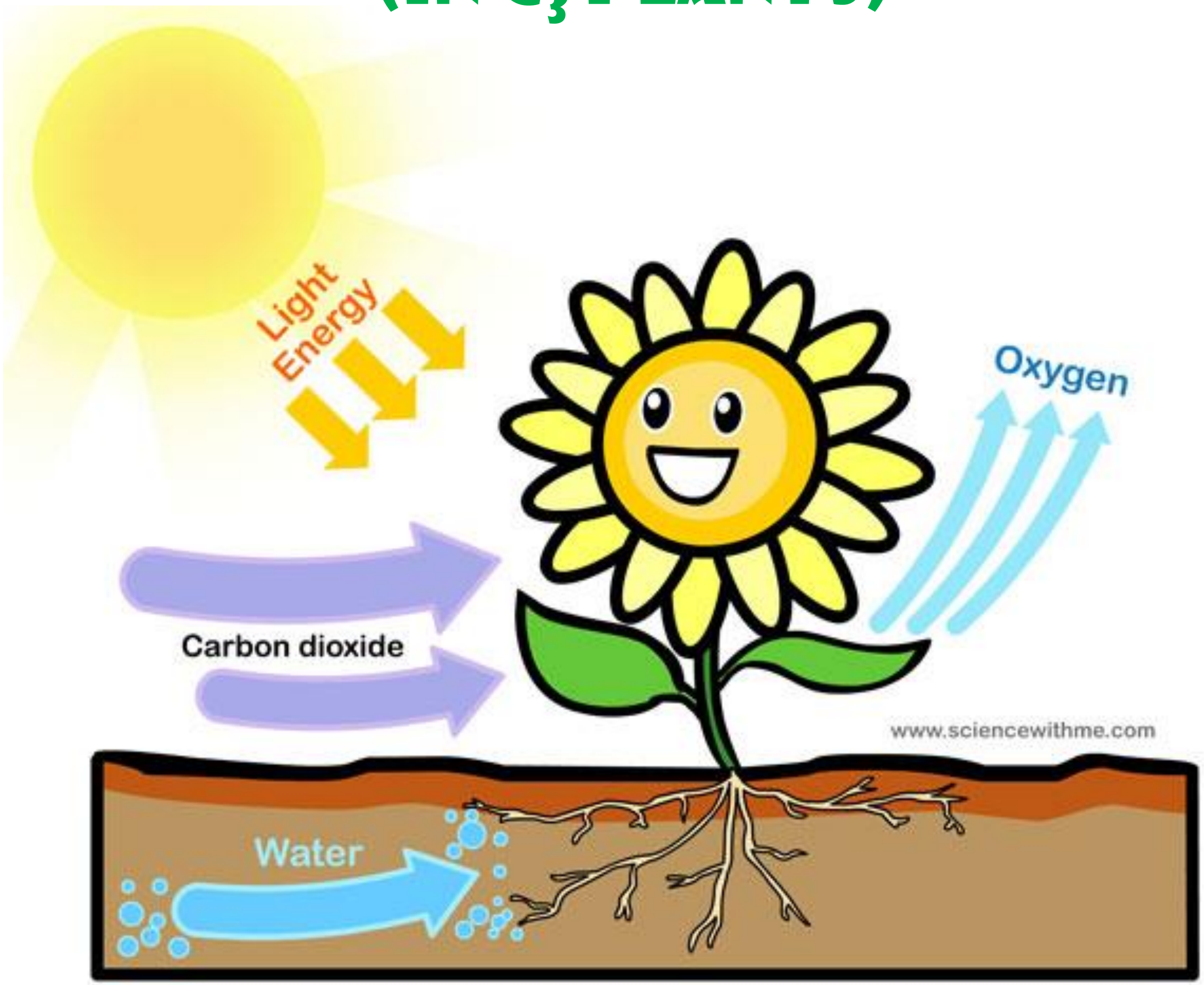
# PHOTOSYNTHESIS

## (IN $C_3$ PLANTS)



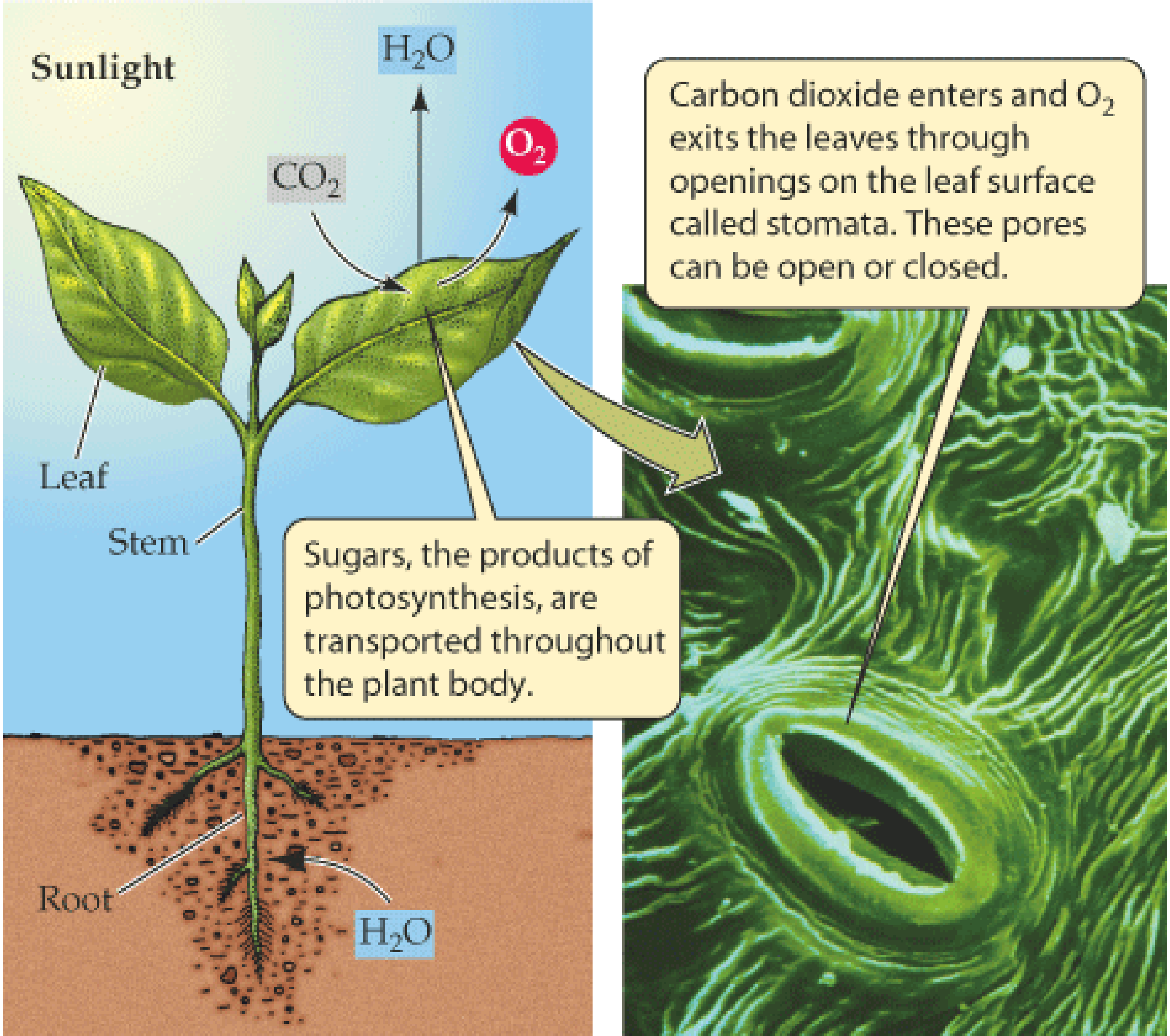
# WHAT DO I REMEMBER FROM GCSE ABOUT PHOTOSYNTHESIS?

