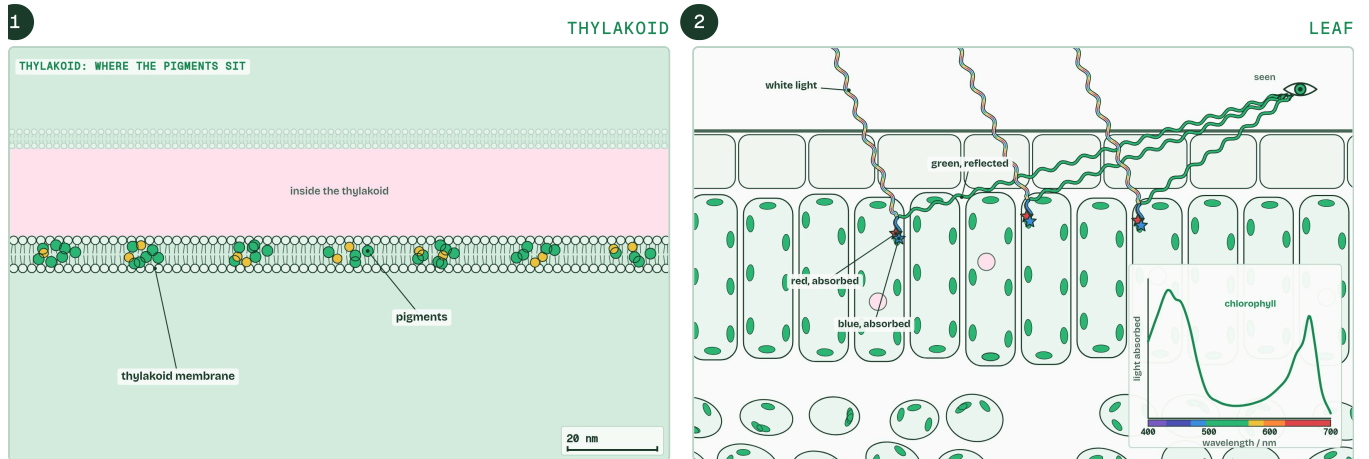
Six atoms or molecules to sort



Six atoms or molecules and two bins. Which molecule going in had the atom at all, and what tells you?

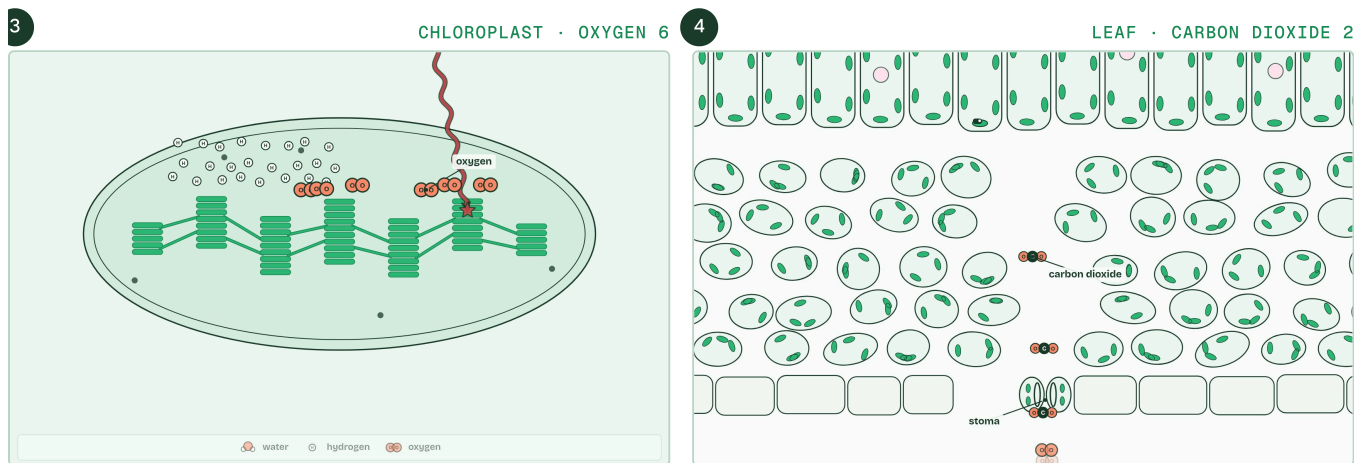
ANIMATION · FROM LIGHT TO SUGAR

6 MOMENTS



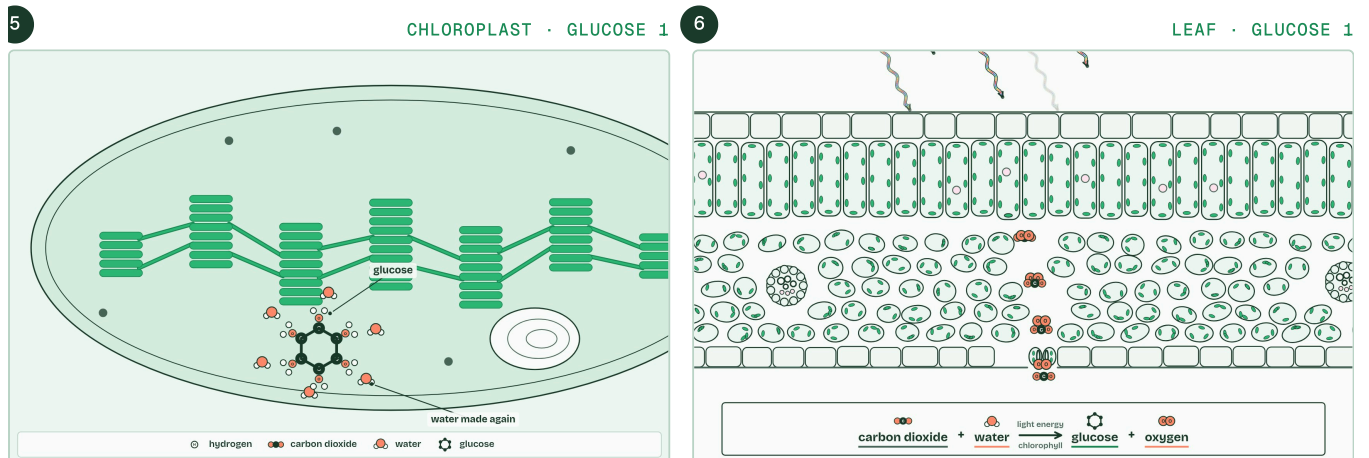
Into a **leaf**, a **palisade cell**, a **chloroplast** and the **thylakoids** where its pigments sit.

Chlorophyll absorbs **red** and **blue** light and reflects **green**.



Energy absorbed by chlorophyll **splits water**. The **oxygen** is given off as a by-product.

Carbon dioxide diffuses in from the air.



Hydrogen from water is added to carbon dioxide, building **glucose**, which can be stored as **starch**.

carbon dioxide + water → glucose + oxygen

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#equation

HOW WE KNOW

In 1941 Ruben and colleagues gave algae water made with a heavy form of oxygen. The oxygen gas the algae gave off was heavy too. When the heavy oxygen was in the carbon dioxide instead, the gas was not. The oxygen had come from the water.

WATCH OUT

"The oxygen comes from carbon dioxide" is the commonest slip, because the equation seems to say so. Carbon dioxide's oxygen ends up in the glucose and in the water that is made again. And light does not split water by itself: chlorophyll catches the light first (chapter 9).

PREDICT

Where does the oxygen gas a leaf gives off come from?

- ☐ (A) From the carbon dioxide it absorbs
- ☐ (B) From both, half and half
- ☐ (C) From the glucose it breaks down
- ☐ (D) From the water it splits

Decide before you look. Answer on page 60.

03

C1.3.4

SEPARATION AND IDENTIFICATION OF PIGMENTS BY CHROMATOGRAPHY

More than one *green*

A leaf's green is not one **pigment** but several, mixed. **Chlorophyll a** is the main one, blue-green. **Chlorophyll b** is yellow-green. Beside them are the yellow and orange carotenoids: **carotenes** and **xanthophylls**. All of them sit in the membranes of the chloroplast's thylakoids.

Chromatography separates a mixture. A small, dark spot of leaf extract goes on a pencil line, the **origin**, near the bottom of a strip of chromatography paper (or a thin-layer plate, the **stationary phase**). The strip stands in a shallow layer of **solvent** (the **mobile phase**) below the spot, in a closed tube. The solvent climbs and carries the pigments with it.

Each pigment travels at its own speed. The more soluble it is in the solvent, and the less it clings to the paper, the further it goes. So the pigments end up as separate bands. The **solvent front** marks how far the solvent went, and the **R_f value** compares the two:

R_f has no units and is always less than 1. You identify a pigment by its colour and its R_f, read against a table made with the same solvent and the same paper or plate. Thin-layer plates run faster and separate better than paper.

KEY POINTS

- Pencil, not ink, for the origin: ink is a mixture and runs too.
- A small, dark spot, built up by drying between drops.
- Solvent below the origin, and a lid on the tube.
- Take the strip out before the front reaches the top, and mark the front at once.
- Work quickly: pigments fade in the light.

KEY TERMS

pigment

A coloured substance that absorbs some wavelengths of light and reflects or passes on the others.

chlorophyll a

The main photosynthetic pigment: blue-green.

chlorophyll b

An accessory pigment: yellow-green.

carotenes

Orange-yellow carotenoid pigments. The carotene of a leaf runs furthest in chromatography.

xanthophylls

Yellow carotenoid pigments that contain oxygen.

chromatography

A way of separating a mixture. The substances travel at different speeds through a stationary phase carried by a moving solvent.

origin

The pencil line on a chromatogram where the spot of mixture is put.

stationary phase

The paper or plate that stays still in chromatography. Substances cling to it to different extents.

solvent

The liquid that climbs the paper and carries the pigments with it.

mobile phase

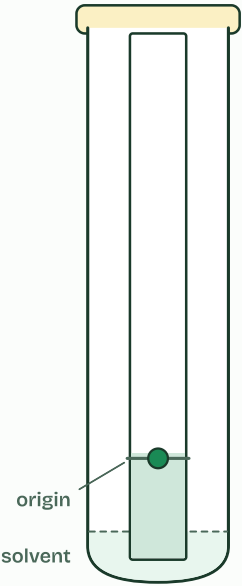
The solvent that moves in chromatography, carrying the substances along the stationary phase.

solvent front

The furthest point the solvent has reached. Mark it at once when you take the strip out, before it dries.

R_f value

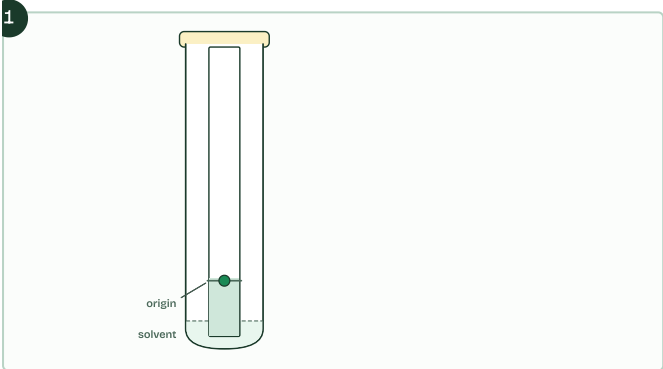
The distance a pigment moved divided by the distance the solvent front moved, both measured from the origin. It has no units and is always less than 1.



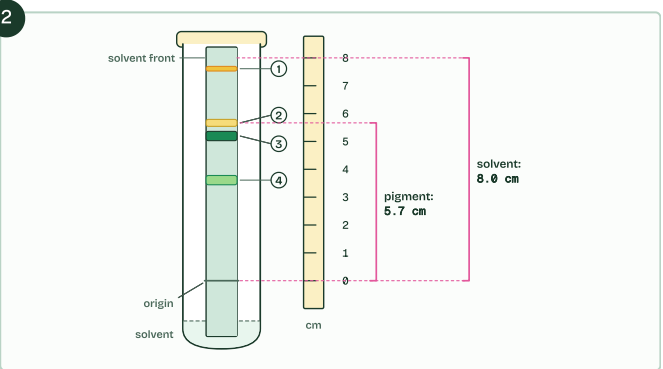
Slide the time. The solvent climbs and the green spot pulls apart into numbered bands. At the end, the distances are measured from the origin line.

SLIDE IT

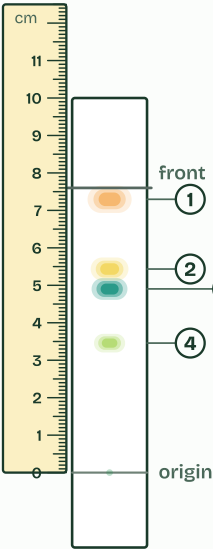
2 SETTINGS



Time 0



Time 100

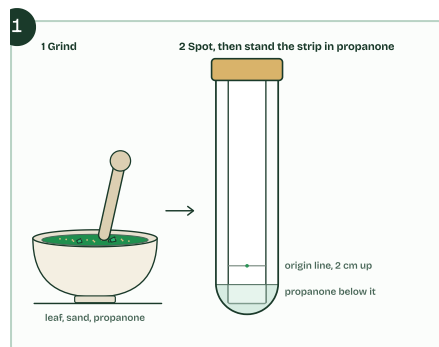


Your results				
Band	Colour	Distance / mm	R _f	Pigment
1				
2				
3				
4				
front				

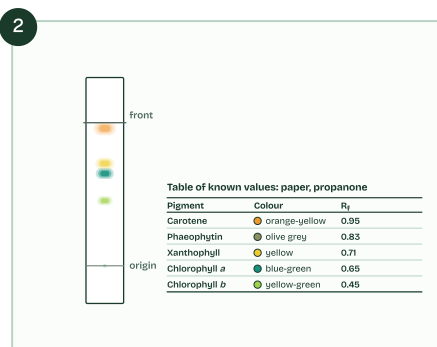
Table of known values: paper, propanone		
Pigment	Colour	R _f
Carotene	orange-yellow	0.95
Phaeophytin	olive grey	0.83
Xanthophyll	yellow	0.71
Chlorophyll <i>a</i>	blue-green	0.65
Chlorophyll <i>b</i>	yellow-green	0.45

STEP BY STEP

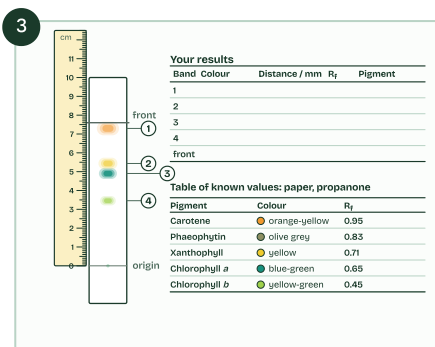
3 STEPS



Grind a leaf with a little sand and a few drops of propanone. Spot the extract on a pencil line 2 cm from the bottom of the strip, then stand the strip in propanone, below the line, with the lid on.



Take the strip out before the solvent reaches the top and mark the front in pencil at once. The pigments have separated into bands. The table beside it lists known values for this solvent.



Measure from the origin line to the middle of each band and to the front. Work out R_f for each band, then name each pigment from its colour and its R_f .

$$R_f = \frac{\text{DISTANCE MOVED BY THE PIGMENT}}{\text{DISTANCE MOVED BY THE SOLVENT FRONT}}$$

, both from the origin, the pigment to the middle of its band.

WATCH OUT

Measure from the origin line, not from the bottom of the paper, and to the middle of the band. And an R_f only means something beside a table made with the same solvent.

WHY IT MATTERS

Chromatography separates and identifies the substances in a biological mixture. The same idea separates amino acids and sugars.

PREDICT

The solvent front has moved 8.0 cm from the origin and a yellow band 5.7 cm. What is the band's R_f ?

- (A) 1.40
(B) 0.71
(C) 0.57
(D) 2.30

Decide before you look. Answer on page 60.

04

C1.3.5 ABSORPTION OF SPECIFIC WAVELENGTHS BY PHOTOSYNTHETIC PIGMENTS

Why some colours and *not* others

Visible light is the band of **wavelengths** from about 400 nm (violet) to about 700 nm (red). White light is every one of them together, and the shorter the wavelength, the more energy each photon carries.

A pigment **absorbs** a photon only if the photon's energy matches a jump one of its electrons can make to a higher energy level. The electron is then **excited**. Photons with other energies are not absorbed: they pass through the pigment or bounce off it, which is **reflection**.

Chlorophyll's electrons can make jumps that match blue and red photons, so it absorbs those strongly and very little green. The green is reflected or passes through. That is why leaves look green: you see the light they did not use. The energy of the excited electron is what photosynthesis turns into chemical energy.

Accessory pigments, the carotenoids, absorb blue and blue-green light that chlorophyll a takes up less, and widen the range of light a leaf can use. In autumn the chlorophyll breaks down first, and the carotenoids show as yellow and orange. An **absorption spectrum** shows, wavelength by wavelength, how much of the light a pigment takes in. Draw it with both the wavelengths in nm and the colours along the horizontal axis.

The pigments are held together in arrays called photosystems (chapter 8).

KEY POINTS

- Visible light runs from about 400 nm (violet) to about 700 nm (red).
- A photon is absorbed only if its energy matches a jump an electron in the pigment can make.
- Chlorophyll absorbs blue and red strongly and reflects green, so a leaf looks green.
- The horizontal axis of an absorption spectrum carries wavelengths and colours.

KEY TERMS

visible light

The wavelengths the human eye sees, from about 400 nm (violet) to about 700 nm (red). White light is all of them together.

wavelengths

The distance from one wave crest to the next. For light it is measured in nanometres (nm).

absorbs

Takes in the energy of light, so that the light does not come out again.

excited

Raised to a higher energy level by absorbing a photon.

reflection

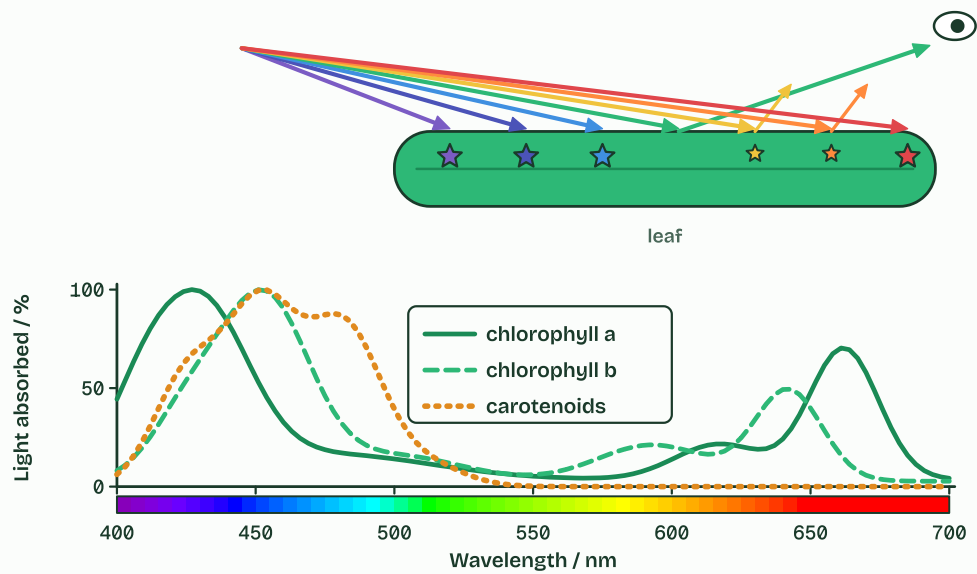
Light bouncing off a surface instead of being absorbed.

accessory pigments

Pigments that absorb light chlorophyll a absorbs less, and pass the energy on. In leaves they are the carotenoids and chlorophyll b.