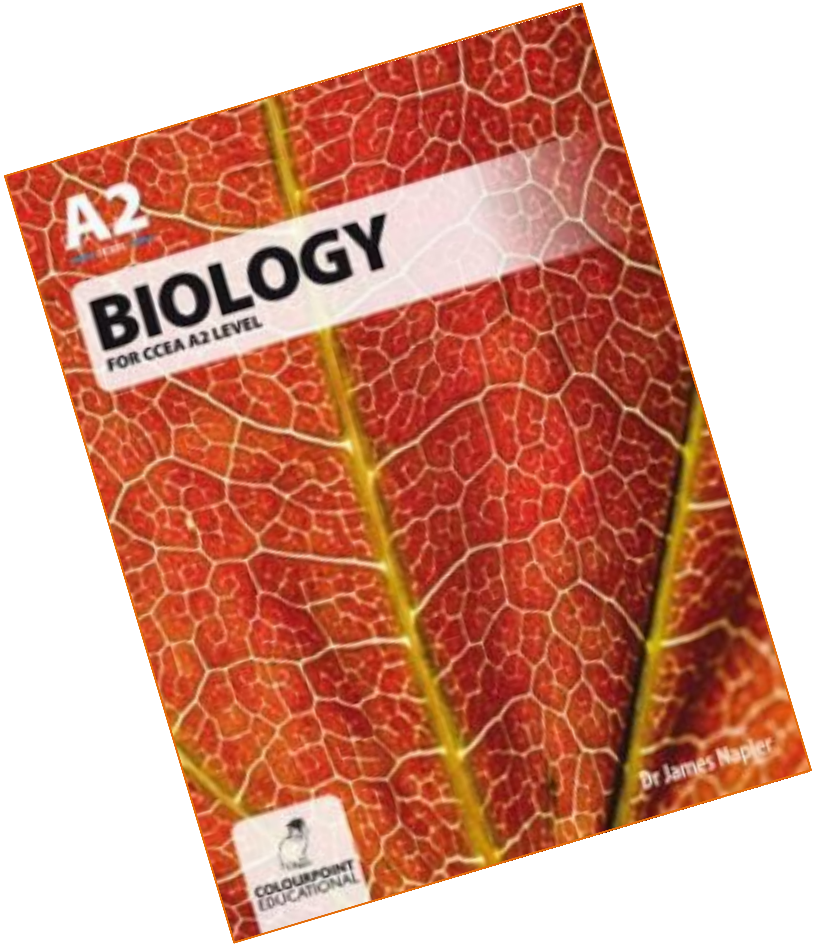
PS WS

Photosynthesis uses [redacted] energy to create complex organic compounds, initially [redacted], from inorganic compounds. Chlorophyll is the light trapping [redacted] involved and water and [redacted] are the raw materials. *The summary equation is:*

[redacted]

The leaf is adapted for the processes of light absorption and gas exchange. [redacted] layer has tightly packed cells with [redacted] chloroplasts and the spongy mesophyll layer has air spaces that are in contact with the [redacted] to provide short [redacted] pathways for gas exchange


Sunlight
$H_2O$
$O_2$
$CO_2$
Carbon dioxide enters and $O_2$ exits the leaves through openings on the leaf surface called stomata. These pores can be open or closed.
Leaf
Stem
Sugars, the products of photosynthesis, are transported throughout the plant body.
Root
$H_2O$




Read
P163-165

5.2.1 Describe the sites in the chloroplast where the reactions of photosynthesis occur:

- light-dependent stage on the thylakoids;
- light-independent stage in the stroma.