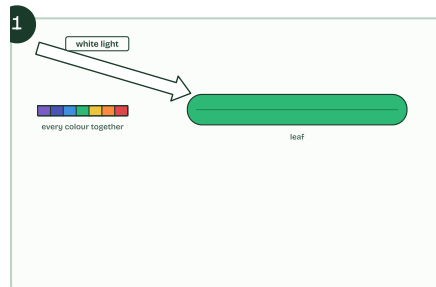
absorption spectrum

A graph of how much light a pigment absorbs at each wavelength.

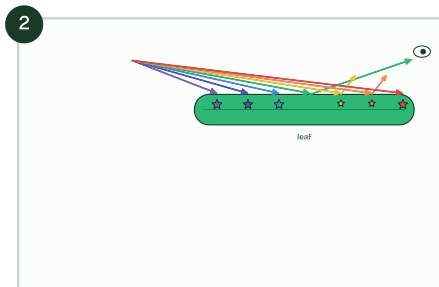


STEP BY STEP

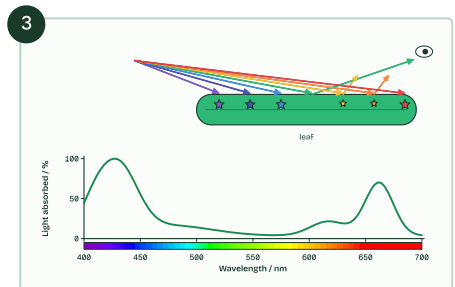
4 STEPS



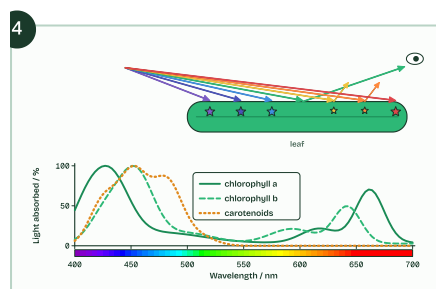
White light is every colour together.



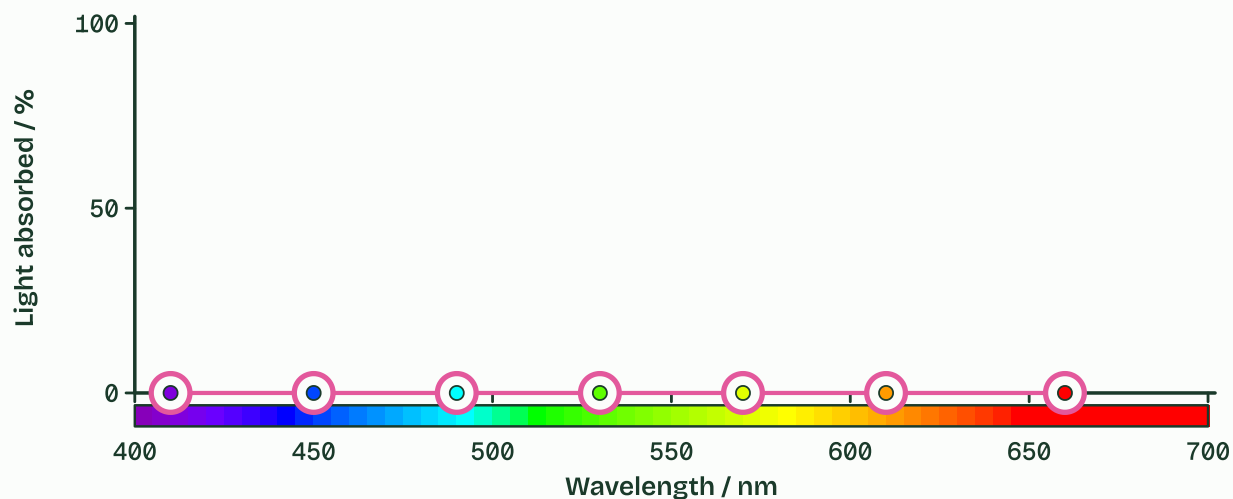
Chlorophyll absorbs **blue** and **red** and reflects most **green**.



An **absorption spectrum**: how much of each wavelength a pigment absorbs. These are for pigments dissolved in a solvent.



Accessory pigments absorb where chlorophyll a absorbs least.



Sketch chlorophyll's absorption spectrum: seven handles, one for each colour band. Chlorophyll a is the pigment to draw.

REMEMBER IT

The colours, longest wavelength first

R Richard	O Of	Y York	G Gave	B Battle	I In	V Vain
Red about 700 nm, absorbed	Orange about 610 nm	Yellow about 580 nm	Green about 530 nm, mostly reflected	Blue about 450 nm, absorbed	Indigo about 440 nm	Violet about 400 nm

WATCH OUT

A leaf is not green because chlorophyll makes green light. Green is the light it did not absorb.

PREDICT

Why does chlorophyll absorb red and blue light but very little green?

- (A) Green light has too little energy to reach the chloroplasts
- (B) Green light is all used up by the leaf's surface
- (C) Chlorophyll is broken down by green light, so avoids it
- (D) Red and blue photons match jumps its electrons can make

Decide before you look. Answer on page 60.

05

C1.3.6 ABSORPTION AND ACTION SPECTRA COMPARED

Absorbed is not the same as *used*

An **action spectrum** plots how fast photosynthesis runs against the wavelength of the light a plant is given. You measure it by lighting the plant with one colour at a time, the same amount of light each time, and measuring the oxygen it gives off or the carbon dioxide it takes in. The **rate of photosynthesis** is the amount of oxygen produced (or carbon dioxide consumed) divided by the time taken, for example cm^3 of oxygen $\div$ 10 minutes, in $\text{cm}^3 \text{ min}^{-1}$. Then plot rate against wavelength.

The two spectra are alike because the light a leaf uses is the light its pigments absorb: both peak in the blue and the red and dip in the green. They are not the same. The action spectrum's green dip is shallower, because chlorophyll b and the carotenoids absorb some of those wavelengths and pass the energy on, and because in a thick leaf green light bounces about and more of it is absorbed in the end. And absorbing light is not always using it: some of the energy that carotenoids absorb in the blue is lost as heat, so the action spectrum's blue peak is lower than the combined absorption there.

KEY TERMS

action spectrum

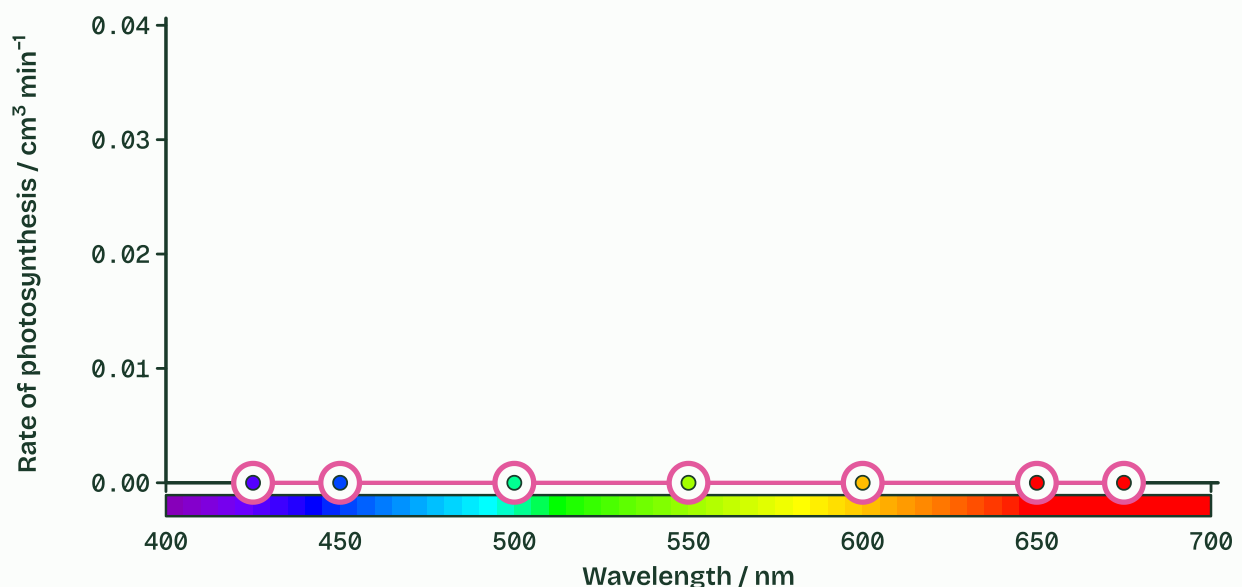
A graph of the rate of photosynthesis against the wavelength of the light given.

rate of photosynthesis

How much oxygen is produced, or carbon dioxide consumed, in a given time, for example in cm^3 per minute.

KEY POINTS

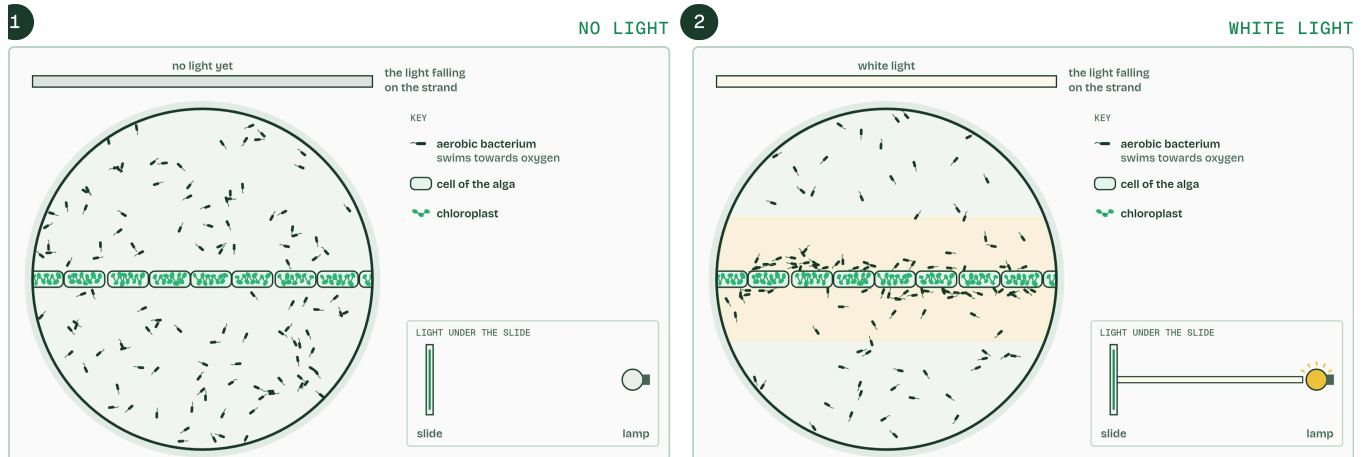
- Rate of photosynthesis = oxygen produced (or carbon dioxide consumed) $\div$ time.
- Similar: both spectra peak in blue and red and dip in green.
- Different: the action spectrum is a rate, its green dip is shallower, and its blue peak is lower than the absorption there.



Seven wavelengths of light, the oxygen a sprig gave off in 10 minutes in each, and empty axes. Rate = volume of oxygen $\div$ time.

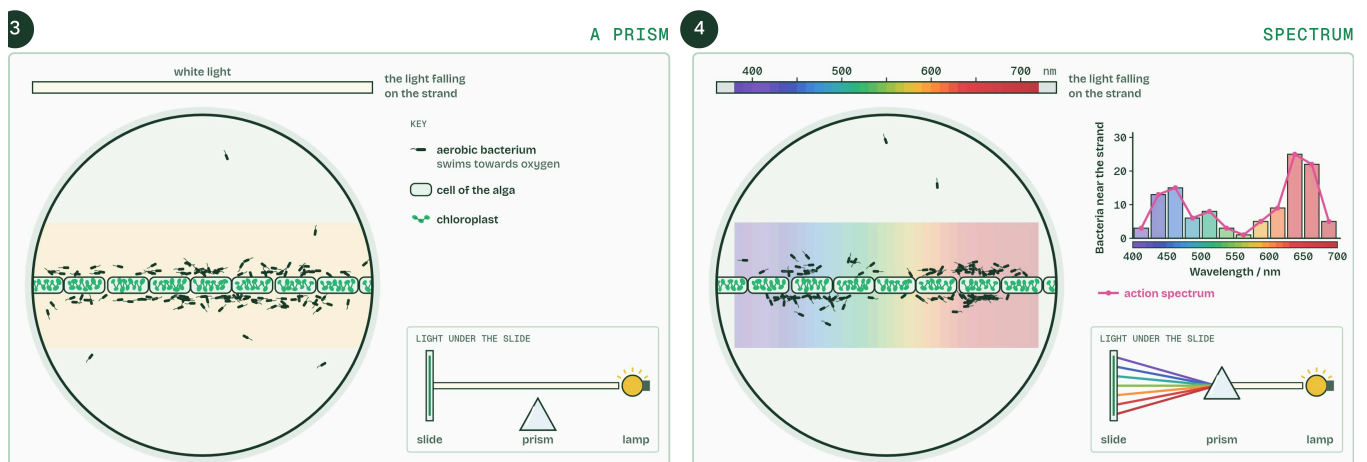
ANIMATION · ENGELMANN'S BACTERIA

4 MOMENTS



A strand of green alga, and bacteria that swim towards **oxygen**.

In white light the whole strand gives off oxygen. The bacteria gather evenly.



Engelmann put a **prism** under the slide. What will the bacteria do?

The bacteria crowd where **red** and **blue** light fall. Counted, they draw an **action spectrum**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#action

HOW WE KNOW

In 1882 Theodor Engelmann lit a strand of a green alga with a spectrum from a prism and added bacteria that swim towards oxygen. They crowded where red and blue light fell. It was the first action spectrum, measured with living bacteria as oxygen detectors. The film below repeats it.

WATCH OUT

An action spectrum is not “the light a plant absorbs”. It is what the plant does with each colour: its rate of photosynthesis.

PREDICT

Engelmann shone a spectrum along a strand of alga and added bacteria that swim towards oxygen. Where did the bacteria gather?

- (A) Under the red and the blue light
- (B) Evenly all along the strand of alga
- (C) Under the green light, and nowhere else
- (D) At the violet end of the strand

Decide before you look. Answer on page 60.

06

C1.3.7

VARYING LIGHT, CARBON DIOXIDE AND TEMPERATURE TO TEST LIMITING FACTORS

Whatever runs short sets the *pace*

Photosynthesis needs light, carbon dioxide and a suitable temperature all at once. When several factors affect a rate, the one in shortest supply holds it back. Raising that **limiting factor** speeds the process up, and raising the others does nothing, until one of them becomes the shortest. Blackman stated this as the law of limiting factors in 1905.

Light intensity limits the supply of energy for splitting water. The rate rises with light, then levels off when something else limits. **Carbon dioxide concentration** limits the fixing of carbon in the same way. Temperature acts on the enzymes (you saw why in C1.1): the rate rises to an optimum, about 25 to 30 °C for many temperate plants, then falls as the enzymes denature. In dim light, temperature matters little, because light is the limit. Where a curve levels off, another factor sets the height of the plateau: raise that one and the plateau rises.

To test each factor, vary it on its own. Move a lamp to change the light (the intensity falls roughly as $1 \div \text{distance}^2$, so use a light meter, with a heat shield between lamp and water). Dissolve sodium hydrogencarbonate in the water round pondweed or leaf discs to change the carbon dioxide (0 to 5 %). Use a water bath for temperature. Measure the rate by counting oxygen bubbles or collecting the gas, by the time leaf discs take to float, by the carbon dioxide taken up (hydrogencarbonate indicator), or by the gain in dry mass, which is slow and indirect.

A **hypothesis** is a provisional explanation that must be tested again and again. You can write it from theory before the experiment ("if carbon dioxide is the limiting factor, the rate will rise and then level off"), or from the evidence of a first run. Either way you name the **independent variable** (what you change), the **dependent variable** (what you measure) and the **controlled variables** (everything else, kept the same). Then test it on the bench, in the dry lab.

KEY POINTS

- Limiting factor: the factor in shortest supply, which sets the rate.
- Light, carbon dioxide and temperature are the three to know; raise the limiting one and the rate rises, until another takes over.
- A hypothesis names the independent, dependent and controlled variables.

KEY TERMS

limiting factor

The factor in shortest supply, which sets the rate of a process. Raising it speeds the process up; raising any other factor does nothing until it takes over as the limit.

light intensity

How much light falls on the plant. It limits the energy available to split water.

carbon dioxide concentration

How much carbon dioxide the plant has to build into sugar. It limits how much carbon can be taken in.

hypothesis

A provisional explanation that has to be tested again and again. It may be based on a theory and tested in an experiment, or based on the evidence of an experiment already done.

independent variable

The variable you change on purpose.

dependent variable

The variable you measure, to see the effect of the change.

controlled variables

Everything else that could affect the result, kept the same.

Rate of photosynthesis

Light intensity

Sketch a hypothesis as a graph, then check it. Three stages: light, then temperature, then carbon dioxide at high and low light.

REMEMBER IT

The three limiting factors

L Lazy	C Cats	T Toast
Light intensity the supply of energy for splitting water	Carbon dioxide concentration the carbon to fix	Temperature the speed of the enzymes, up to their optimum

WATCH OUT

A limiting factor is not “a factor that stops photosynthesis”. It is the one in shortest supply, setting the rate. Raise it and the rate rises, until another one takes over.

PREDICT

A plant at 15 °C is given more and more light until its rate levels off. Then it is warmed to 25 °C. What happens to the rate?

- (A) Nothing: light was never the problem
- (B) It rises to a higher plateau
- (C) It falls, as the enzymes denature
- (D) It drops, then climbs back to where it was

Decide before you look. Answer on page 60.

07

C1.3.8

CARBON DIOXIDE ENRICHMENT EXPERIMENTS

Tomorrow's air, *today*

The air's carbon dioxide has risen from about 280 parts per million before the industrial revolution to over 420 now, mostly from burning fossil fuels and clearing forests (D4.3 returns to this). Carbon dioxide is often a limiting factor, so will crops and forests grow faster in tomorrow's air?

Carbon dioxide enrichment experiments grow plants in the carbon dioxide expected later this century (about 550 to 600 ppm) beside plants in today's air, and compare photosynthesis, growth and yield. They ask whether the rate of photosynthesis rises and stays up, how much growth and yield gain, which plants gain most, and whether another factor (water, nitrogen or temperature) soon takes over as the limit.

In an enclosed **greenhouse** experiment, carbon dioxide from a gas cylinder holds the air at the chosen level. Temperature, light, water and nutrients can be controlled, so carbon dioxide is the only variable that differs. But pots restrict roots, the enclosure changes light and humidity, and only small plants fit. Commercial growers already enrich greenhouses to raise yields of crops such as tomatoes.

In **free-air carbon dioxide enrichment (FACE)**, a ring of pipes up to about 20 to 30 m across stands in a field or a forest. A sensor in the middle measures the carbon dioxide, and a computer sets how much the upwind pipes release to hold the target level. Control rings with the same pipes but no added carbon dioxide stand nearby. The plants grow in real soil, weather and competition, and whole trees can be studied. But temperature, rain and light cannot be controlled, and the gas is costly.

Careful control of variables is part of designing an experiment. It is easier in a **laboratory or greenhouse**, but some questions can only be answered in the **field**. A controlled variable in a greenhouse is the temperature; in FACE it is the crop variety, the sowing date or the pipes in the control rings. Crops in FACE rings gained less yield from extra carbon dioxide than enclosure studies had predicted, probably because in a field another factor soon becomes limiting.

KEY POINTS

- Enrichment experiments predict how plants will respond to the carbon dioxide of the future.
- A greenhouse controls more variables; FACE keeps field conditions and real ecosystems.
- Name a controlled variable for each: the greenhouse's temperature, FACE's crop variety and sowing date.

KEY TERMS

carbon dioxide enrichment

Growing plants in the carbon dioxide level expected later this century, beside plants in today's air, to predict how plants will respond.

greenhouse

A glass or plastic building in which temperature, light, water and the air can be controlled. In an enrichment experiment, carbon dioxide from a cylinder holds the air at the chosen level.

free-air carbon dioxide enrichment (FACE)

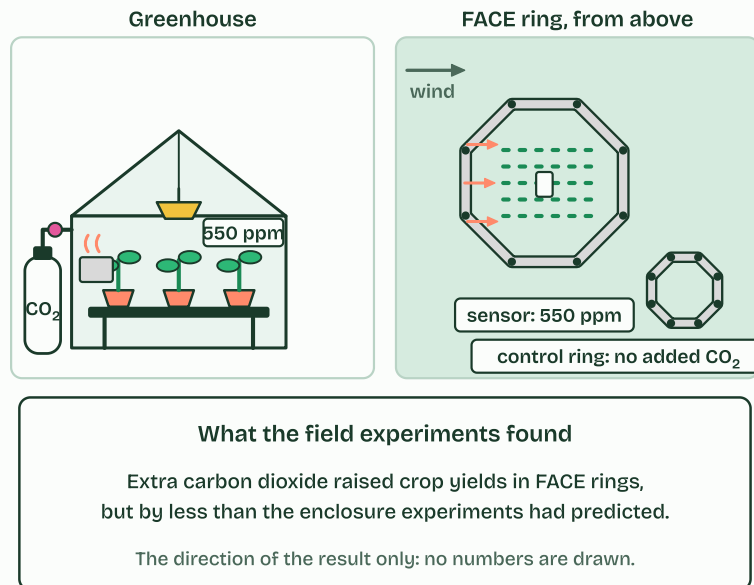
A field experiment in which a ring of pipes, up to about 20 to 30 m across, releases carbon dioxide round growing plants in the open air. Control rings have the same pipes but no added gas.

laboratory or greenhouse

A place where the variables can be controlled closely.

field

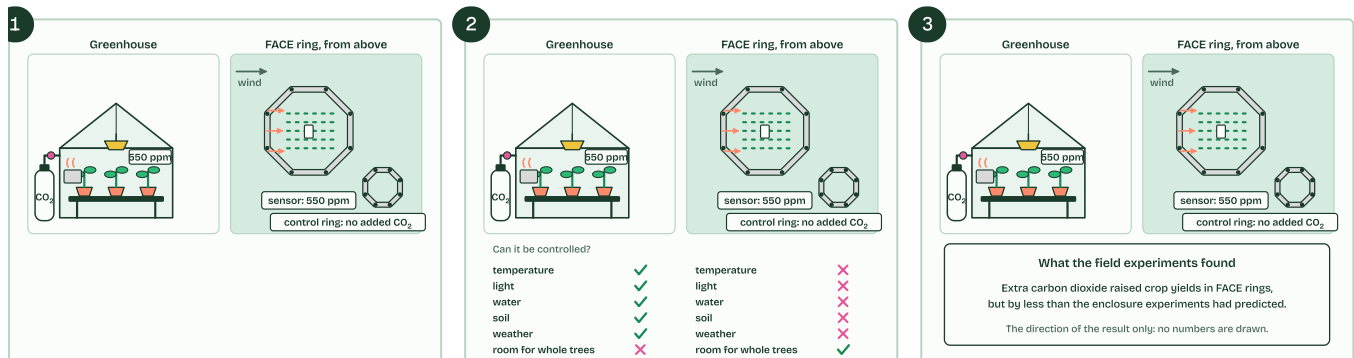
The natural setting: real soil, weather and competition, where variables cannot be controlled but the results apply to real ecosystems.



Greenhouse against FACE. Step 3 gives the direction of the result only, as reported by Long and colleagues (2006) in *Science*; no numbers are drawn.

STEP BY STEP

3 STEPS



Two ways to grow plants in **tomorrow's air**.

A greenhouse **controls** more variables; a **FACE** ring keeps real field conditions.

In the field, the gain in yield was smaller.

WATCH OUT

More carbon dioxide does not mean more growth for ever. It helps only while carbon dioxide is the limiting factor (chapter 6).

PREDICT

Crops given extra carbon dioxide gained less yield in FACE rings than in enclosures. What is the most likely reason?

- (A) FACE rings leak most of their carbon dioxide
- (B) Field crops are a different variety
- (C) In fields, another factor soon limits
- (D) Field soil absorbs the extra carbon dioxide

Decide before you look. Answer on page 60.

08

C1.3.9 HL

C1.3.10 HL

PHOTOSYSTEMS, AND THE ADVANTAGE OF THE ARRAY

Pigments in an *array*

A **photosystem** is an array of a few hundred pigment molecules, chlorophylls and accessory pigments, held in fixed positions by proteins. Photosystems are always in a membrane: the **thylakoid membranes** of a chloroplast, or the internal membranes of a cyanobacterium. At the heart of each is the **reaction centre**, a special chlorophyll a.

Light absorbed by any pigment in the array excites an electron in that pigment. The energy, not the electron, passes from pigment to pigment, inwards, until it reaches the reaction centre. There an **excited electron** is emitted: it leaves the chlorophyll altogether, passing to an electron acceptor beside it in the membrane. There are two kinds of photosystem, **photosystem II** and **photosystem I**, numbered in the order they were discovered. Electrons pass through II first.

Why an array? A single chlorophyll molecule, even in sunlight, absorbs a photon only every so often, and its excitation lasts only a few billionths of a second. On its own, the energy is lost as heat or given out again as red light, and it cannot do any part of photosynthesis. In an array, hundreds of pigments collect light and funnel it to one reaction centre, which keeps it busy. Different pigments widen the range of wavelengths caught. And their fixed spacing lets energy jump from one to the next before it is lost.

KEY POINTS

- A photosystem is an array of pigments round a reaction centre, always in a membrane.
- Pigments pass on energy; only the reaction centre emits an excited electron.
- One pigment alone could not do any part of photosynthesis.

KEY TERMS**photosystem**

An array of a few hundred pigment molecules, chlorophylls and accessory pigments, held in fixed positions by proteins in a membrane, with a reaction centre at its heart.

thylakoid membranes

The membranes inside a chloroplast where the light-dependent reactions happen. In cyanobacteria the photosystems are in internal membranes.

reaction centre

A special chlorophyll a at the heart of a photosystem, from which an excited electron is emitted.

excited electron

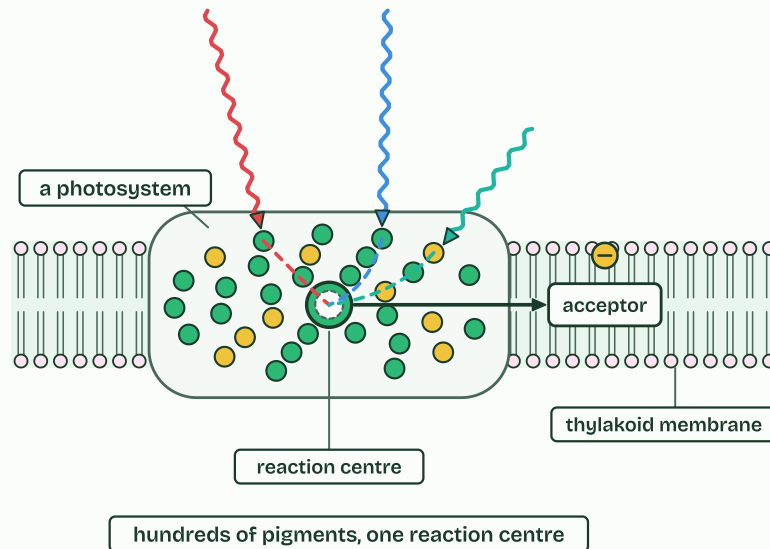
An electron raised to a higher energy level. In the reaction centre it is emitted, passing to an electron acceptor.

photosystem II

The photosystem that splits water and passes its electrons to the chain. Electrons pass through it first, though it was discovered second.

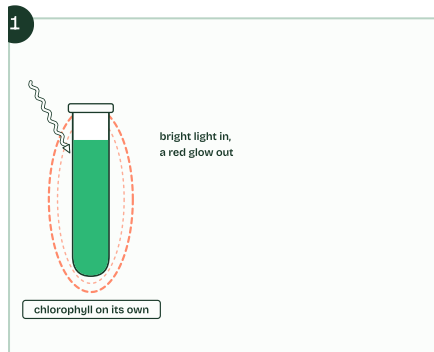
photosystem I

The photosystem that passes electrons on to reduce NADP.

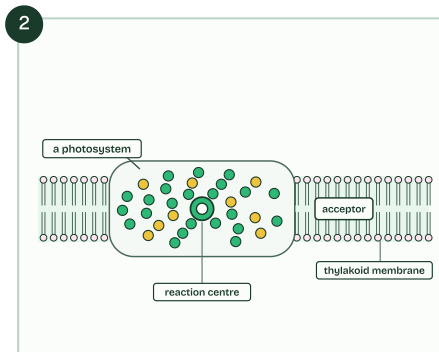


STEP BY STEP

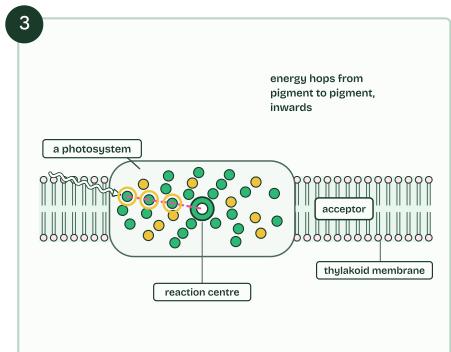
5 STEPS



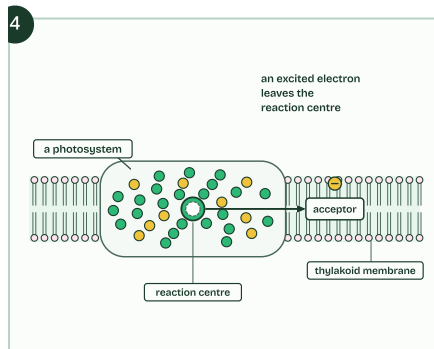
On its own, chlorophyll gives the energy straight back, as **red light**.



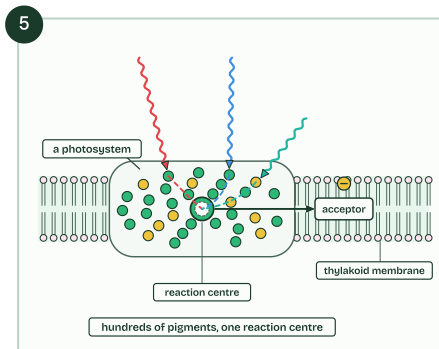
A **photosystem**: hundreds of pigments around a **reaction centre**, in a membrane.



The **energy** hops from pigment to pigment, inwards.



The reaction centre emits an **excited electron**.



Many pigments, many colours, all feeding one reaction centre.

SEEING IT

Chlorophyll extracted into propanone glows deep red under a bright light. Chlorophyll in a leaf hardly glows. In the leaf the energy is used. In the tube there is no array and no acceptor, so it comes straight back out as light.

WATCH OUT

Pigments in the array pass on energy, not electrons. Only the reaction centre emits an electron.

PREDICT

Chlorophyll dissolved in propanone glows red under a bright light. Chlorophyll in a leaf hardly glows at all. Why?

- ☐ (A) The leaf's chlorophyll is a different molecule
- ☐ (B) Propanone makes the chlorophyll absorb more light
- ☐ (C) Leaves reflect all of their red light away
- ☐ (D) In a leaf the energy is passed on and used

Decide before you look. Answer on page 60.

09

C1.3.11 HL

OXYGEN FROM THE PHOTOLYSIS OF WATER IN PHOTOSYSTEM II

Water split, *oxygen* spare

Photosystem II's reaction centre has emitted its electrons, so it needs more. It takes them from water. The splitting of water, **photolysis**, is done by an enzyme on the lumen side of photosystem II. Two water molecules give four electrons, four protons and one oxygen molecule.

The electrons refill the reaction centre, so it can be excited again. The **protons** are released into the lumen, where they add to the proton gradient (chapter 10). Both are used. The oxygen is a **waste product**: it diffuses out of the chloroplast, the cell and the leaf. Light does not split water directly. It excites the reaction centre, and the electron-short reaction centre pulls electrons from water.

The advent of oxygen from photolysis had immense consequences on Earth. Cyanobacteria were the first organisms to split water. The oxygen they released first reacted with iron dissolved in the oceans, which settled as layers of iron oxide on the sea floor: the **banded iron formations**. When the iron was used up, oxygen built up in the air, in the **Great Oxidation Event**, about 2.4 billion years ago. Oxygen poisoned many anaerobic organisms. It formed the ozone layer, which screens ultraviolet light. And it made aerobic respiration possible, with its far higher yield of ATP (C1.2), on which large, active organisms depend.

KEY POINTS

- Photolysis at photosystem II: 2 water give 4 electrons, 4 protons and 1 oxygen.
- The electrons and protons are used; the oxygen is waste.
- Light excites the reaction centre; the reaction centre takes electrons from water.

KEY TERMS

photolysis

The splitting of water by light-driven photosystem II, giving electrons, protons and oxygen. Two water molecules give four electrons, four protons and one oxygen molecule.

protons

Hydrogen ions, H⁺. Photolysis releases them into the thylakoid lumen.

waste product

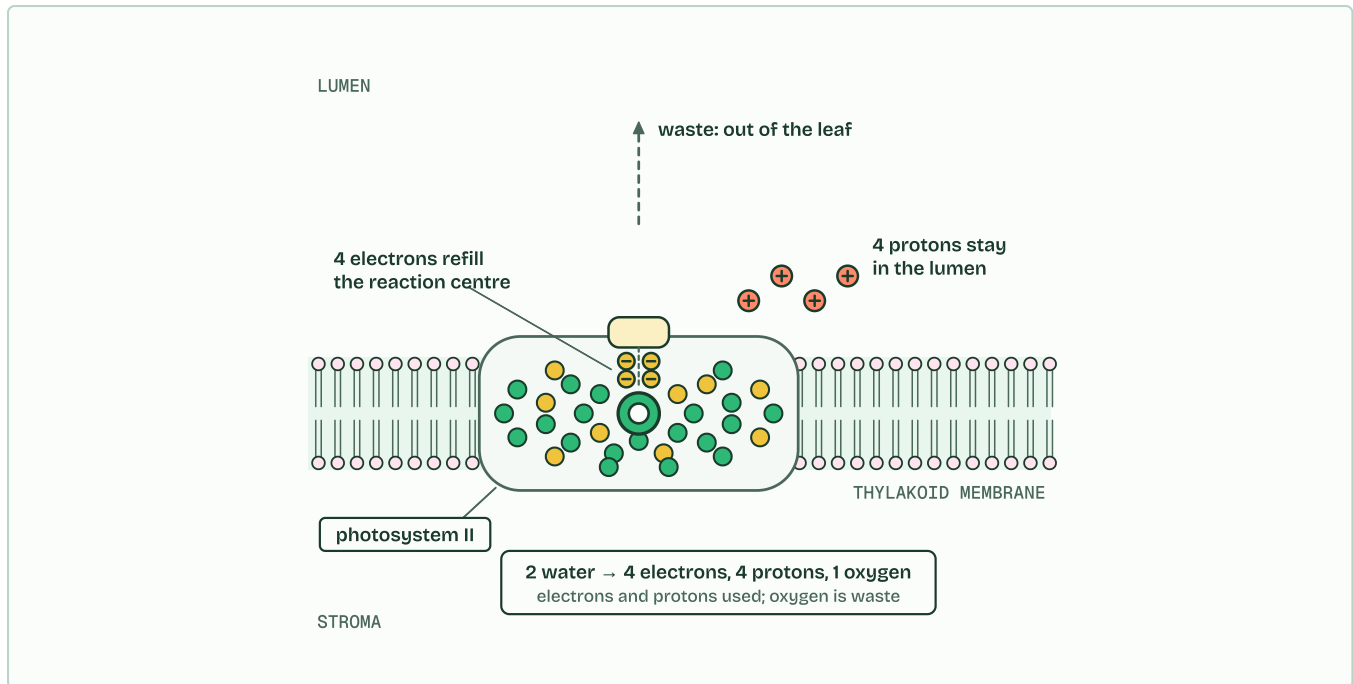
A substance a process makes but does not use. The oxygen from photolysis diffuses out of the chloroplast, the cell and the leaf.

banded iron formations

Layers of iron oxide in ancient rock, laid down when oxygen from cyanobacteria reacted with iron dissolved in the oceans.

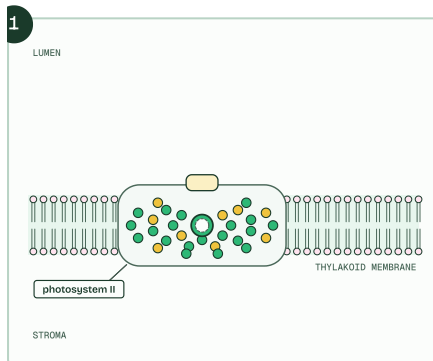
Great Oxidation Event

The rise of oxygen in the Earth's atmosphere, about 2.4 billion years ago, after cyanobacteria had been splitting water for a long time.

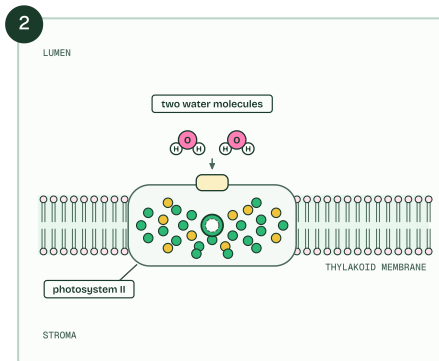


STEP BY STEP

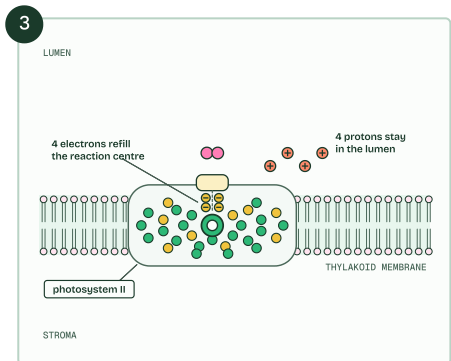
4 STEPS



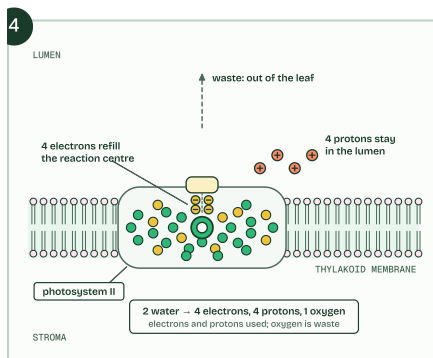
Photosystem II has lost electrons.