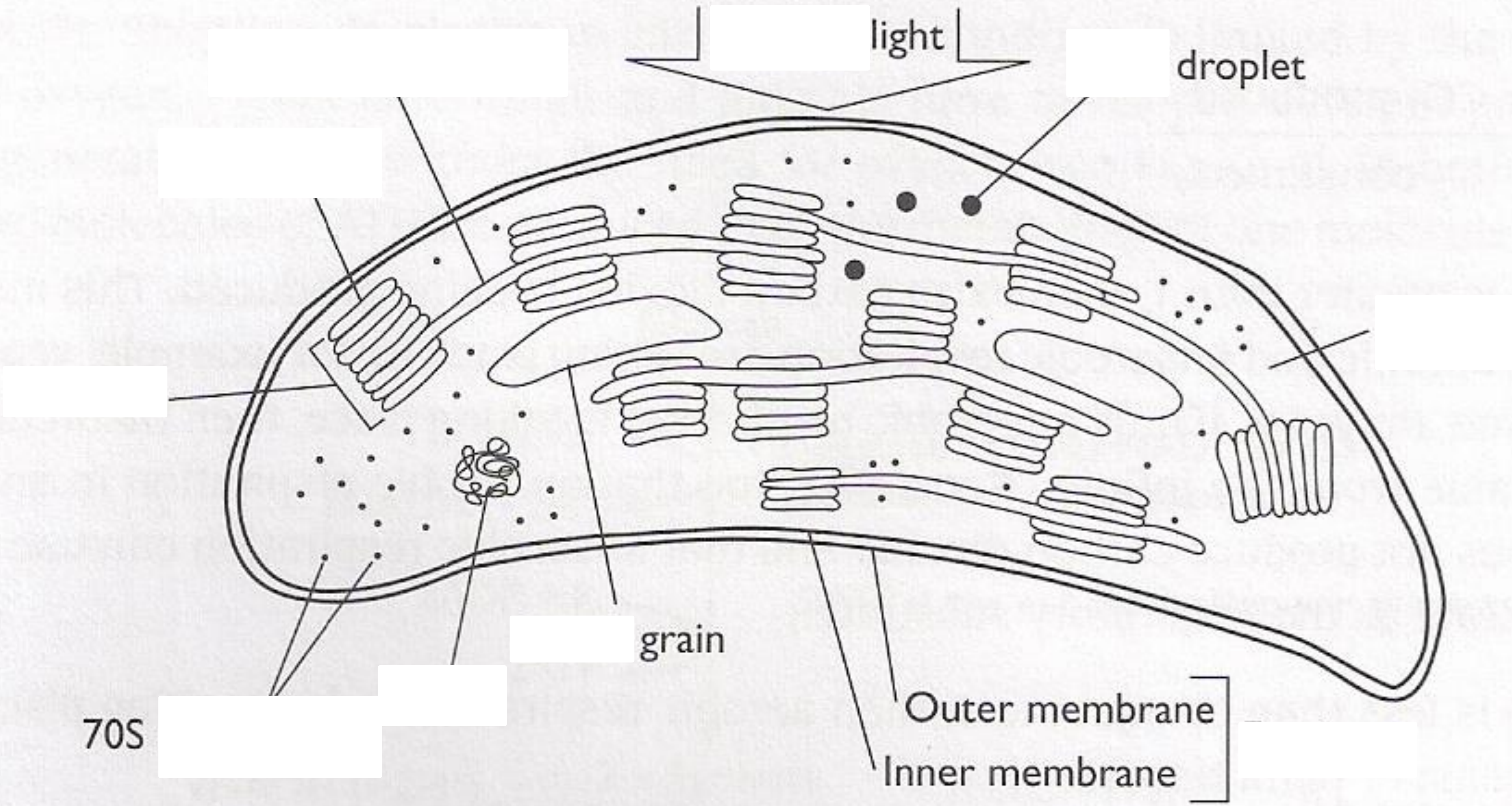



*Figure 10 The structure of a chloroplast*

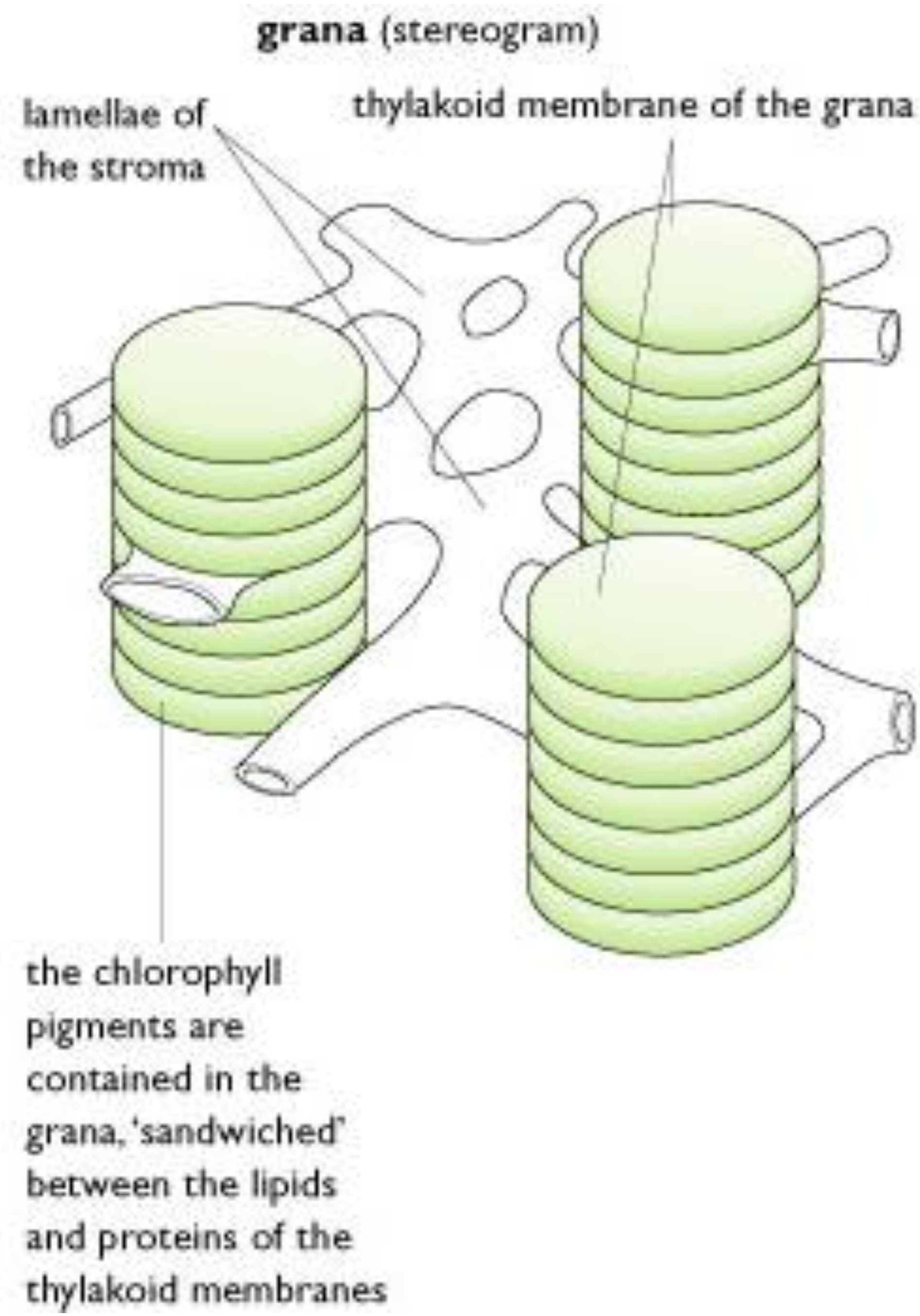
# Chloroplast structure

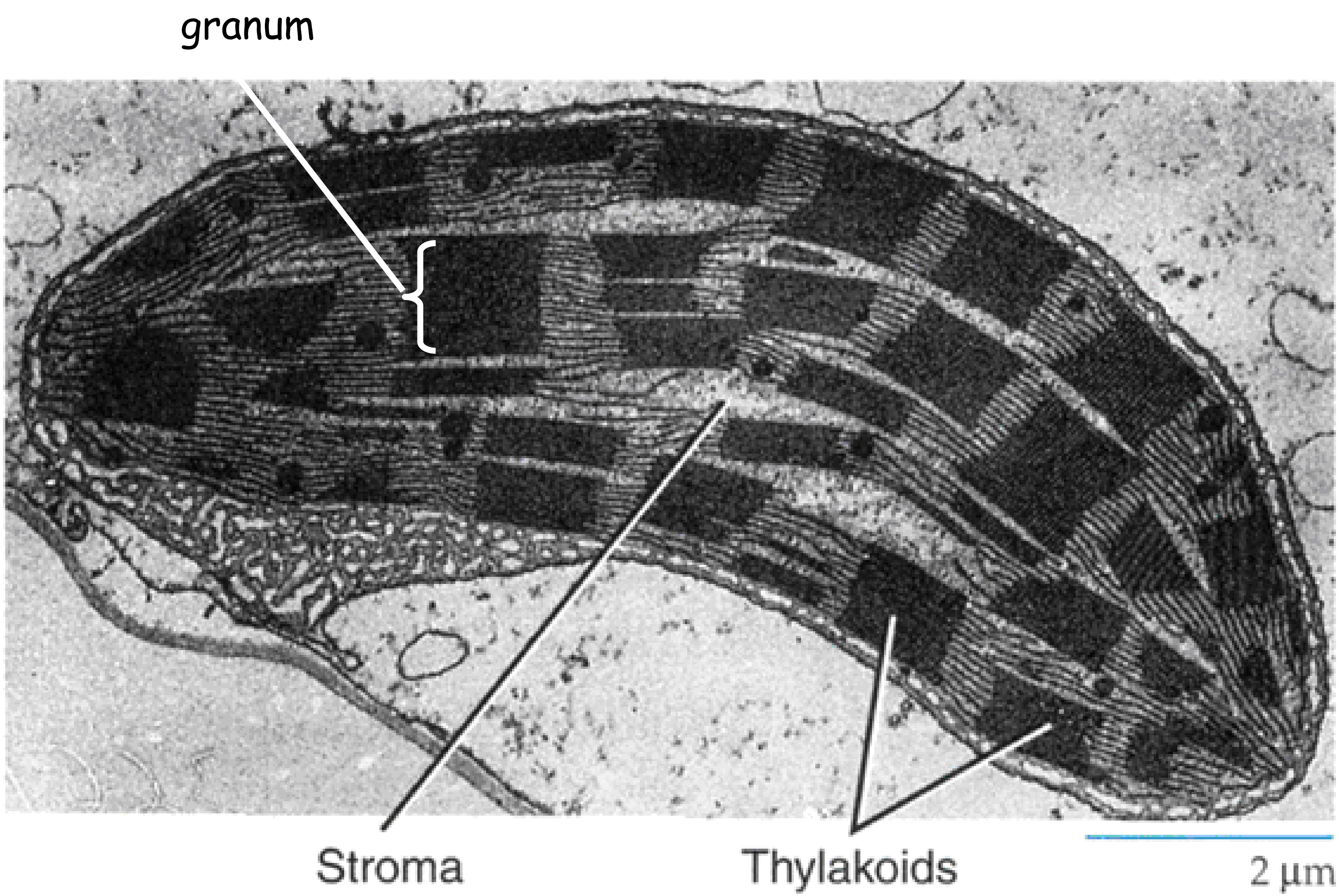
- Chloroplasts are aprox. 20 um long and 5um wide (a large organelle)
- Has an internal flattened membrane system organised into sac like thylakoids
- Stacks of thylakoids called grana
- Thylakoids have a large surface area which increases the amount of chlorophyll (and other pigments) accommodated in them

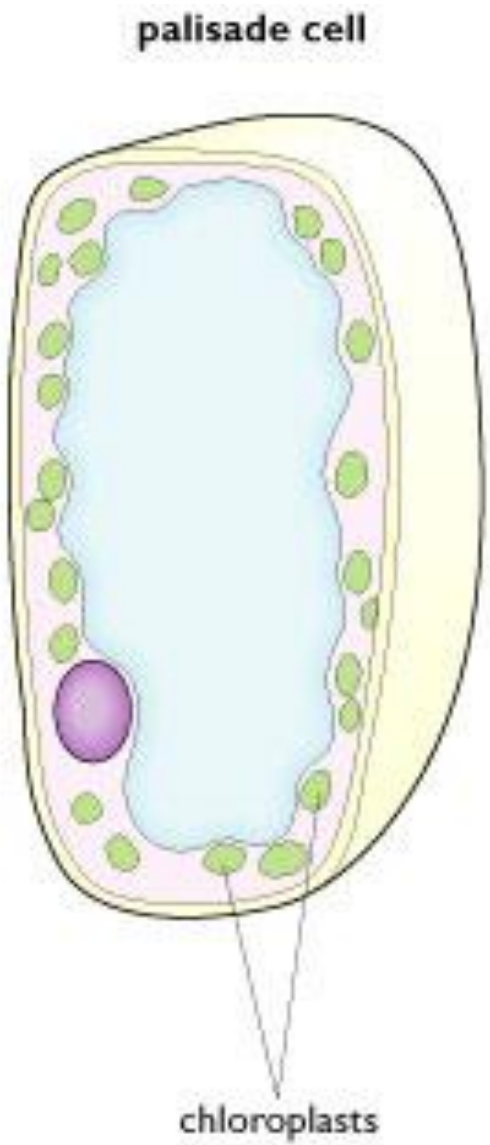
remember

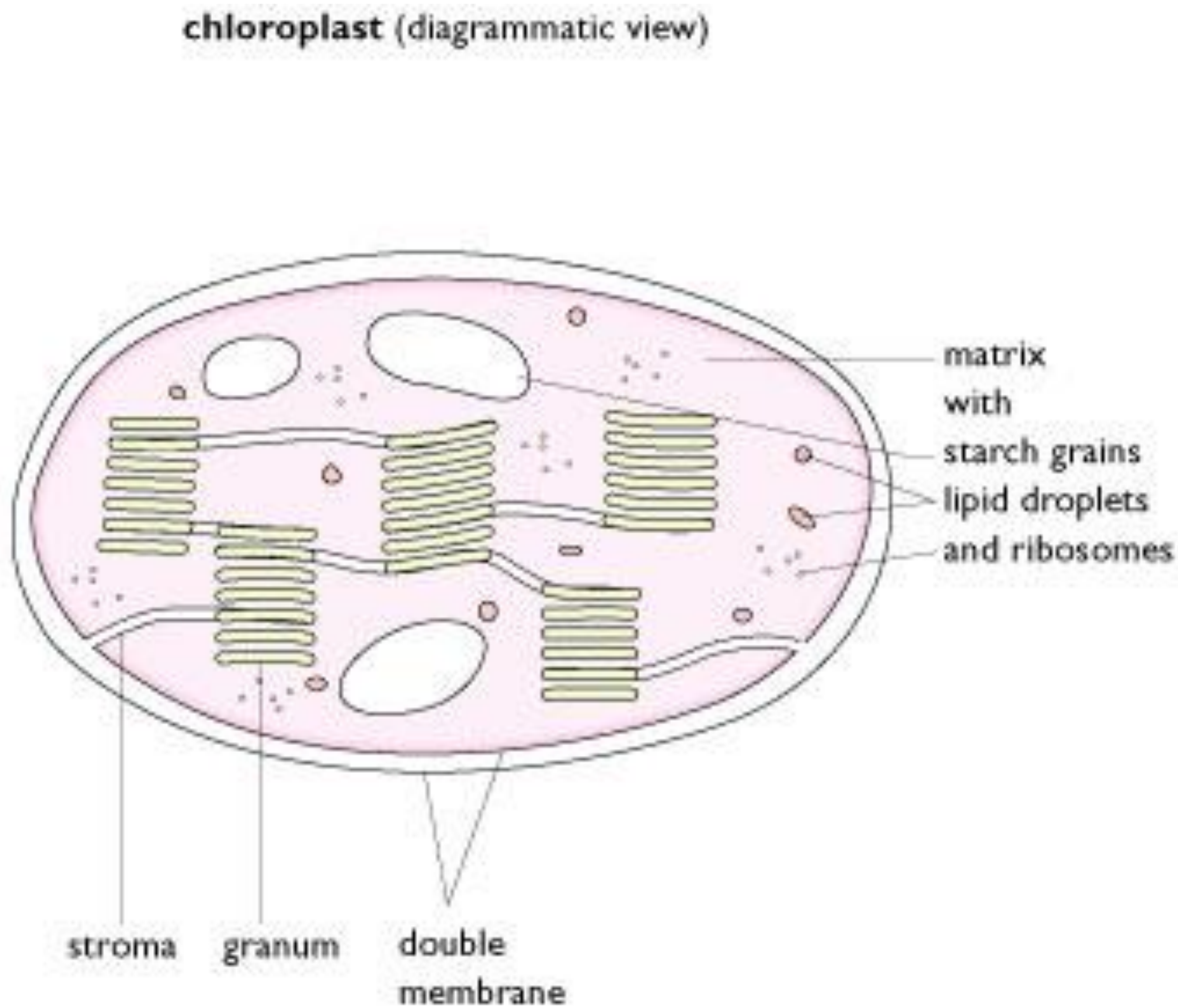
- **Thylakoid membranes** - series of flattened sacs
- **Grana** (singular granum) - stacks of thylakoids

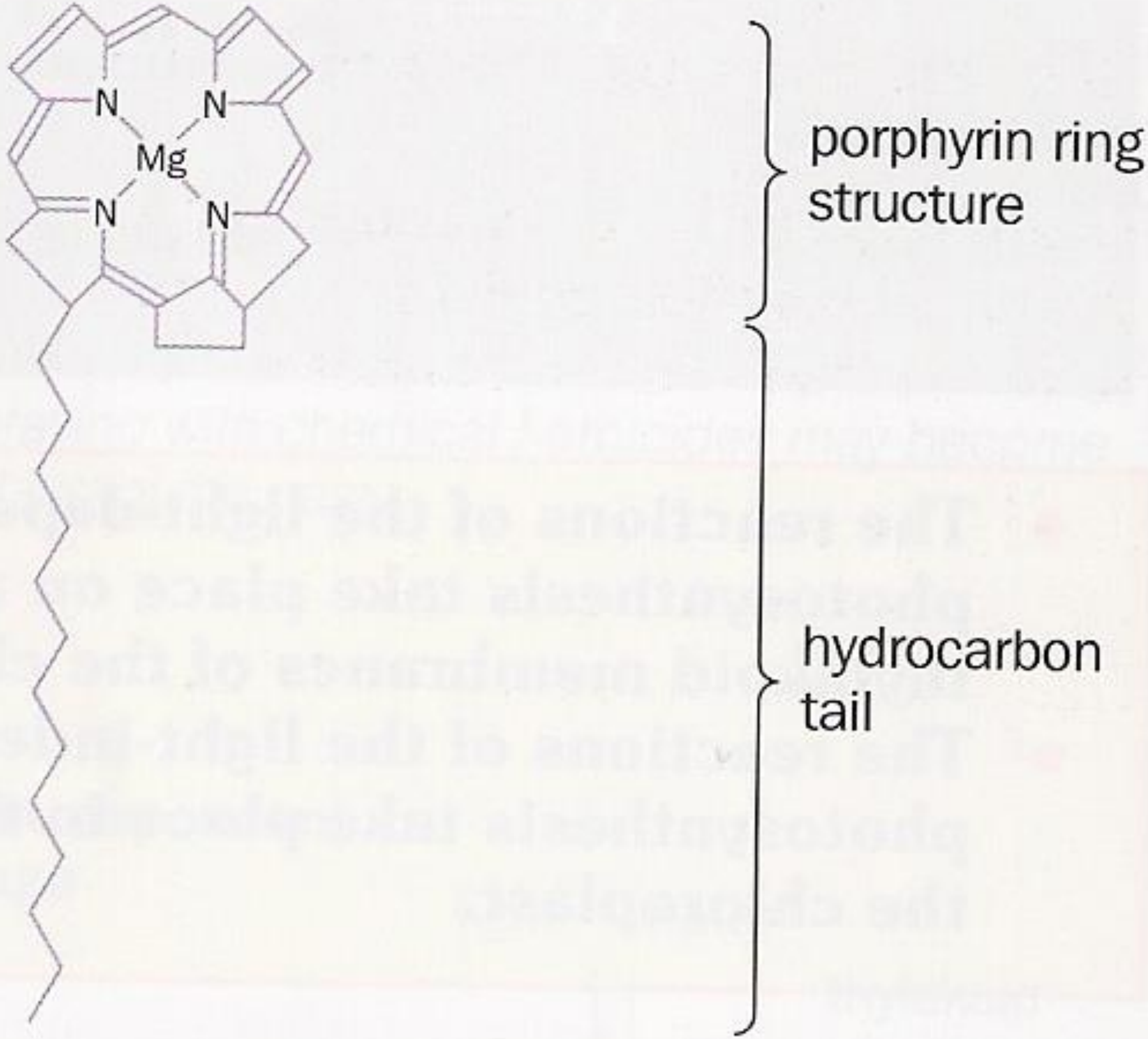
- Most light absorption occurs in the stacks of thylakoids (grana) as here the photopigments are concentrated
- Each granum is linked to one or more by intergranal lamellae
- They also contain systems of electron carriers and associated enzymes involved in photosynthesis