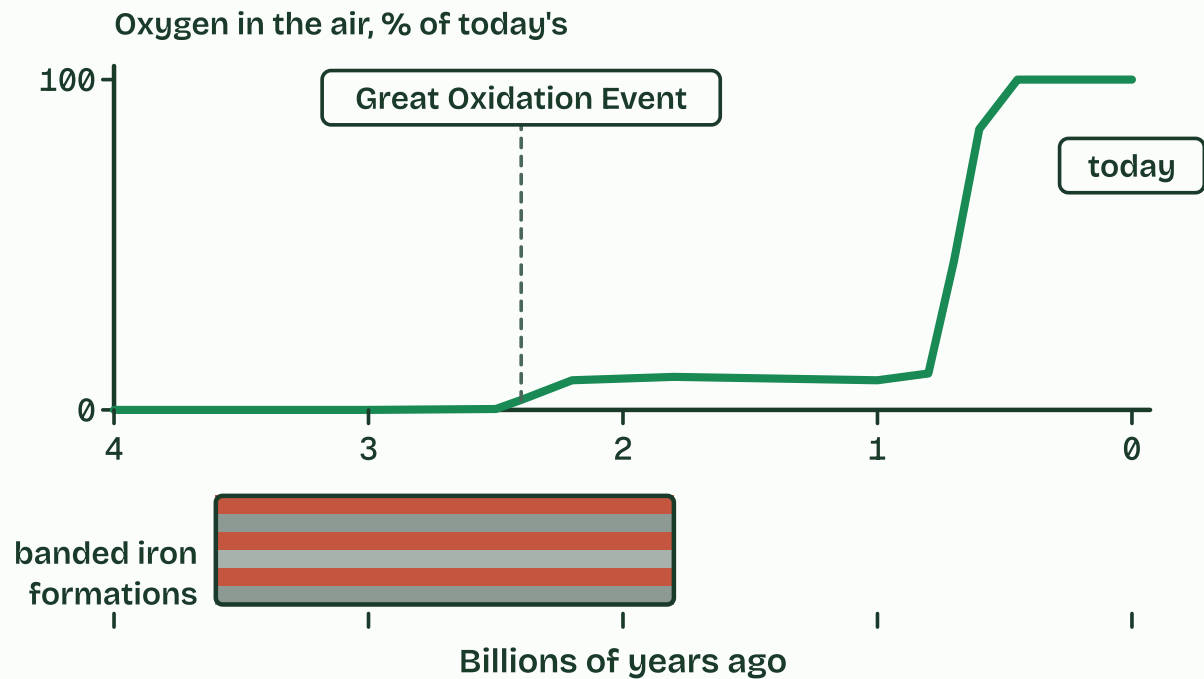
It takes more from **water**.



Photolysis: electrons refill the reaction centre; **protons** stay in the lumen.



The **oxygen** is a waste product.



The shape of the rise is known better than the numbers, so only 0 and today's level are marked. Banded iron formations are mostly older than about 1.8 billion years.

REMEMBER IT

What photolysis gives

P Please	E Eat	O Oranges
Protons into the lumen, for the gradient	Electrons back into photosystem II's reaction centre	Oxygen thrown away as waste

WATCH OUT

The protons and electrons from water are used; only the oxygen is waste. And it is photosystem II, not photosystem I, that splits water.

PREDICT

Cyanobacteria were splitting water for a long time before oxygen built up in the air. Where did their oxygen go at first?

- (A) Into iron dissolved in the oceans
- (B) Into an ozone layer forming high above
- (C) Back into their own respiration, all of it
- (D) Out into space through the thin air

Decide before you look. Answer on page 61.

10

C1.3.12 HL ATP PRODUCTION BY CHEMIOSMOSIS IN THYLAKOIDS

Protons downhill make *ATP*

The excited electron from photosystem II passes along a **chain of electron carriers** in the thylakoid membrane towards photosystem I, giving up energy at each step. One carrier uses that energy for **proton pumping**: it moves protons across the membrane from the stroma into the **thylakoid lumen**.

Protons come into the lumen two ways: pumped by the chain, and released by photolysis. The lumen is small, so their concentration rises fast, and the membrane does not let them back. That difference is the **proton gradient**. The only way back to the stroma is through **ATP synthase**, a protein that spans the membrane. Protons flowing down their gradient turn part of it, and the energy joins ADP and phosphate: ATP, made on the stroma side. Making ATP with energy from a proton gradient is **chemiosmosis**, and when light is the first source the whole process is photophosphorylation.

You met the same machine in mitochondria (C1.2). The difference is direction: a thylakoid pumps protons into its lumen and makes ATP outside it, in the stroma, while a mitochondrion pumps them out of the matrix and makes ATP inside it.

In **non-cyclic photophosphorylation** the electrons come from photosystem II, pass along the chain to photosystem I and on to NADP (chapter 11). In **cyclic photophosphorylation**, electrons excited at photosystem I go back to the chain, pump more protons and return to photosystem I. It makes ATP only: no reduced NADP, no water split, no oxygen. It tops up the ATP, because the Calvin cycle uses more ATP than reduced NADP.

KEY POINTS

- Electrons along the chain pump protons from the stroma into the lumen; photolysis adds more.
- Protons flow back through ATP synthase, which makes ATP on the stroma side.
- Non-cyclic: electrons from photosystem II to NADP. Cyclic: electrons from photosystem I round the chain again, for ATP only.

KEY TERMS

chain of electron carriers

A series of carrier molecules in the thylakoid membrane. An electron passes from one to the next, giving up energy at each step.

proton pumping

Moving protons across a membrane against their gradient, using the energy of electrons passing along a chain of carriers. In a thylakoid the protons go from the stroma into the lumen.

thylakoid lumen

The space inside a thylakoid, where protons collect.

proton gradient

A difference in the concentration of protons across a membrane. The protons flow back down it through ATP synthase.

ATP synthase

A protein that spans a membrane. Protons flowing down their gradient through it turn part of it, and the energy joins ADP and phosphate to make ATP.

chemiosmosis

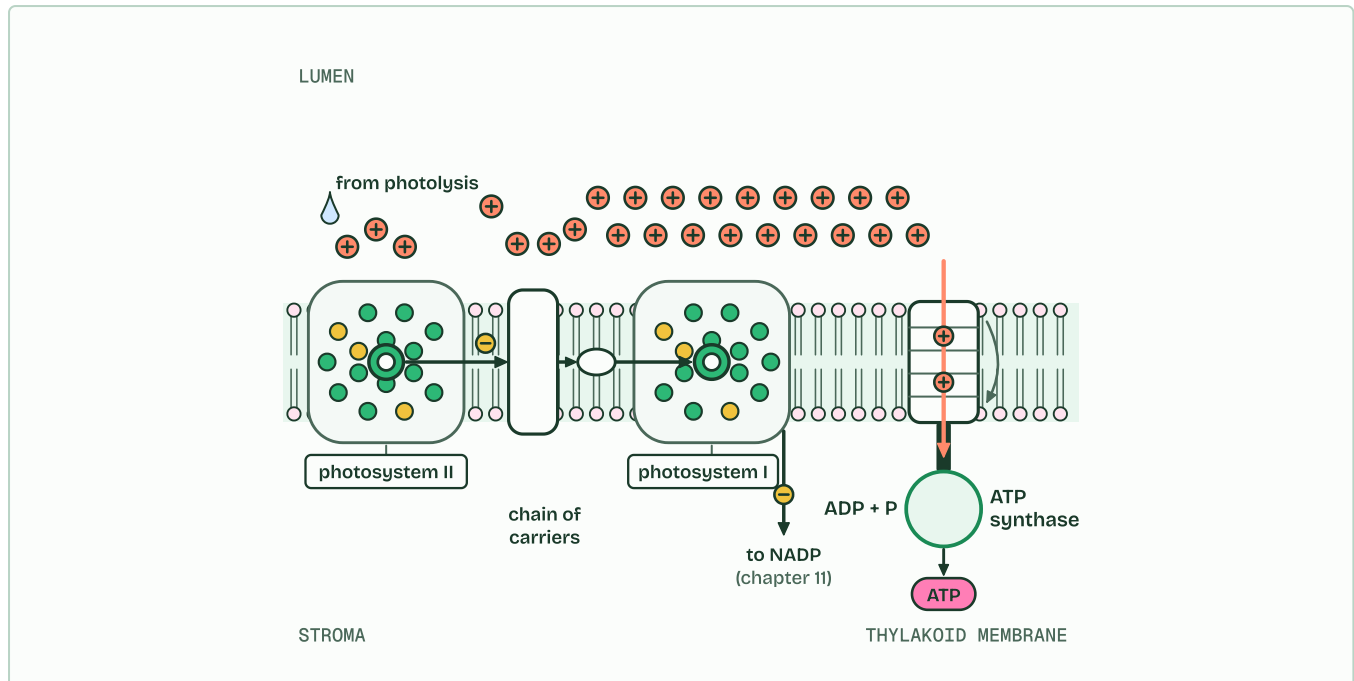
Making ATP using energy from a proton gradient across a membrane, through ATP synthase.

non-cyclic photophosphorylation

ATP made using electrons from photosystem II, passed along the chain to photosystem I and on to NADP. Water is split and oxygen is given off.

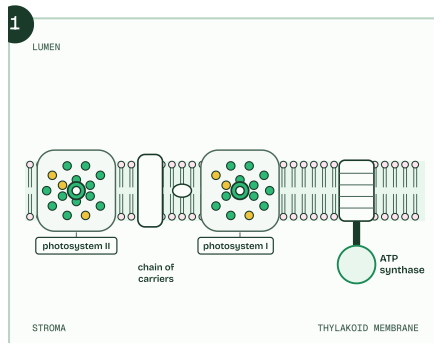
cyclic photophosphorylation

ATP made using electrons that come from photosystem I and return to the chain, then to photosystem I again. It makes ATP only: no NADP is reduced, no water is split and no oxygen is given off.

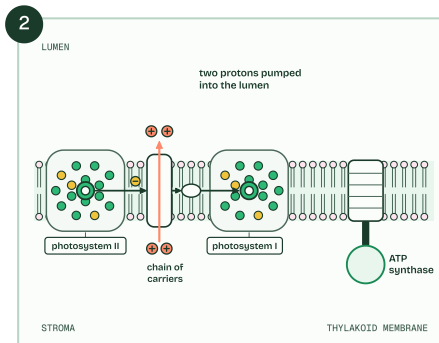


STEP BY STEP

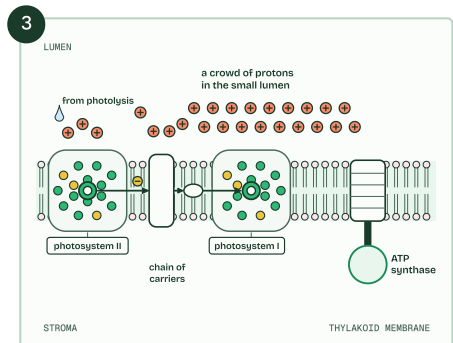
5 STEPS



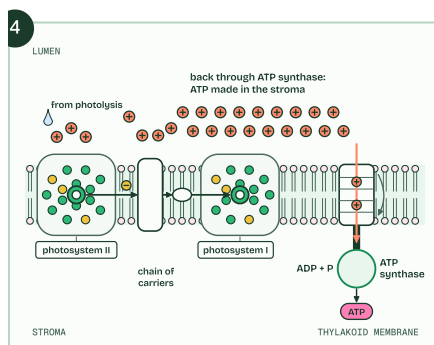
The thylakoid membrane: **photosystems**, a **chain of carriers** and **ATP synthase**.



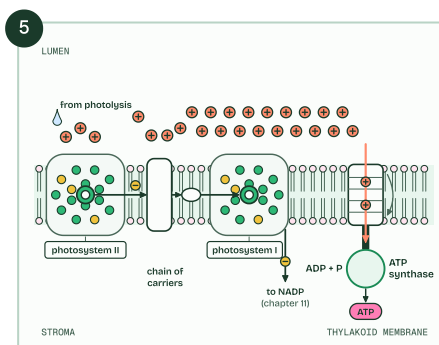
Electrons give up energy along the chain, which **pumps protons** into the lumen.



Protons pile up in the small lumen: a **proton gradient**.



They flow back through **ATP synthase**, which makes **ATP** in the stroma: **chemiosmosis**.



Non-cyclic: on to NADP. **Cyclic:** back round the chain, for more ATP.

WATCH OUT

Protons do not collect in an “intermembrane space”, as they do in a mitochondrion. In a chloroplast they collect in the thylakoid lumen.

PREDICT

In a working chloroplast, where do protons build up?

- (A) In the stroma, round the thylakoids
- (B) In the intermembrane space of the chloroplast
- (C) In the lumen, inside each thylakoid
- (D) In the cytoplasm, outside the chloroplast

Decide before you look. Answer on page 61.

11

C1.3.13 HL

C1.3.14 HL

NADP REDUCED BY PHOTOSYSTEM I, AND THE THYLAKOID AS A SYSTEM

NADP reduced, and the thylakoid as a *system*

Electrons arriving at photosystem I have given up energy along the chain. Light absorbed by photosystem I's array excites them again, and from its reaction centre they pass, by a short carrier on the stroma side, to **NADP**. NADP picks up two electrons from photosystem I and one hydrogen ion (a proton) from the stroma, and becomes **reduced NADP**. This is a **reduction**, and taking that proton from the stroma steepens the gradient a little.

Reduced NADP carries the hydrogen, as electrons and a proton, to the Calvin cycle in the **stroma**, where it reduces carbon compounds (chapter 13). This is how the hydrogen from chapter 2 gets from water to carbon dioxide: water's electrons go through photosystem II, the chain and photosystem I, to NADP.

A thylakoid is a system in which every part has its place. On the lumen side: photolysis at photosystem II, and the store of protons. In the membrane: the photosystems, the chain and ATP synthase, held in order so electrons pass from one to the next. On the stroma side: ATP is made and NADP is reduced, right where the Calvin cycle's enzymes are. Thylakoids are stacked in **grana**, joined by single unstacked sheets of membrane that run through the stroma; the stacking gives a large area of membrane, and the small lumen builds a steep gradient fast. Nothing has to "move to the stroma": ATP and reduced NADP are made in it.

KEY POINTS

- NADP is reduced at photosystem I, by two electrons from it and a proton from the stroma.
- Photolysis and the proton store are on the lumen side; ATP and reduced NADP are made on the stroma side.
- Grana give a large area of membrane; the small lumen gives a steep gradient fast.

KEY TERMS

NADP

A carrier molecule that picks up electrons and a proton and delivers them to the Calvin cycle. It is written NADP when empty and reduced NADP when it holds them.

reduced NADP

NADP carrying two electrons and a proton. It is the carrier of hydrogen to the Calvin cycle.

reduction

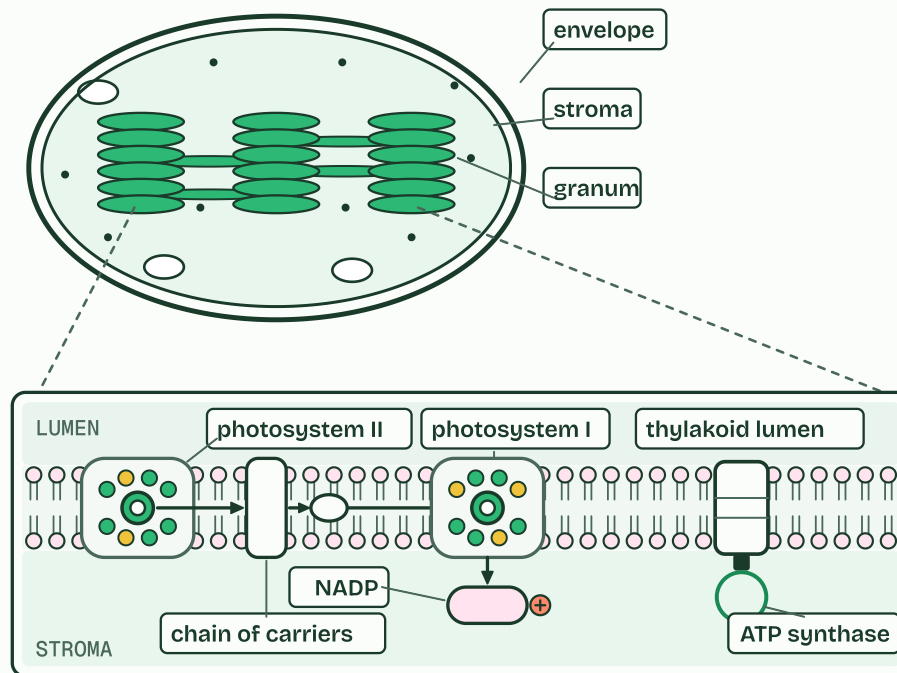
The gain of electrons (or hydrogen) by a molecule.

stroma

The fluid inside a chloroplast around the thylakoids. The Calvin cycle runs here.

grana

Stacks of thylakoids (one is a granum). Stacking gives a large area of membrane.



A chloroplast cut open, and one thylakoid membrane enlarged. Which side of the membrane does each part work on?

Stroma The fluid round the thylakoids. The Calvin cycle runs here, and ATP and reduced NADP are made and used here.

Granum A stack of thylakoids. Stacking gives a large area of membrane in a small space, and single sheets join one stack to the next.

Granum A stack of thylakoids. Stacking gives a large area of membrane in a small space, and single sheets join one stack to the next.

Stroma The fluid round the thylakoids. The Calvin cycle runs here, and ATP and reduced NADP are made and used here.

Chain of carriers Passes electrons from photosystem II towards photosystem I, and pumps protons into the lumen.

NADP Reduced here, on the stroma side, by two electrons from photosystem I and a proton from the stroma.

Envelope Two membranes round the chloroplast. The thylakoids are a separate system inside it.

Granum A stack of thylakoids. Stacking gives a large area of membrane in a small space, and single sheets join one stack to the next.

Thylakoid lumen The small space inside a thylakoid. Photolysis happens on its side of photosystem II, and protons pile up here.

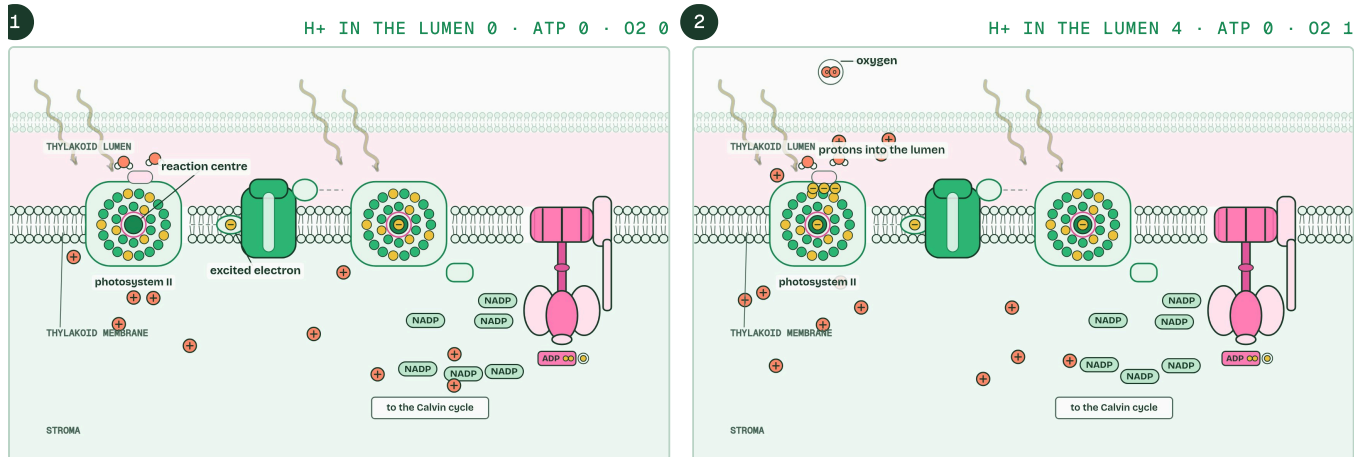
Photosystem II Splits water on the lumen side and passes its electrons on.