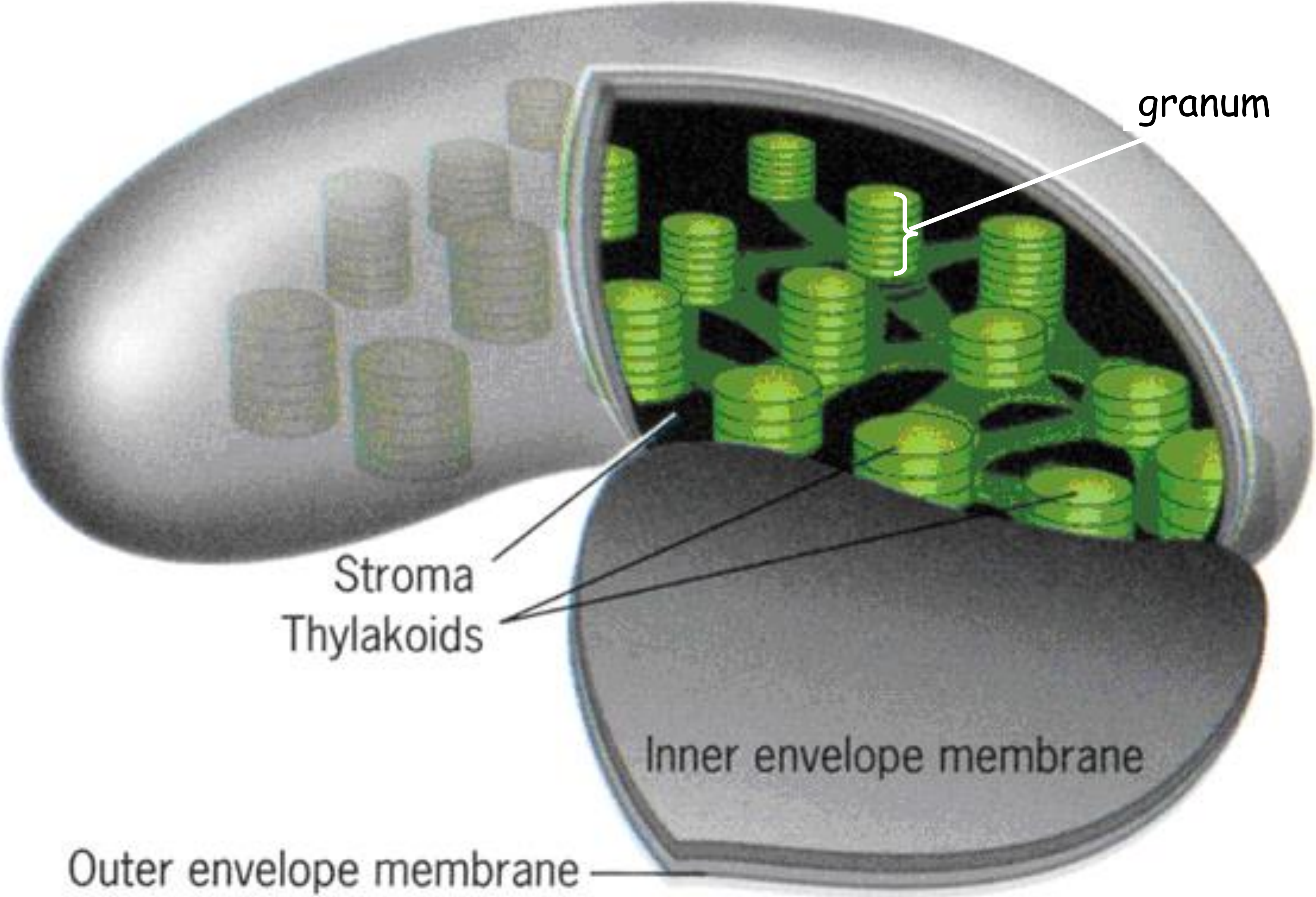

granum
Stroma
Thylakoids
2 μm


palisade cell
chloroplasts


chloroplast (diagrammatic view)
matrix
with
starch grains
lipid droplets
and ribosomes
stroma
granum
double
membrane