Photosystem I Its excited electrons pass on, on the stroma side, to NADP.

ATP synthase Lets protons flow back from the lumen to the stroma and makes ATP on the stroma side.

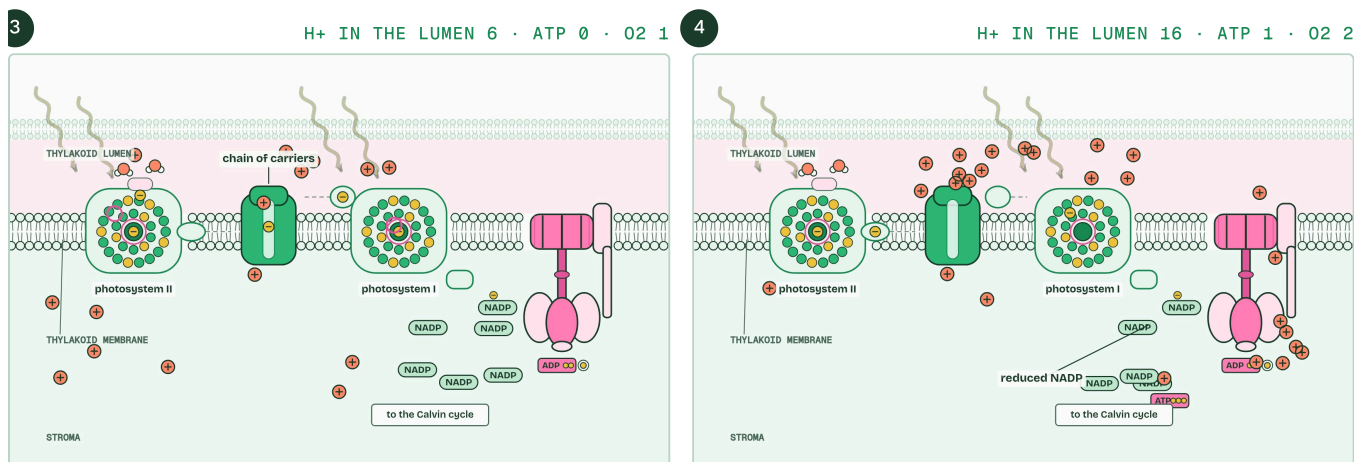
ANIMATION · THE THYLAKOID AT WORK

6 MOMENTS



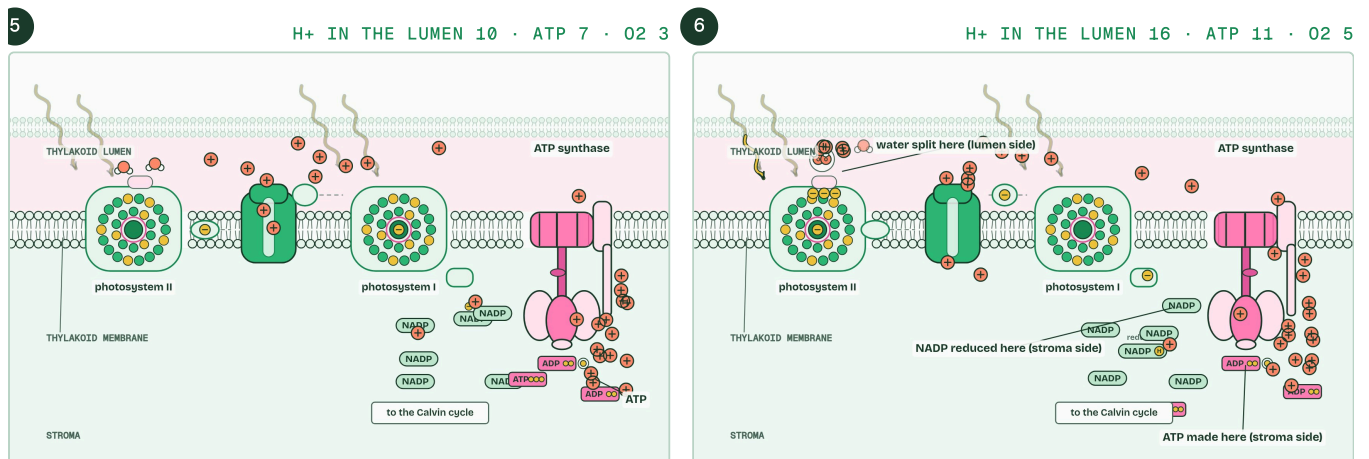
Light energy is passed through an **array of pigments** to the **reaction centre**, a special chlorophyll, which gives off an **excited electron**.

The reaction centre replaces its lost electrons by **splitting water** (photolysis). The protons stay in the lumen; the **oxygen** is a waste product.



The electron passes along a **chain of carriers**, which uses its energy to **pump protons** from the stroma into the lumen.

At **photosystem I** light lifts the electron again. Two electrons and a proton from the stroma **reduce NADP**.



Protons flow out of the lumen through **ATP synthase**, making **ATP** in the stroma, where the Calvin cycle will use it.

The thylakoid as a system: water split on the lumen side, **ATP** and **reduced NADP** made on the stroma side.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#nadh

REMEMBER IT

Two sides of the thylakoid

L Loads	S Spends
Lumen where protons pile up and water is split	Stroma where ATP and reduced NADP are made, then spent by the Calvin cycle

WATCH OUT

NADP is reduced at photosystem I, not photosystem II; photosystem II splits water. Electrons go through II first: the numbers record the order of discovery.

PREDICT

On which side of the thylakoid membrane is NADP reduced, and why does that side make sense?

- Ⓐ The stroma side, where the Calvin cycle uses it
- Ⓑ The lumen side, where protons are most crowded
- Ⓒ The lumen side, so it can cross to the stroma
- Ⓓ Either side, since NADP passes through the membrane

Decide before you look. Answer on page 61.

12

C1.3.15 HL CARBON FIXATION BY RUBISCO

Fixing carbon, *slowly*

The light-independent reactions are a cycle in the stroma, the **Calvin cycle**, named after Melvin Calvin, who worked it out with radioactive carbon in algae. Its first step is **carbon fixation**. Carbon dioxide joins a five-carbon sugar already in the stroma, **ribulose biphosphate (RuBP)**. The six carbons split at once into two molecules of the three-carbon **glycerate 3-phosphate (GP)**. The enzyme is **Rubisco**. So the substrates are RuBP and carbon dioxide, and the product is GP.

“Fixation” means turning carbon from a gas into part of an organic molecule: the carbon is now held. Adding carbon dioxide to a molecule is also called carboxylation, so fixation by Rubisco is the carboxylation of RuBP.

Rubisco is slow. Each active site fixes only about three carbon dioxide molecules a second, where catalase (C1.1) breaks down millions of hydrogen peroxide molecules a second. And it is not effective at low carbon dioxide concentrations: when carbon dioxide is scarce (on a hot day, with the stomata closed) it works far below its best. So the stroma needs a high concentration of Rubisco to fix carbon dioxide as fast as the light-dependent reactions supply ATP and reduced NADP. Rubisco is up to about half of the soluble protein in a leaf, and it is the most abundant enzyme on Earth.

KEY POINTS

- Carbon fixation: carbon dioxide joins RuBP (5 carbons), which splits into two GP (3 carbons each).
- The enzyme is Rubisco: slow, and poor at low carbon dioxide concentrations.
- The stroma needs a high concentration of Rubisco for that reason.

KEY TERMS

Calvin cycle

The cycle of reactions in the stroma that fixes carbon dioxide into carbon compounds, using ATP and reduced NADP from the light-dependent reactions. Melvin Calvin worked it out in the 1950s, using radioactive carbon in algae.

carbon fixation

Turning carbon from a gas, carbon dioxide, into part of an organic molecule.

ribulose biphosphate (RuBP)

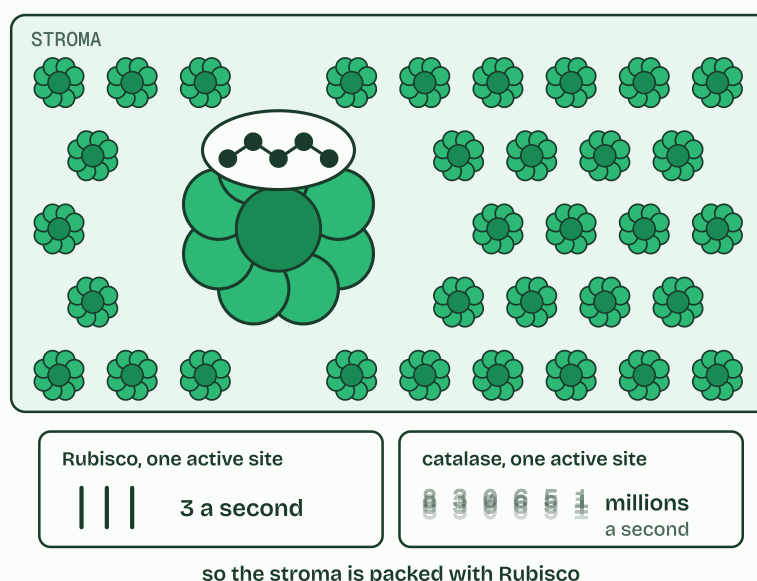
The five-carbon sugar that carbon dioxide joins in carbon fixation. It is remade by the Calvin cycle.

glycerate 3-phosphate (GP)

The three-carbon compound that RuBP and carbon dioxide make. Two GP form from each fixation.

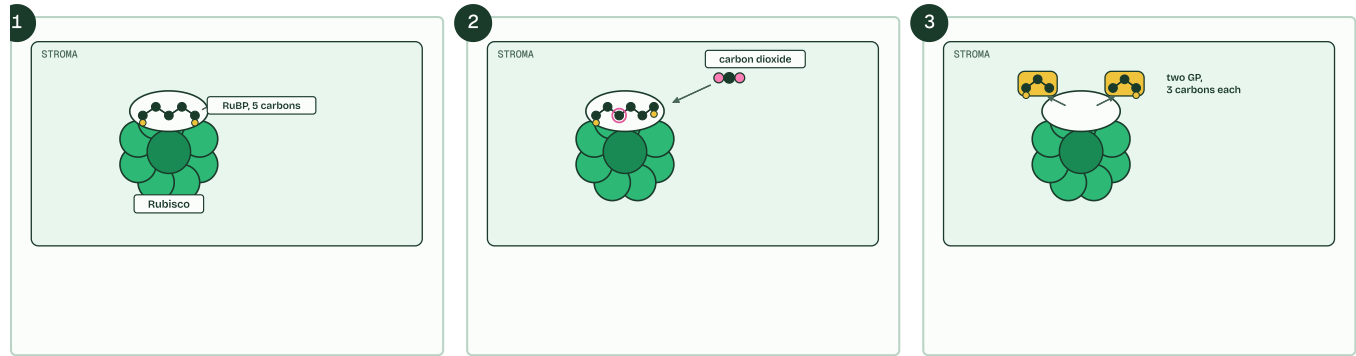
Rubisco

The enzyme that fixes carbon dioxide onto RuBP. It is slow, so a leaf needs a great deal of it, and it is the most abundant enzyme on Earth.



STEP BY STEP

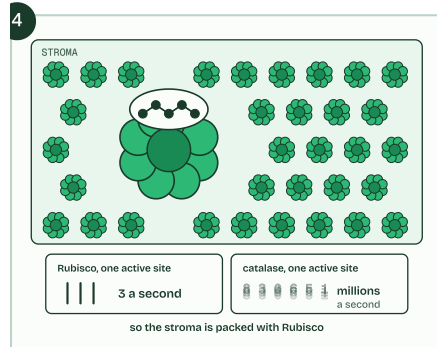
4 STEPS



RuBP, a five-carbon sugar, waits in **Rubisco's** active site.

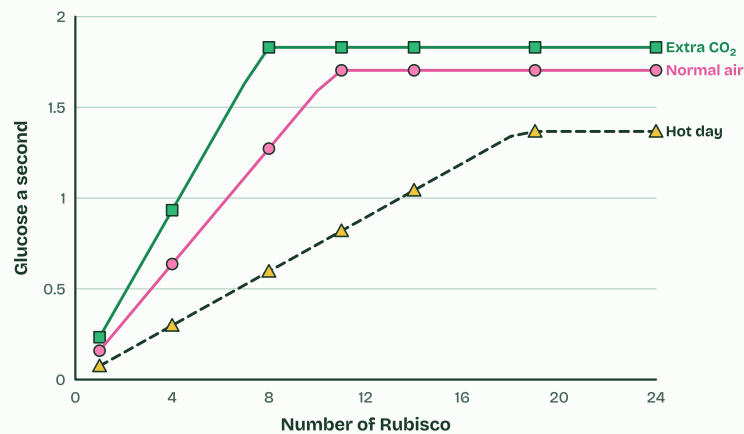
Carbon dioxide joins it: **carbon fixation**.

The six carbons split into two **GP**.



Rubisco is slow, so a leaf makes **a lot** of it.

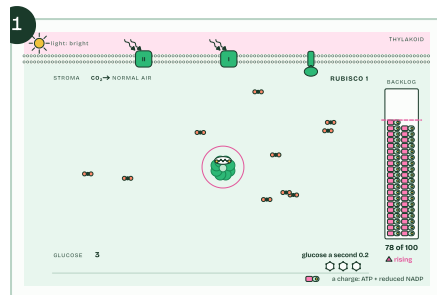
The record



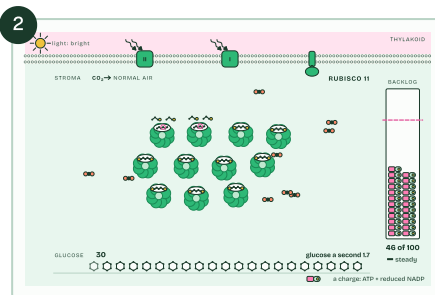
bright light, each point held steady

STEP BY STEP

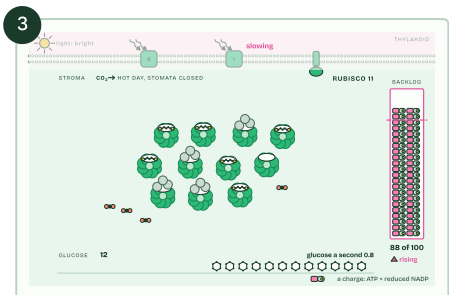
4 STEPS



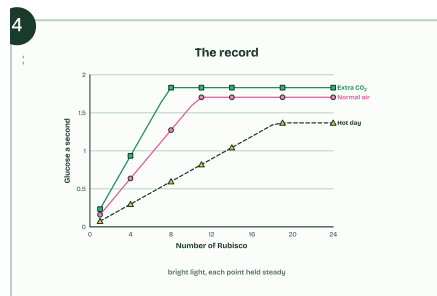
One Rubisco cannot keep up.



Eleven keep pace with bright light.



With little carbon dioxide, each does less and fumbles more.



More Rubisco helps until light is the limit.

WATCH OUT

Rubisco is an enzyme, not a product of the cycle, and it is not used up. It is abundant because it is slow, not because it is special in any other way.

PREDICT

A leaf cell could save a lot of protein by making less Rubisco. Why doesn't it?

- (A) Rubisco is used up in every reaction it runs
- (B) Rubisco is also the leaf's main green pigment
- (C) Spare Rubisco is where the leaf stores sugar
- (D) Each Rubisco fixes only a few CO_2 a second

Decide before you look. Answer on page 61.

13

C1.3.16 HL

C1.3.17 HL

TRIOSE PHOSPHATE FROM GP, AND RUBP REGENERATED

GP to TP, and RuBP *made again*

Reduced NADP and ATP from the light-dependent reactions turn GP into **triose phosphate (TP)**, a three-carbon sugar, in the stroma. Reduced NADP gives the hydrogen (it reduces GP) and ATP gives the energy. NADP and ADP go back to the thylakoid. TP is the first sugar and the cycle's product: some of it leaves to make glucose and everything else (chapter 14).

The rest has to remake RuBP, using more ATP. Five TP (fifteen carbons) are rearranged into three RuBP (fifteen carbons), so the cycle can fix carbon dioxide again. This is **regeneration**. You do not need the steps in between. Counting a round: three RuBP fix three carbon dioxide to give six GP; six GP give six TP; one TP leaves; five remake three RuBP. Three carbons in, three carbons out as one TP.

To make one glucose (six carbons, two TP), six carbon dioxide must be fixed, and five-sixths of all the TP made goes back to RuBP. Without regenerating RuBP, fixation would stop within moments. One turn of the cycle fixes one carbon dioxide, so six turns make one glucose. The figure runs three turns at a time (a "round") only because three is the smallest number that gives a whole TP out.

Why a cycle? The molecule that accepts carbon dioxide is remade every turn, so a small stock of RuBP keeps fixing carbon as long as ATP and reduced NADP keep coming. The tally in the corner counts ATP and reduced NADP as they are used; it is there to show the cost, not to be learned.

KEY POINTS

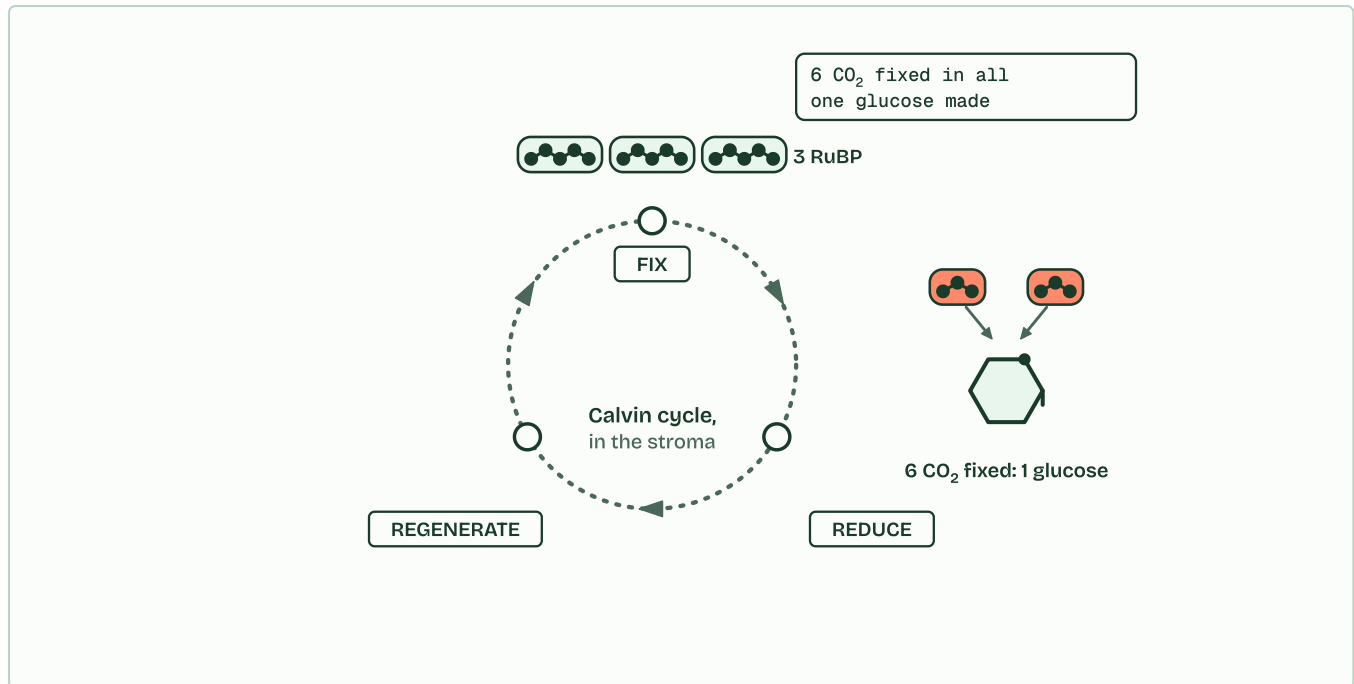
- GP is reduced to TP, using reduced NADP and ATP.
- Five TP of every six made are remade into three RuBP, using ATP; one in six leaves.
- Six turns of the cycle fix six carbon dioxide and make one glucose.