*The shape of a chlorophyll molecule*


granum
Stroma
Thylakoids
Inner envelope membrane
Outer envelope membrane

## Read this summary and note where in the chloroplast these stages take place…

### The biochemistry of photosynthesis

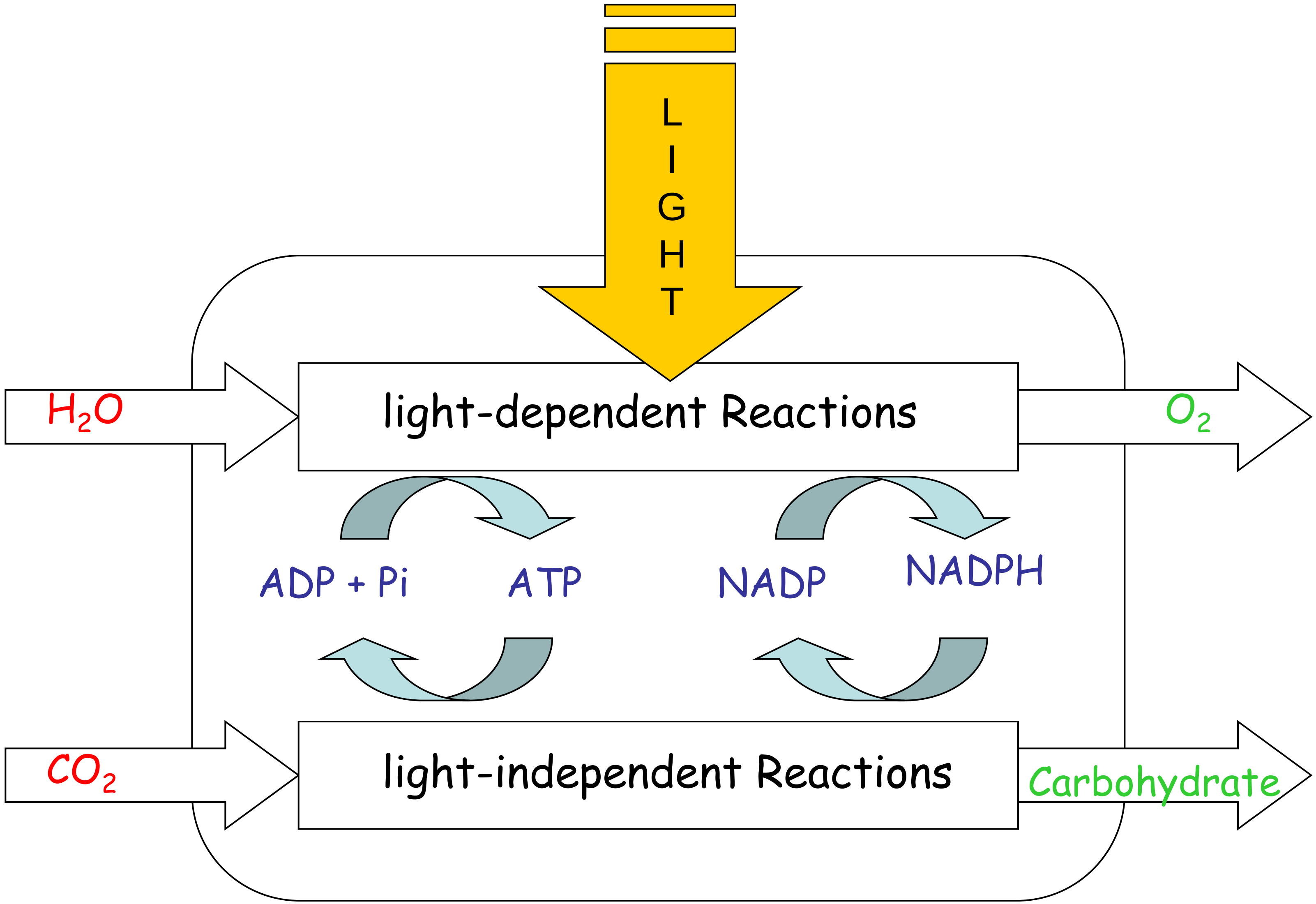
The process of photosynthesis can be conveniently separated into three main stages:

- **light harvesting** - the absorption of light in the thylakoids; a consequence of which is to raise the energy level of the electrons in chlorophyll.
- the **light-dependent stage** – energised electrons are used to make the energy-rich compounds ATP and reduced NADP. These reactions take place in or on the thylakoid membranes of the grana.
- The **light-independent stage** – the products of the light reaction are used to make simple carbohydrate. Carbon dioxide is fixed as part of the cyclical series of reactions that take place in the stroma.

| Stage | Where it occurs | Products |
|---|---|---|
| Light Harvesting | | • |
| Light Dependent | | • <br> • <br> • |
| Light Independent | | • |

**“Light harvesting” takes place in the thylakoids but it is in the stroma where carbon dioxide is used (“fixed”) and the sugar actually made.**

**The processes of photosynthesis are interlinked, with the light independent reaction being reliant on products from the light dependent reaction in order to proceed.**




**NB that NADP is used in PS., $NAD^+$ is used in Resp.**

**Light energy must be absorbed, but what type and by what molecule?...**

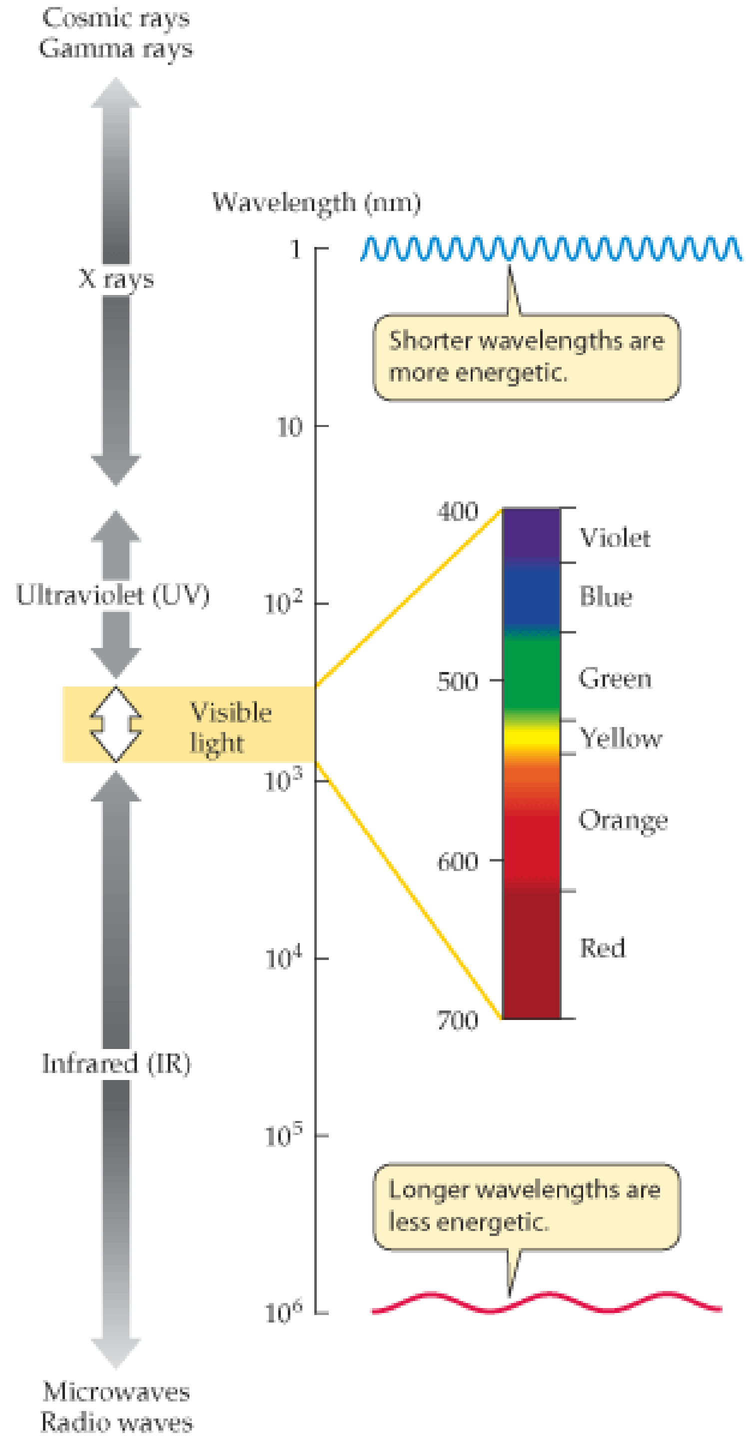
5.2.4 Appreciate that light is absorbed by chlorophyll and associated pigments:

- absorption spectra to show peak absorption by different pigments;
- action spectrum showing which wavelengths of light promote the optimum rate of photosynthesis.