KEY TERMS**triose phosphate (TP)**

The three-carbon sugar phosphate made when ATP and reduced NADP reduce GP. It is the first sugar and the product of the cycle.

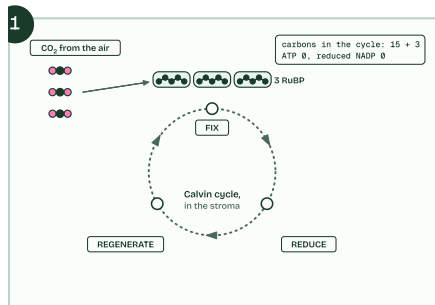
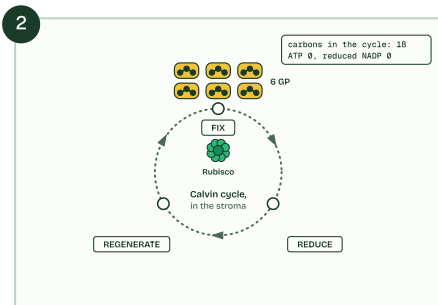
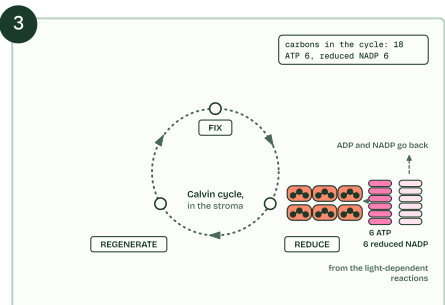
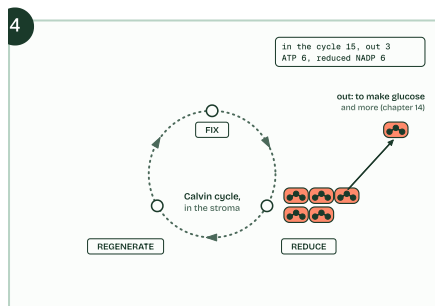
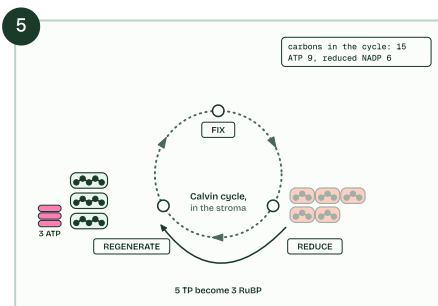
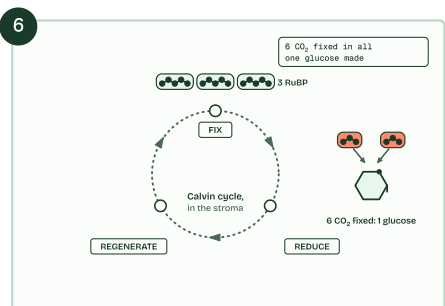
regeneration

Remaking RuBP from triose phosphate, using ATP, so the cycle can fix more carbon dioxide.



STEP BY STEP

6 STEPS

Three **RuBP** wait for three **carbon dioxide**.**Rubisco** fixes them: six **GP**.**Reduced NADP** and **ATP** turn GP into **TP**.One **TP** in six leaves the cycle.Five **TP** are remade into three **RuBP**, using **ATP**.Six turns, six carbon dioxide: one **glucose**.

REMEMBER IT

The Calvin cycle's three stages

F Fresh	R Rolls	R Rise
Fix Rubisco joins carbon dioxide to RuBP, making GP	Reduce ATP and reduced NADP turn GP into TP	Regenerate five TP in six remade into RuBP, using ATP

WATCH OUT

It is GP (glycerate 3-phosphate) that is reduced, to TP. "Glyceraldehyde 3-phosphate" is another name for a triose phosphate, so "the reduction of glyceraldehyde 3-phosphate" has the stages muddled.

PREDICT

Of every six TP the Calvin cycle makes, how many must be used to remake RuBP?

- ☐ A One
- ☐ B Three
- ☐ C Five
- ☐ D Six

Decide before you look. Answer on page 61.

14

Every carbon came this way

C1.3.18 HL

CARBOHYDRATES, AMINO ACIDS AND OTHER COMPOUNDS FROM THE CALVIN CYCLE

Every carbon atom in every compound of a photosynthesising organism was fixed in the Calvin cycle. Its other carbon compounds are made by metabolic pathways that can be traced back to triose phosphate, or to another intermediate of the cycle. You do not need the details of the pathways.

Carbohydrates come first: TP makes glucose, and glucose makes sucrose (the sugar carried in the phloem), starch (the store) and cellulose (the cell walls). Lipids follow: TP makes glycerol and, through the acetyl groups of respiration, fatty acids, which join into triglycerides and, with phosphate, into phospholipids.

Amino acids need nitrogen as well as carbon. It comes from nitrate (or ammonium) taken up from the soil, and two amino acids need sulfur too. Nucleotides need nitrogen for their bases and phosphorus for their phosphate. These **mineral nutrients** come in through the roots by active transport (B2.1).

Fixation in the Calvin cycle is how carbon enters every food web: the carbon fixed in a leaf ends up in the plant's own body, in whatever eats it, or back in the air through respiration. The carbon trail below follows one atom.

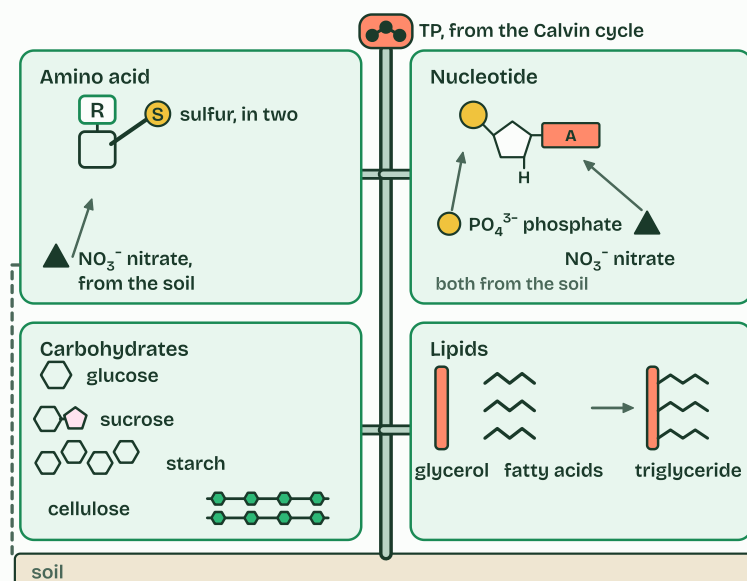
KEY TERMS

mineral nutrients

Inorganic ions the plant takes up from the soil, such as nitrate and phosphate. They supply the elements that carbon dioxide and water do not.

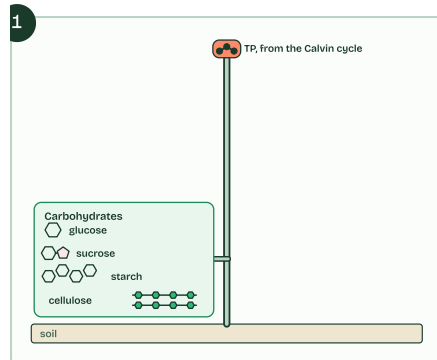
KEY POINTS

- All the carbon in a plant's compounds was fixed in the Calvin cycle.
- Sugars, starch, cellulose, lipids, amino acids and nucleotides are made by pathways that start from TP.
- Amino acids and nucleotides also need mineral nutrients: nitrate, and phosphate.

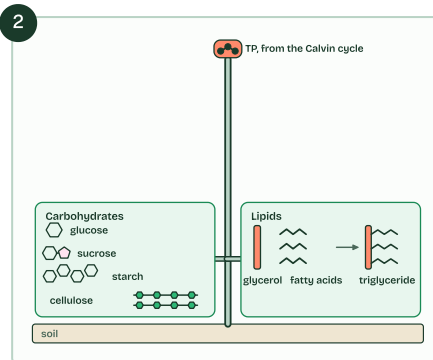


STEP BY STEP

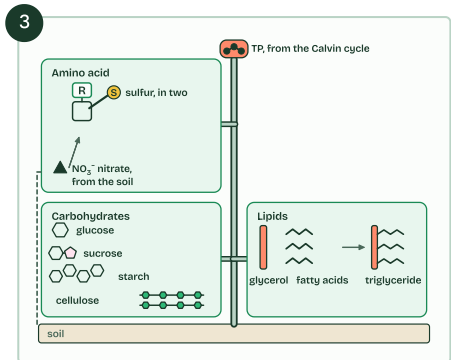
4 STEPS



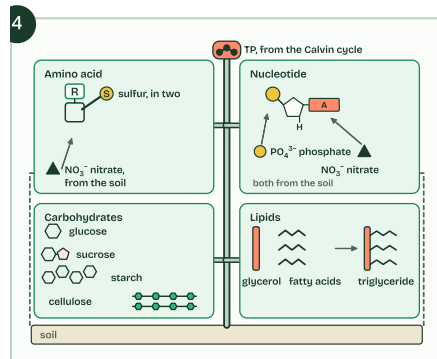
From TP: **sugars, starch** and **cellulose**.



Lipids.



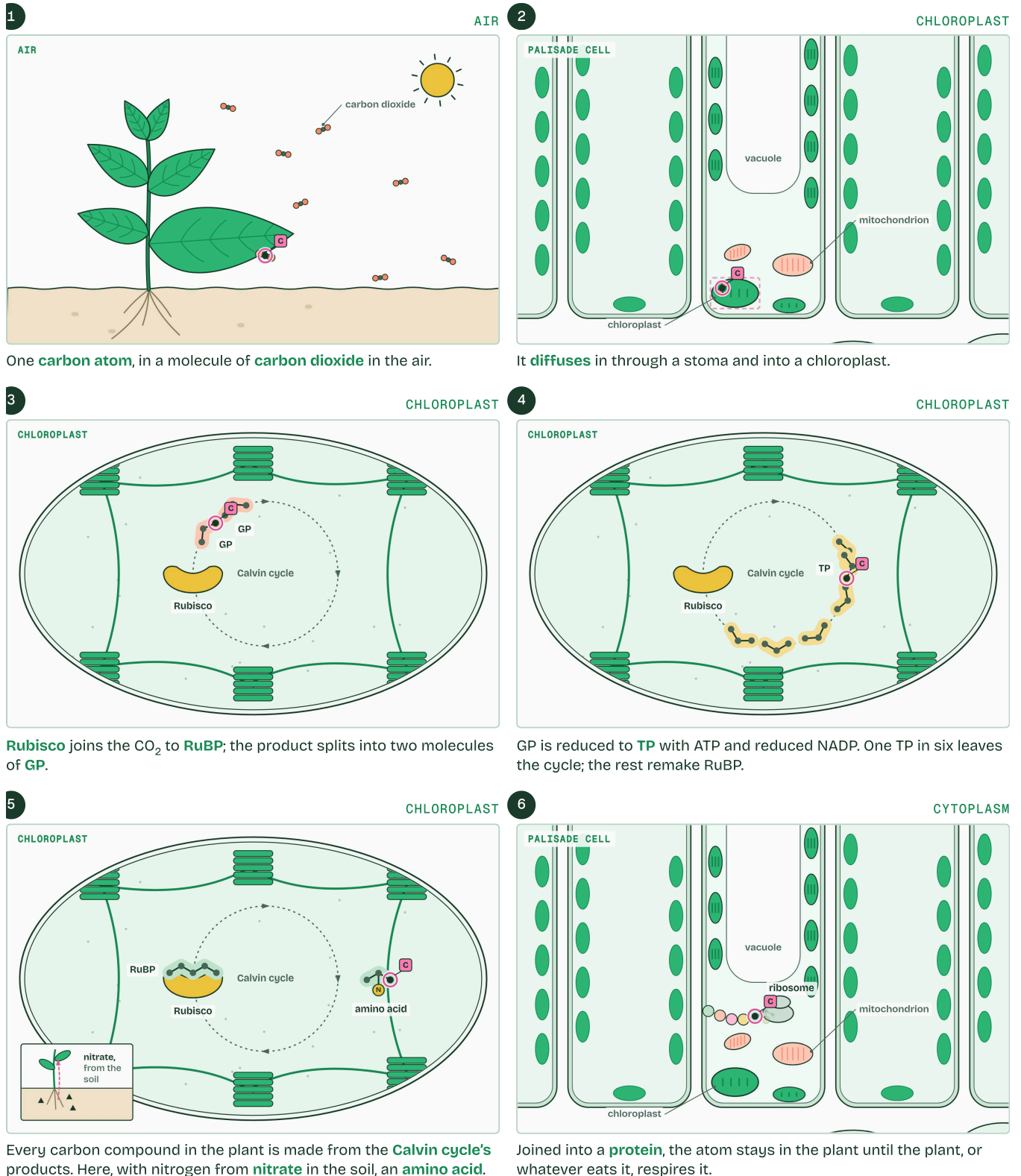
Amino acids, with nitrogen from **nitrate**.



Nucleotides, with nitrogen and **phosphate**.

ANIMATION · FOLLOW ONE CARBON ATOM

6 MOMENTS



Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#products

WATCH OUT

Plants do not take carbon from the soil. Every carbon atom came from carbon dioxide, in the air or dissolved in water, through the Calvin cycle.

PREDICT

A plant has plenty of light, water and carbon dioxide, but its soil has no nitrate. Which will it fail to make?

- ☐ (A) Proteins
- ☐ (B) Starch
- ☐ (C) Cellulose
- ☐ (D) Sucrose

Decide before you look. Answer on page 61.

15

C1.3.19 HL

INTERDEPENDENCE OF THE LIGHT-DEPENDENT AND LIGHT-INDEPENDENT REACTIONS

Each half needs the *other*

The **light-dependent reactions** in the thylakoids make ATP and reduced NADP. The **light-independent reactions**, the Calvin cycle in the stroma, use them and hand back ADP, phosphate and NADP. Each half needs what the other makes: that is their **interdependence**.

No light. The photosystems are not excited, so no ATP or reduced NADP is made. The Calvin cycle runs on for a few seconds on what is left, then stops.

No carbon dioxide. The Calvin cycle cannot fix carbon, so it stops using ATP and reduced NADP, and no NADP comes back. Once all the stroma's NADP is reduced, photosystem I has nothing to pass its electrons to. The chain backs up, and photosystem II cannot pass its electrons on, so it stops, and so does photolysis.

So a leaf's two halves run at the pace of the slower one, which links back to limiting factors (chapter 6). In bright light, carbon dioxide or Rubisco limits the rate; in dim light, the light-dependent reactions do. And a plant in the dark still respire. Everything in Unit 4 so far is on one map below, the metabolism map, where you can see both.

KEY POINTS

- Light-dependent reactions make ATP and reduced NADP; the Calvin cycle uses them and returns ADP, phosphate and NADP.
- No light: the Calvin cycle stops a few seconds later.
- No carbon dioxide: NADP is not returned, so photosystem I fills, then the chain, then photosystem II stops.

KEY TERMS

light-dependent reactions

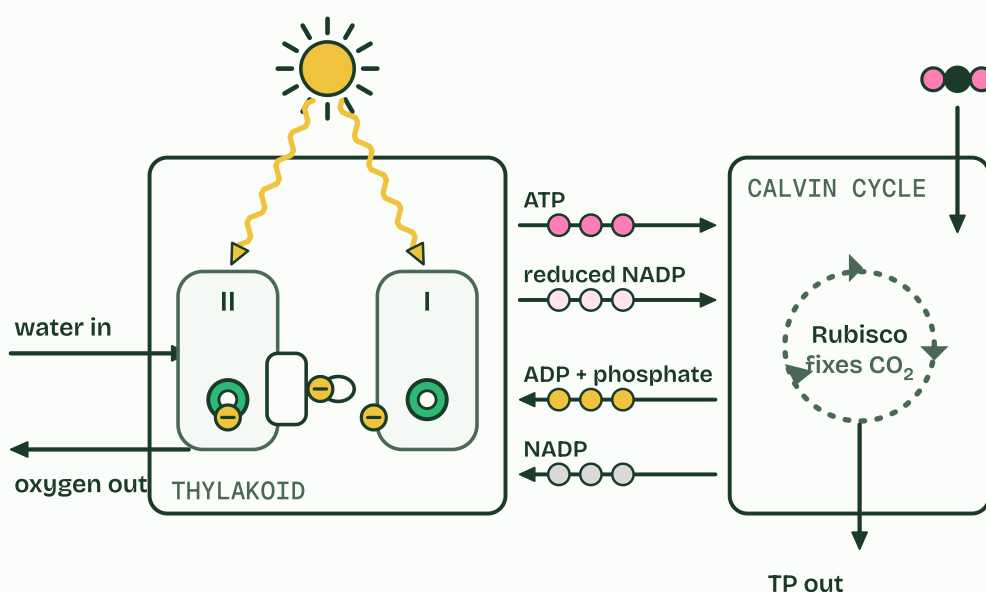
The reactions in the thylakoids that need light: photolysis, the chain and ATP synthase, and the reduction of NADP. They make ATP and reduced NADP.

light-independent reactions

The Calvin cycle in the stroma. They do not use light directly, but need the ATP and reduced NADP of the light-dependent reactions.

interdependence

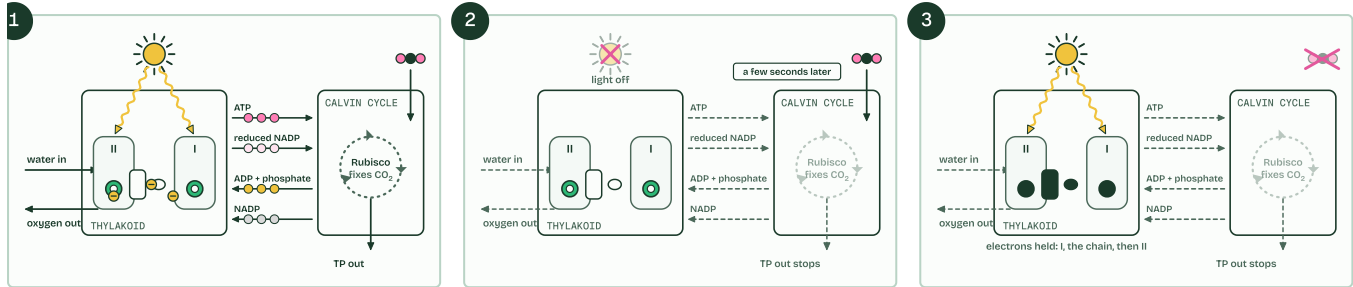
Each half of photosynthesis relying on the products of the other, so neither can run alone for long.



The thylakoid makes ATP and reduced NADP for the Calvin cycle, and the Calvin cycle hands back ADP, phosphate and NADP. Switch off the light, or the carbon dioxide, and watch what stops.

SWITCH IT

3 SETTINGS



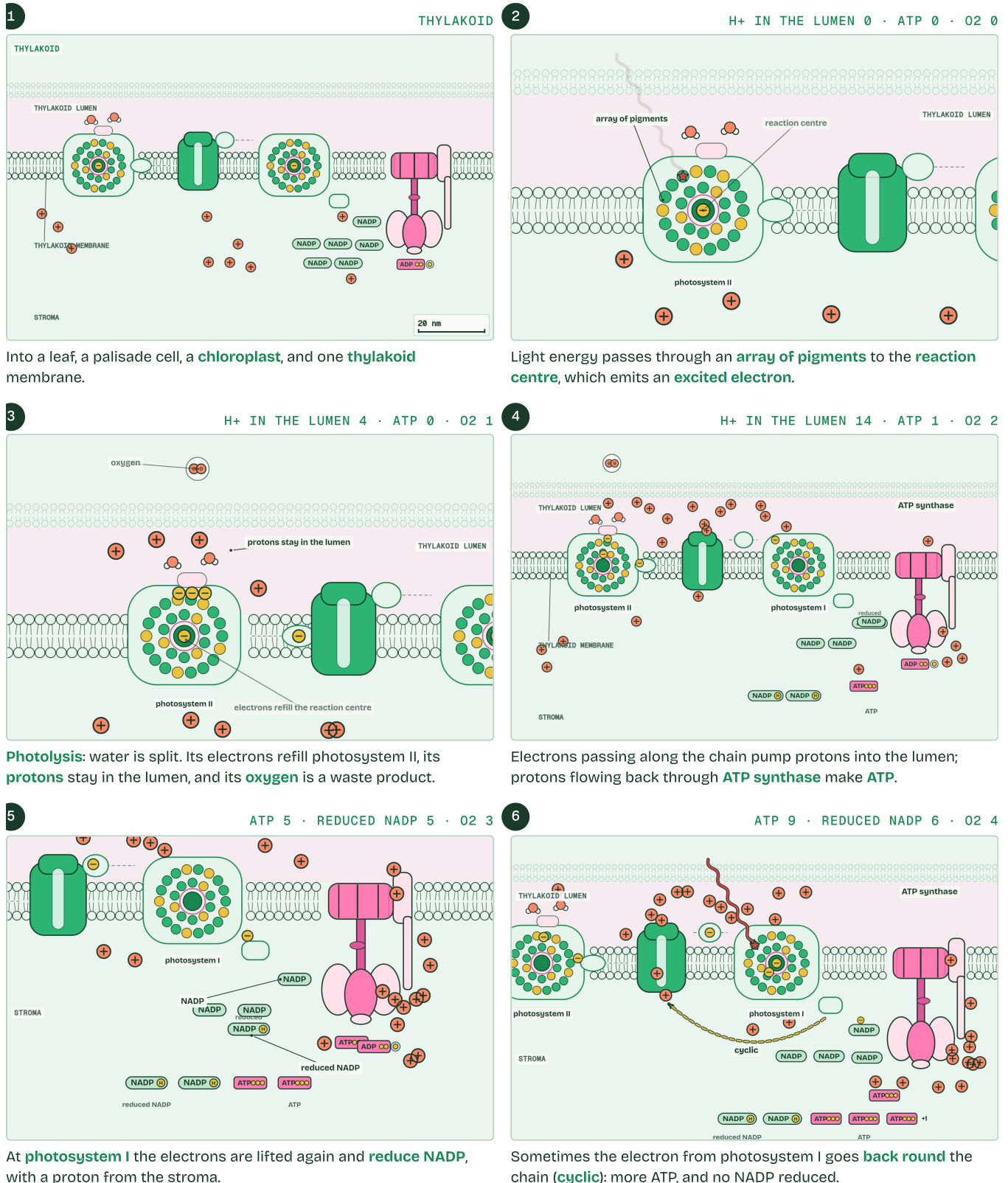
Light and carbon dioxide

Lights off

No carbon dioxide

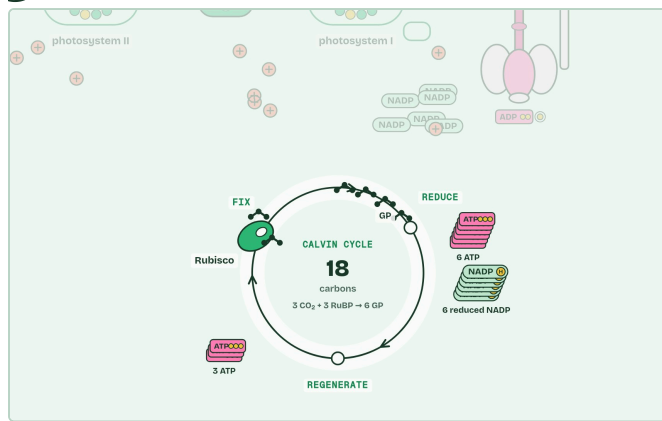
ANIMATION · PHOTOSYNTHESIS, THE WHOLE SYSTEM

10 MOMENTS



7

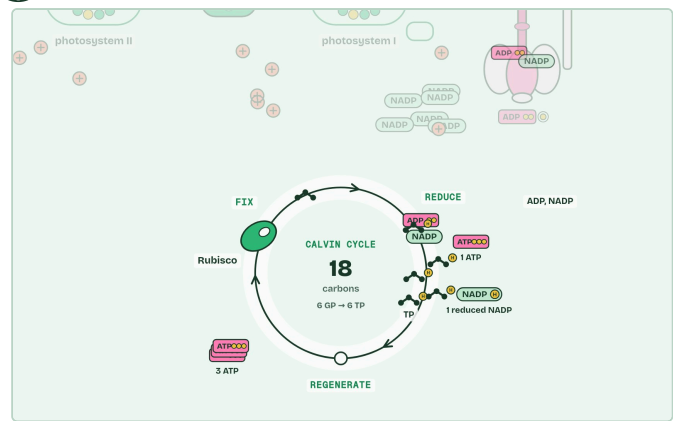
STROMA · CARBONS 18



Rubisco fixes 3 CO_2 onto 3 RuBP: 6 GP.

8

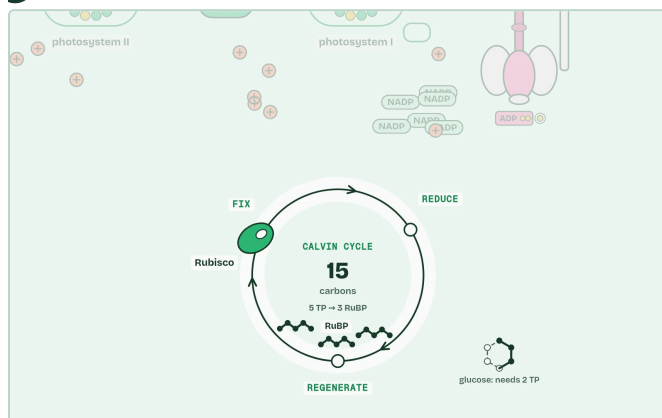
STROMA · CARBONS 18



ATP and reduced NADP turn 6 GP into 6 TP; ADP and NADP go back to the thylakoid.

9

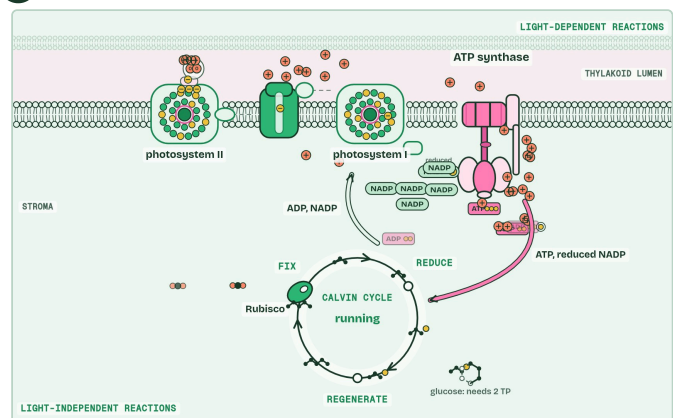
STROMA · CARBONS 15



1 TP leaves the cycle; the other 5 are remade into 3 RuBP, using ATP.

10

ATP 36 · 02 11



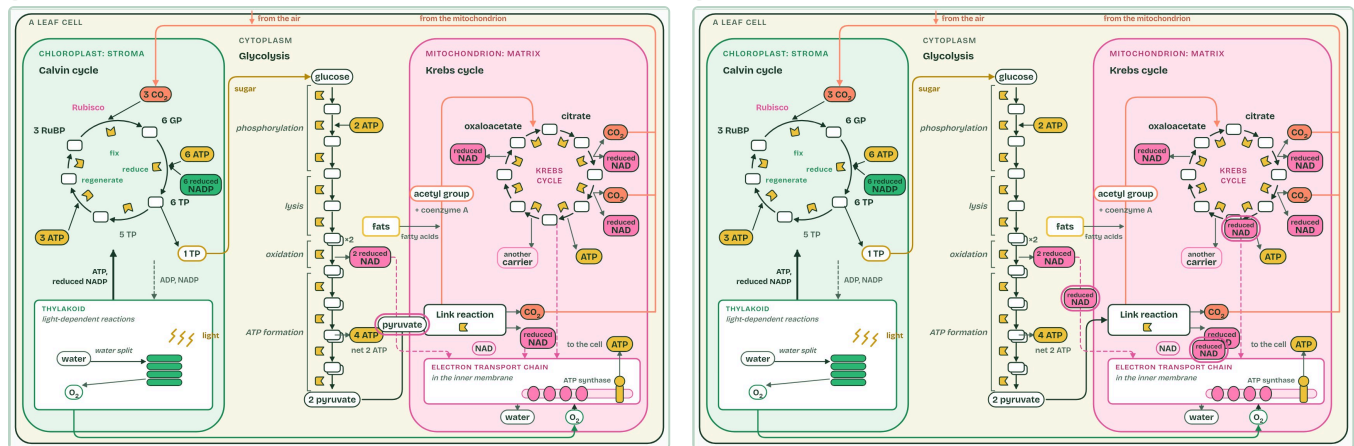
Two halves, each running on what the other makes: ATP and reduced NADP one way, ADP and NADP the other.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#interdependence

ANIMATION · RESPIRATION AND PHOTOSYNTHESIS ON ONE MAP

4 MOMENTS

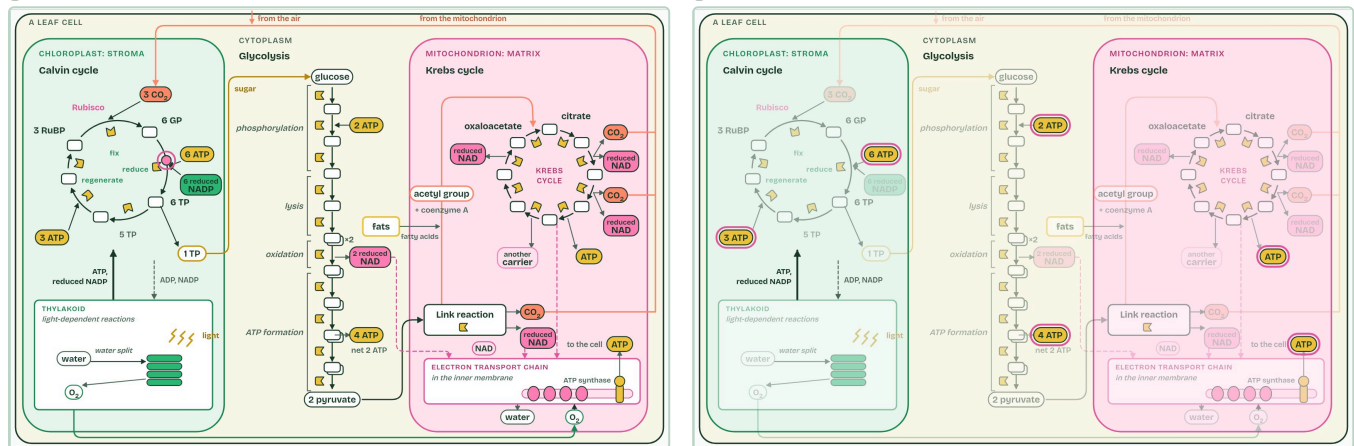
1 LINK REACTION 2 TO THE CHAIN



The **link reaction**, in the matrix: each pyruvate loses carbon dioxide and is oxidised, making reduced NAD, and coenzyme A carries the acetyl group on.

Reduced NAD from glycolysis, the link reaction and the Krebs cycle hands its electrons to the **electron transport chain**, and goes back as NAD.

3 CALVIN CYCLE 4 FOLLOW ATP



ATP and reduced NADP from the thylakoid reduce GP to TP. One TP in six leaves; the other five, with more ATP, remake RuBP.

Follow **ATP**: made in glycolysis, the Krebs cycle, at the electron transport chain and in the thylakoid; used in glycolysis, the Calvin cycle and all over the cell.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#interdependence

WATCH OUT

“Light-independent” does not mean “happens in the dark”. The Calvin cycle needs the products of the light reactions, so in a leaf it runs only in the light.

PREDICT

A leaf in bright light is suddenly given no carbon dioxide. What happens to photosystem II?

- (A) It speeds up, with nothing to slow it
- (B) It goes on, but sends electrons round cyclically
- (C) It stops, as NADP runs out further on
- (D) It starts splitting carbon dioxide instead

Decide before you look. Answer on page 61.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

absorbs 04

Takes in the energy of light, so that the light does not come out again.

absorption spectrum 04

A graph of how much light a pigment absorbs at each wavelength.

accessory pigments 04

Pigments that absorb light chlorophyll a absorbs less, and pass the energy on. In leaves they are the carotenoids and chlorophyll b.

action spectrum 05

A graph of the rate of photosynthesis against the wavelength of the light given.

algae 02

Eukaryotic organisms that photosynthesise but are not plants, from single-celled species to the seaweeds.

ATP synthase 10

A protein that spans a membrane. Protons flowing down their gradient through it turn part of it, and the energy joins ADP and phosphate to make ATP.

banded iron formations 09

Layers of iron oxide in ancient rock, laid down when oxygen from cyanobacteria reacted with iron dissolved in the oceans.

by-product 02

A substance made in a process that is not the aim of it. The oxygen from photosynthesis is a by-product of splitting water: the plant needs the hydrogen, not the oxygen.

Calvin cycle 12

The cycle of reactions in the stroma that fixes carbon dioxide into carbon compounds, using ATP and reduced NADP from the light-dependent reactions. Melvin Calvin worked it out in the 1950s, using radioactive carbon in algae.

carbon compounds 01

Molecules built on a skeleton of carbon atoms, such as sugars, lipids, proteins and nucleic acids.

carbon dioxide concentration 06

How much carbon dioxide the plant has to build into sugar. It limits how much carbon can be taken in.

carbon dioxide enrichment 07

Growing plants in the carbon dioxide level expected later this century, beside plants in today's air, to predict how plants will respond.

carbon fixation 12

Turning carbon from a gas, carbon dioxide, into part of an organic molecule.

carotenes 03

Orange-yellow carotenoid pigments. The carotene of a leaf runs furthest in chromatography.

chain of electron carriers 10

A series of carrier molecules in the thylakoid membrane. An electron passes from one to the next, giving up energy at each step.

chemical energy 01

Energy stored in the bonds between atoms, and released when those bonds are rearranged.

chemiosmosis 10

Making ATP using energy from a proton gradient across a membrane, through ATP synthase.

chlorophyll a 03

The main photosynthetic pigment: blue-green.

chlorophyll b 03

An accessory pigment: yellow-green.

chromatography 03

A way of separating a mixture. The substances travel at different speeds through a stationary phase carried by a moving solvent.

controlled variables 06

Everything else that could affect the result, kept the same.

cyanobacteria 02

Photosynthetic bacteria. They were the first organisms to split water and give off oxygen.

cyclic photophosphorylation 10

ATP made using electrons that come from photosystem I and return to the chain, then to photosystem I again. It makes ATP only: no NADP is reduced, no water is split and no oxygen is given off.

dependent variable 06

The variable you measure, to see the effect of the change.

energy transformation 01

A change of energy from one form into another, for example light into chemical energy. Energy is not made or destroyed, and some is lost as heat at every step.

excited 04

Raised to a higher energy level by absorbing a photon.

excited electron 08

An electron raised to a higher energy level. In the reaction centre it is emitted, passing to an electron acceptor.

field 07

The natural setting: real soil, weather and competition, where variables cannot be controlled but the results apply to real ecosystems.

free-air carbon dioxide enrichment (FACE) 07

A field experiment in which a ring of pipes, up to about 20 to 30 m across, releases carbon dioxide round growing plants in the open air. Control rings have the same pipes but no added gas.

glucose 02

A six-carbon sugar, C₆H₁₂O₆. It is the first carbohydrate that photosynthesis is usually said to make, and the fuel that respiration releases energy from.

glycerate 3-phosphate (GP) 12

The three-carbon compound that RuBP and carbon dioxide make. Two GP form from each fixation.

grana 11

Stacks of thylakoids (one is a granum). Stacking gives a large area of membrane.

Great Oxidation Event 09

The rise of oxygen in the Earth's atmosphere, about 2.4 billion years ago, after cyanobacteria had been splitting water for a long time.

greenhouse 07

A glass or plastic building in which temperature, light, water and the air can be controlled. In an enrichment experiment, carbon dioxide from a cylinder holds the air at the chosen level.

hypothesis 06

A provisional explanation that has to be tested again and again. It may be based on a theory and tested in an experiment, or based on the evidence of an experiment already done.

independent variable 06

The variable you change on purpose.

interdependence 15

Each half of photosynthesis relying on the products of the other, so neither can run alone for long.

laboratory or greenhouse 07

A place where the variables can be controlled closely.

light energy 01

Energy carried by light. A pigment absorbs it.

light intensity 06

How much light falls on the plant. It limits the energy available to split water.

light-dependent reactions 15

The reactions in the thylakoids that need light: photolysis, the chain and ATP synthase, and the reduction of NADP. They make ATP and reduced NADP.

light-independent reactions 15

The Calvin cycle in the stroma. They do not use light directly, but need the ATP and reduced NADP of the light-dependent reactions.

limiting factor 06

The factor in shortest supply, which sets the rate of a process. Raising it speeds the process up; raising any other factor does nothing until it takes over as the limit.

mineral nutrients 14

Inorganic ions the plant takes up from the soil, such as nitrate and phosphate. They supply the elements that carbon dioxide and water do not.

mobile phase 03

The solvent that moves in chromatography, carrying the substances along the stationary phase.

NADP 11

A carrier molecule that picks up electrons and a proton and delivers them to the Calvin cycle. It is written NADP when empty and reduced NADP when it holds them.

non-cyclic photophosphorylation 10

ATP made using electrons from photosystem II, passed along the chain to photosystem I and on to NADP. Water is split and oxygen is given off.

origin 03

The pencil line on a chromatogram where the spot of mixture is put.

photolysis 02

The splitting of water, using energy from light absorbed by chlorophyll. At higher level it is the job of photosystem II.

photosynthesis 01

The process that turns the energy of light into chemical energy held in the bonds of carbon compounds. It happens in the chloroplasts of plants and algae, and in cyanobacteria.

photosystem 08

An array of a few hundred pigment molecules, chlorophylls and accessory pigments, held in fixed positions by proteins in a membrane, with a reaction centre at its heart.

photosystem I 08

The photosystem that passes electrons on to reduce NADP.

photosystem II 08

The photosystem that splits water and passes its electrons to the chain. Electrons pass through it first, though it was discovered second.

pigment 03

A coloured substance that absorbs some wavelengths of light and reflects or passes on the others.

producers 01

Organisms that make their own carbon compounds from simple inorganic substances, using light energy in photosynthesis.

proton gradient 10

A difference in the concentration of protons across a membrane. The protons flow back down it through ATP synthase.

proton pumping 10

Moving protons across a membrane against their gradient, using the energy of electrons passing along a chain of carriers. In a thylakoid the protons go from the stroma into the lumen.

protons 09

Hydrogen ions, H⁺. Photolysis releases them into the thylakoid lumen.

rate of photosynthesis 05

How much oxygen is produced, or carbon dioxide consumed, in a given time, for example in cm³ per minute.

reaction centre 08

A special chlorophyll a at the heart of a photosystem, from which an excited electron is emitted.

reduced NADP 11

NADP carrying two electrons and a proton. It is the carrier of hydrogen to the Calvin cycle.

reduction 11

The gain of electrons (or hydrogen) by a molecule.

reflection 04

Light bouncing off a surface instead of being absorbed.

regeneration 13

Remaking RuBP from triose phosphate, using ATP, so the cycle can fix more carbon dioxide.

Rf value 03

The distance a pigment moved divided by the distance the solvent front moved, both measured from the origin. It has no units and is always less than 1.

ribulose biphosphate (RuBP) 12

The five-carbon sugar that carbon dioxide joins in carbon fixation. It is remade by the Calvin cycle.

Rubisco 12

The enzyme that fixes carbon dioxide onto RuBP. It is slow, so a leaf needs a great deal of it, and it is the most abundant enzyme on Earth.

solvent 03

The liquid that climbs the paper and carries the pigments with it.

solvent front 03

The furthest point the solvent has reached. Mark it at once when you take the strip out, before it dries.

stationary phase 03

The paper or plate that stays still in chromatography. Substances cling to it to different extents.

stroma 11

The fluid inside a chloroplast around the thylakoids. The Calvin cycle runs here.

thylakoid lumen 10

The space inside a thylakoid, where protons collect.

thylakoid membranes 08

The membranes inside a chloroplast where the light-dependent reactions happen. In cyanobacteria the photosystems are in internal membranes.

triose phosphate (TP) 13

The three-carbon sugar phosphate made when ATP and reduced NADP reduce GP. It is the first sugar and the product of the cycle.

visible light 04

The wavelengths the human eye sees, from about 400 nm (violet) to about 700 nm (red). White light is all of them together.

waste product 09

A substance a process makes but does not use. The oxygen from photolysis diffuses out of the chloroplast, the cell and the leaf.

wavelengths 04

The distance from one wave crest to the next. For light it is measured in nanometres (nm).

word equation 02

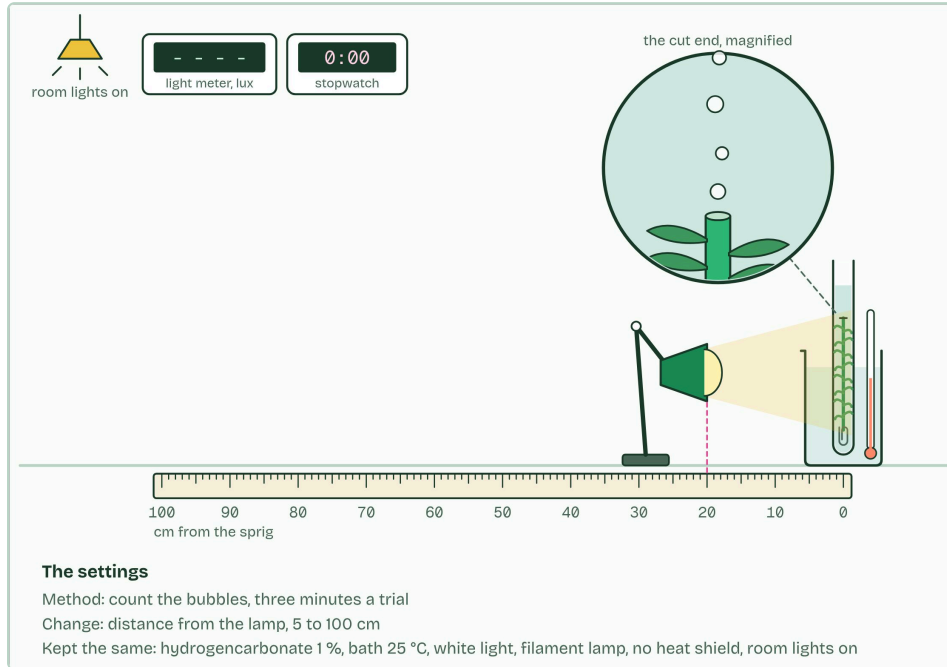
The chemicals of a reaction written as words: the reactants, an arrow, then the products. For photosynthesis, carbon dioxide + water becomes glucose + oxygen.

xanthophylls 03

Yellow carotenoid pigments that contain oxygen.

Dry lab: *Pondweed and the lamp*

A sprig of pondweed in hydrogencarbonate solution gives off bubbles of oxygen as it photosynthesises. Move the lamp, change the carbon dioxide or the temperature, count the bubbles, then plan and write it up as an investigation with the coach beside you. Or float leaf discs instead.



room lights on

light meter, lux

stopwatch

the cut end, magnified

100 90 80 70 60 50 40 30 20 10 0
cm from the sprig

The settings

Method: count the bubbles, three minutes a trial

Change: distance from the lamp, 5 to 100 cm

Kept the same: hydrogencarbonate 1 %, bath 25 °C, white light, filament lamp, no heat shield, room lights on



Run it online: change the variables, run the trials, and the table and graph fill in as you go.
biologybybradford.com/guides/ib-biology-c1-3-photosynthesis#lab

Your question

How does one limiting factor change the rate of photosynthesis? Start with the lamp: how does the rate change as the lamp moves away, and is it the distance or the light that matters?

What you can change

One independent variable at a time: the distance of the lamp (with a light meter to read the light), the concentration of sodium hydrogencarbonate, the temperature of the water, or the colour of a filter. Everything else stays fixed unless you change it on purpose, and some of it changes when you are not looking.

What to record

Bubbles counted in each of three minutes, after the sprig has settled, then the mean rate in bubbles per minute; or the time for half the leaf discs to float. Three trials at each value, a mean and a standard deviation, and a graph of the means with error bars. The coach under the bench helps you plan, process and evaluate.

Find out

- **How does the rate change with distance?** Move the lamp from 5 to 100 cm: at least six distances, three trials at each, after the sprig has settled. Graph the rate against distance, then against $1 \div \text{distance}^2$. Where is the graph a straight line, and where not?
- **Light is not the only thing changing.** Read the thermometer before and after a run with the lamp 5 cm away, with and without the heat shield.
- **Carbon dioxide.** Run hydrogencarbonate from 0 to 5 % with the lamp at 10 cm, then again at 40 cm. Where does each level off?
- **Temperature.** Run the bath from 5 to 45 °C, lamp at 10 cm, 1 % hydrogencarbonate. Then cool a sprig you ran at 45 °C back to 25 °C and run it again.
- **Colour.** Run white light and the four filters with the lamp at 10 cm, reading the light meter each time. Then improve your method so the comparison is fair. Comparing colours, the lamp may sit at a different distance for each filter: the table writes it down with each trial.
- **Leaf discs.** Switch the method to leaf discs and run hydrogencarbonate at 0, 0.1, 0.2, 0.5 and 1 % with the lamp at 10 cm. Find the time for half the discs to float.

Record

- Every run's settings: what you changed, and everything you kept the same.
- Change one thing at a time, and let the sprig settle after each change before you count.
- The bubbles in each of three minutes, or the gas bubble's two ends on the scale, or the discs floating each minute.
- Three or more trials at each value, then a mean and its standard deviation.
- Use the graph under the lab, or download the CSV and plot it yourself.
- When you are done, choose one investigation and write it up with the IA coach under the bench. **Improve your method**, under the graph, opens better apparatus as you think of it.

QUESTIONS ON THE LAB

QUESTION 1

With the lamp 80 cm away you count no bubbles at all. Has the sprig stopped photosynthesising?

- (A) Yes: no bubbles means no oxygen is being made
- (B) Yes: below 1,000 lux photosynthesis cannot happen
- (C) No: at 80 cm the bubbles are too small to see
- (D) Not necessarily: some oxygen never bubbles

Answer on page 61.

QUESTION 2

Without the heat shield, your rates with the lamp close to the tube sit above the trend of the others. Why?

- (A) The sprig grows faster near the light
- (B) Bubbles are bigger close to the lamp
- (C) The lamp warmed the water
- (D) The light meter was misread

Answer on page 62.

QUESTION 3

The rate plotted against $1 \div \text{distance}^2$ is a straight line for distant lamps but bends over close up. Why?

- ☐ (A) Light stops being the limiting factor
- ☐ (B) The sprig's chlorophyll is bleached by the lamp
- ☐ (C) The sprig is shaded by the tank's glass
- ☐ (D) The light meter reads too high close up

Answer on page 62.

QUESTION 4

Under the green filter the light meter reads more lux than under the red one, yet the sprig gives fewer bubbles. Why?

- ☐ (A) The red filter lets more of the lamp's heat through
- ☐ (B) A lux meter is built to match the eye, not a leaf
- ☐ (C) Green light slowly bleaches the leaf's chlorophyll
- ☐ (D) The green filter was set further from the lamp

Answer on page 62.

WRITE IT UP AS AN INVESTIGATION

Your results from this dry lab can be written up the way an IB scientific investigation is: four criteria, each worth 6 marks. Tick each line as your write-up does it. The coach on the page checks these as you go; it never gives a mark.

1 Research design

A focused question set in its biology; your choices of what to measure, how, over what range and how often, explained rather than listed; what you kept the same and how; safety, ethics and the environment; a method someone else could follow and repeat.

- ☐ My question names what I changed.
- ☐ It gives the range I used, with units.
- ☐ It names what I measured and how.
- ☐ It names the organism or system.
- ☐ My background explains, with the biology, why the two should be linked.
- ☐ I cite my sources, and each reference can be traced.
- ☐ If I give a hypothesis, it predicts and explains.
- ☐ Every variable has its How, Why and Units.
- ☐ For each thing kept the same, I say how I kept it so.
- ☐ I list at least three things I kept the same.
- ☐ I name the apparatus that set what I changed, and the instrument that measured.
- ☐ I test enough values.
- ☐ My values spread wide enough.
- ☐ I run at least three trials at every value.
- ☐ I run a control.
- ☐ I explain why these values, this many and this often.
- ☐ Someone else could repeat my method.
- ☐ I deal with safety, ethics and the environment.

3 Conclusion

Your question answered from the processed data, with numbers quoted and the spread taken into account; the biology that explains the pattern; a comparison with published work; no claim bigger than the data.

- ☐ I answer my question in a sentence, naming both variables.
- ☐ I quote my processed numbers.
- ☐ I say how sure the spread lets me be.
- ☐ I say whether my hypothesis is supported.
- ☐ I explain the pattern with biology.
- ☐ I compare my result with published work, and cite it.
- ☐ I claim no more than my data show.

2 Data analysis

Raw data recorded clearly, with titles, units, uncertainties and the same decimal places down a column; what you saw as well as what you measured; processing that suits the question, shown with a worked example; the spread shown; a graph a reader can trust.

- ☐ Each table has a numbered title that says what it shows.
- ☐ Every heading has its quantity and its unit.
- ☐ Every raw data heading has its uncertainty.
- ☐ Each uncertainty is realistic for the instrument.
- ☐ Each uncertainty has the same decimal places as its readings.
- ☐ I record what I saw as well as what I measured.
- ☐ I show one worked example of my processing, and it is right.
- ☐ I say why I left out any trial.
- ☐ My error bars show a spread my repeats can support.
- ☐ My graph has a numbered title and labelled axes with units.
- ☐ I say what the error bars show.
- ☐ A straight line, if I draw one, has its R^2 .
- ☐ A statistical test, if I run one, has its hypotheses and suits the data.

4 Evaluation

Weaknesses and limitations of this method (not slips in carrying it out), with evidence from your own data, the effect each had on the results, which mattered most and why, and a realistic improvement for each.

- ☐ I give at least three weaknesses or limitations.
- ☐ Every row is filled in.
- ☐ No slips in carrying it out: weaknesses of the method itself.
- ☐ Each improvement is specific: which instrument, how many, what changes.
- ☐ Each effect says what it did to my data.
- ☐ At least two rows point to evidence in my own data.
- ☐ At least one limitation: what this experiment cannot tell me.
- ☐ I say which mattered most, and why.
- ☐ I deal with what stands out in my data.
- ☐ My improvements improve this investigation, not a new one.

Variables

Variable	How?	Why?	Units
Independent: distance from the lamp			
Dependent: rate of bubble production			
Kept the same: the lamp (filament or LED)			
Kept the same: concentration of sodium hydrogencarbonate			
Kept the same: temperature of the water			
Kept the same: colour of the light			
Kept the same: the room lights			
Kept the same: the sprig (the same sprig, or matched sprigs)			
Kept the same: length of the sprig			
Kept the same: volume of solution in the tube			
Kept the same: time left to settle after each change			

Evaluation

Weakness or limitation	Which?	Evidence in my data	Effect on my results	Improvement

Data generated with the pondweed dry lab, biologybybradford.com (a simulation). These checks catch what is missing. They cannot judge how good it is: that is what your teacher does.

**Check yourself**

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on C1.3 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=C1.3&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 The chemical energy in a slice of cheese: where did it first come from?

B Light caught by the grass it ate

From sunlight, caught by grass. The cow turned some of the grass's chemical energy into milk; the cheese holds what is left. Follow the energy in almost any food back far enough and you reach a leaf in the light.

02 Where does the oxygen gas a leaf gives off come from?

D From the water it splits

From water. The plant splits water to get hydrogen, and the oxygen left over is given off. Ruben's heavy-oxygen experiment showed it: heavy oxygen in the water came out as heavy oxygen gas; heavy oxygen in the carbon dioxide did not.

03 The solvent front has moved 8.0 cm from the origin and a yellow band 5.7 cm. What is the band's R_f ?

B 0.71

$5.7 \div 8.0 = 0.71$. Pigment distance over solvent distance, both from the origin; R_f is always less than 1, so 1.40 has the division upside down. In propanone on paper, a yellow band at 0.71 is a xanthophyll.

04 Why does chlorophyll absorb red and blue light but very little green?

D Red and blue photons match jumps its electrons can make

A photon is absorbed only if its energy matches a jump an electron in the pigment can make. Chlorophyll's electrons have jumps that match red and blue photons, not green ones, so green passes through or bounces off. (Green photons carry more energy than red ones: it is the match that matters, not the amount.)

05 Engelmann shone a spectrum along a strand of alga and added bacteria that swim towards oxygen. Where did the bacteria gather?

A Under the red and the blue light

Under the red and the blue. Those are the colours the alga's pigments absorb and use, so those parts of the strand gave off most oxygen. Engelmann measured an action spectrum with no instruments but a microscope and a prism.

06 A plant at 15 °C is given more and more light until its rate levels off. Then it is warmed to 25 °C. What happens to the rate?

B It rises to a higher plateau

On the plateau, light was no longer limiting: temperature was. Warming speeds up the enzymes, so the rate climbs to a new, higher plateau, until something else (carbon dioxide, perhaps) limits it.

07 Crops given extra carbon dioxide gained less yield in FACE rings than in enclosures. What is the most likely reason?

C In fields, another factor soon limits

In a field, water, nitrogen or temperature soon becomes limiting, so extra carbon dioxide helps less than it did where everything else was kept ideal. That is why the field experiments are the better guide to tomorrow's harvests, even though they control fewer variables.

08 Chlorophyll dissolved in propanone glows red under a bright light. Chlorophyll in a leaf hardly glows at all. Why?

D In a leaf the energy is passed on and used

In the leaf, chlorophyll is part of a photosystem. The energy it absorbs is passed inwards to a reaction centre and used to emit an electron. In the tube there is no array and nowhere to pass the energy, so it comes back out as red light.

- 09** Cyanobacteria were splitting water for a long time before oxygen built up in the air. Where did their oxygen go at first?
- A Into iron dissolved in the oceans**
- Into iron. The oceans held dissolved iron, which oxygen turned into insoluble iron oxide that settled as red bands in the rock. Only when that iron was used up could oxygen build up in the air.
-
- 10** In a working chloroplast, where do protons build up?
- C In the lumen, inside each thylakoid**
- In the lumen. The chain pumps protons in from the stroma, and photolysis releases more there. The lumen's small volume lets a steep gradient build fast, and ATP synthase lets them back out into the stroma, where the ATP is made.
-
- 11** On which side of the thylakoid membrane is NADP reduced, and why does that side make sense?
- A The stroma side, where the Calvin cycle uses it**
- The stroma side. Photosystem I hands its electrons to NADP there, with a proton from the stroma, and the reduced NADP is made exactly where the Calvin cycle will use it. Nothing has to cross the membrane.
-
- 12** A leaf cell could save a lot of protein by making less Rubisco. Why doesn't it?
- D Each Rubisco fixes only a few CO₂ a second**
- Rubisco is slow, and slower still when carbon dioxide is low. To fix carbon dioxide as fast as the light reactions supply ATP and reduced NADP, a leaf needs a great many Rubisco molecules. That is why it is the most abundant enzyme on Earth.
-
- 13** Of every six TP the Calvin cycle makes, how many must be used to remake RuBP?
- C Five**
- Five. They hold fifteen carbons, exactly enough for three RuBP, so the cycle can fix three more carbon dioxide. Only one TP in six, three carbons, leaves: the three carbons that came in as carbon dioxide.
-
- 14** A plant has plenty of light, water and carbon dioxide, but its soil has no nitrate. Which will it fail to make?
- A Proteins**
- Proteins. Their amino acids need nitrogen, and nitrate is the plant's source of it. It can still fix carbon and make sugars, starch and cellulose, but it cannot build enzymes, Rubisco included, so it soon grows poorly and its leaves yellow.
-
- 15** A leaf in bright light is suddenly given no carbon dioxide. What happens to photosystem II?
- C It stops, as NADP runs out further on**
- It stops. With no carbon dioxide the Calvin cycle stops using reduced NADP, so no NADP comes back. Photosystem I has nowhere to put its electrons, the chain fills up, and photosystem II cannot pass its electrons on. Water stops being split, and no oxygen is given off.
-

QUESTIONS ON THE DRY LAB

- Q1** With the lamp 80 cm away you count no bubbles at all. Has the sprig stopped photosynthesising?
- D Not necessarily: some oxygen never bubbles**
- Some of the oxygen the sprig makes is used straight away in its own respiration, and some dissolves in the water before a bubble can form. In dim light the sprig can still be photosynthesising, just too slowly to give bubbles. Collecting the gas, or an oxygen probe in the water, would show it.
-

Q2 Without the heat shield, your rates with the lamp close to the tube sit above the trend of the others. Why?

C The lamp warmed the water

A filament lamp close to the tube warms the water by a few degrees within minutes. Below the optimum, warmer water speeds up the enzymes of carbon fixation, so the rate rises above the trend. Temperature changed along with distance: an uncontrolled variable. A glass tank of water between lamp and tube, or an LED lamp, keeps it out; reading the thermometer at the start and end of each trial shows it.

Q3 The rate plotted against $1 \div \text{distance}^2$ is a straight line for distant lamps but bends over close up. Why?

A Light stops being the limiting factor

Far away, light limits the rate, so the rate rises in step with the light. Close up, carbon dioxide or temperature limits it instead, and more light adds little: the plateau of chapter 6. (The lamp head is not a point, so close up the light itself also rises a little less than $1 \div \text{distance}^2$ says.)

Q4 Under the green filter the light meter reads more lux than under the red one, yet the sprig gives fewer bubbles. Why?

B A lux meter is built to match the eye, not a leaf

A lux meter weighs light as the human eye does, and the eye is most sensitive to green. A leaf absorbs red and blue best and reflects much of the green. To compare colours fairly, measure the photons a leaf can use with a PAR meter, and match them.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.