# photosynthetic pigments

## There is a close link between the absorption of light and the rate of photosynthesis

Plants absorb light for photosynthesis from the visible spectrum using chlorophyll and a number of other associated pigments



# These pigments include:

- Chlorophyll a blue-green
- Chlorophyll b yellow-green
- Carotene orange
- Xanthophyll yellow
- Phaeophytin grey

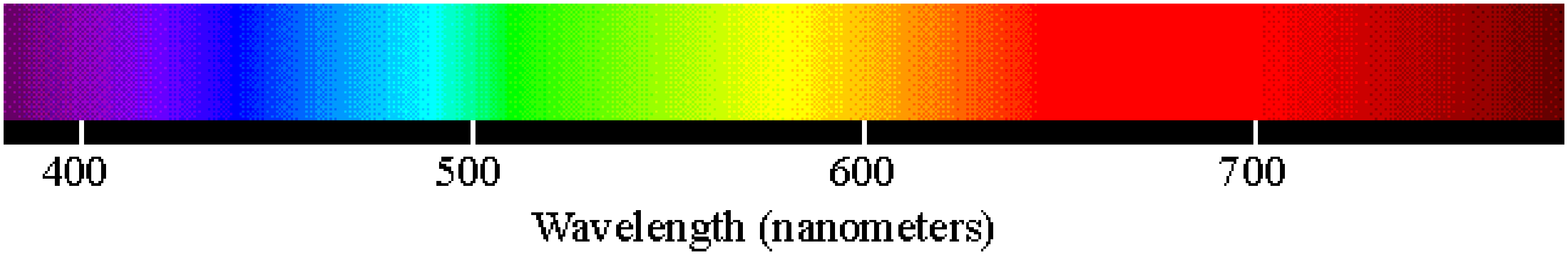
Chlorophyll a is the most abundant photosynthetic pigment and is found in all photosynthesising plants.

The others occur in varying proportions, which gives their variety of shades of green

# Why is there a variety of Pigments?

White light is made of light of different wavelengths (400-700nm).

**In order for a plant to absorb the maximum amount of light they have a range of pigments**

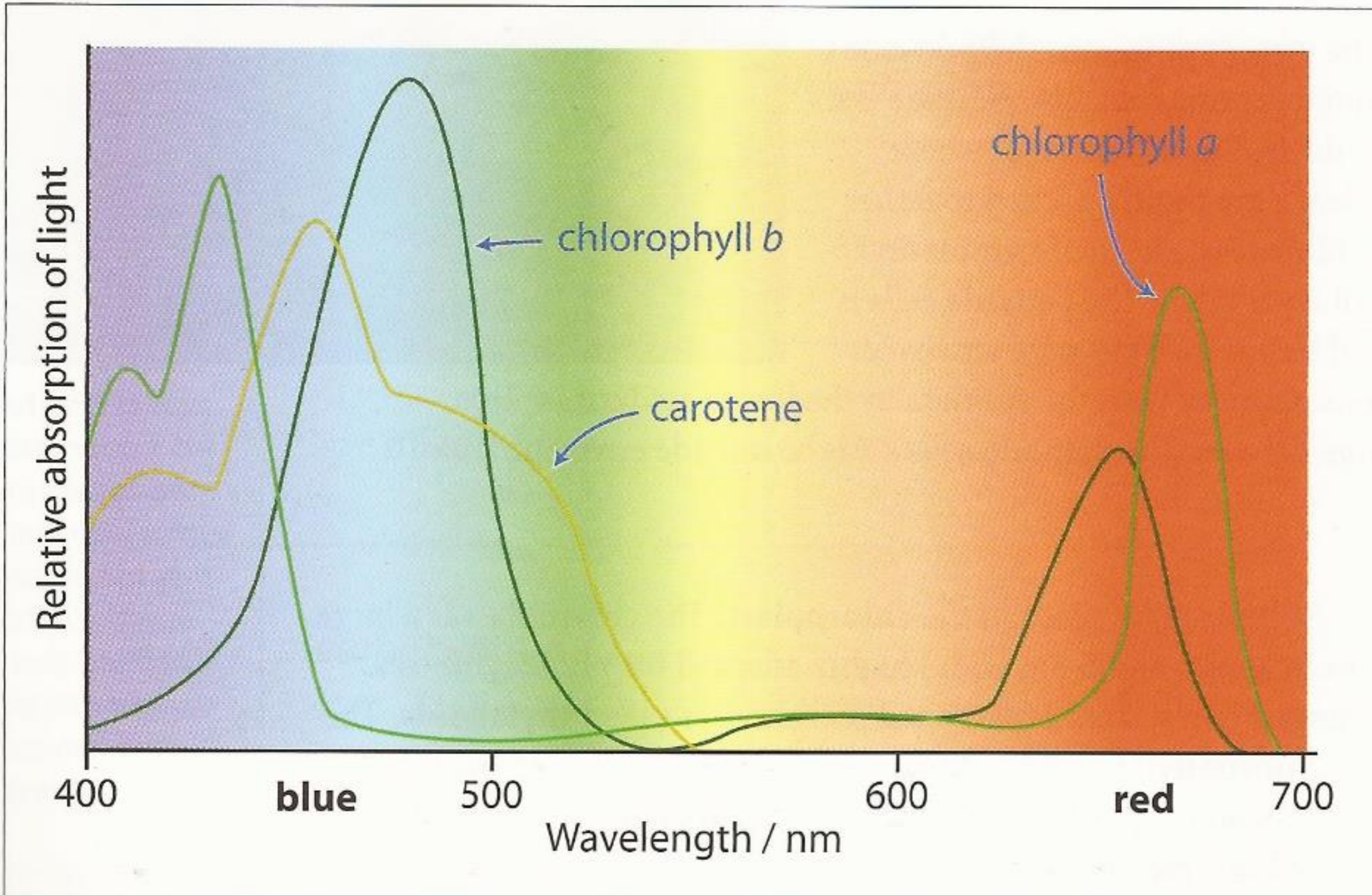


- Each different pigment absorbs light efficiently from a particular area of the spectrum
- However none of the pigments absorb well in the green/yellow spectrum (500-550nm). This light is reflected, giving plants their green colour

*The absorbance of different pigments at different wavelengths can be represented on a graph called the...*

# Absorption Spectrum

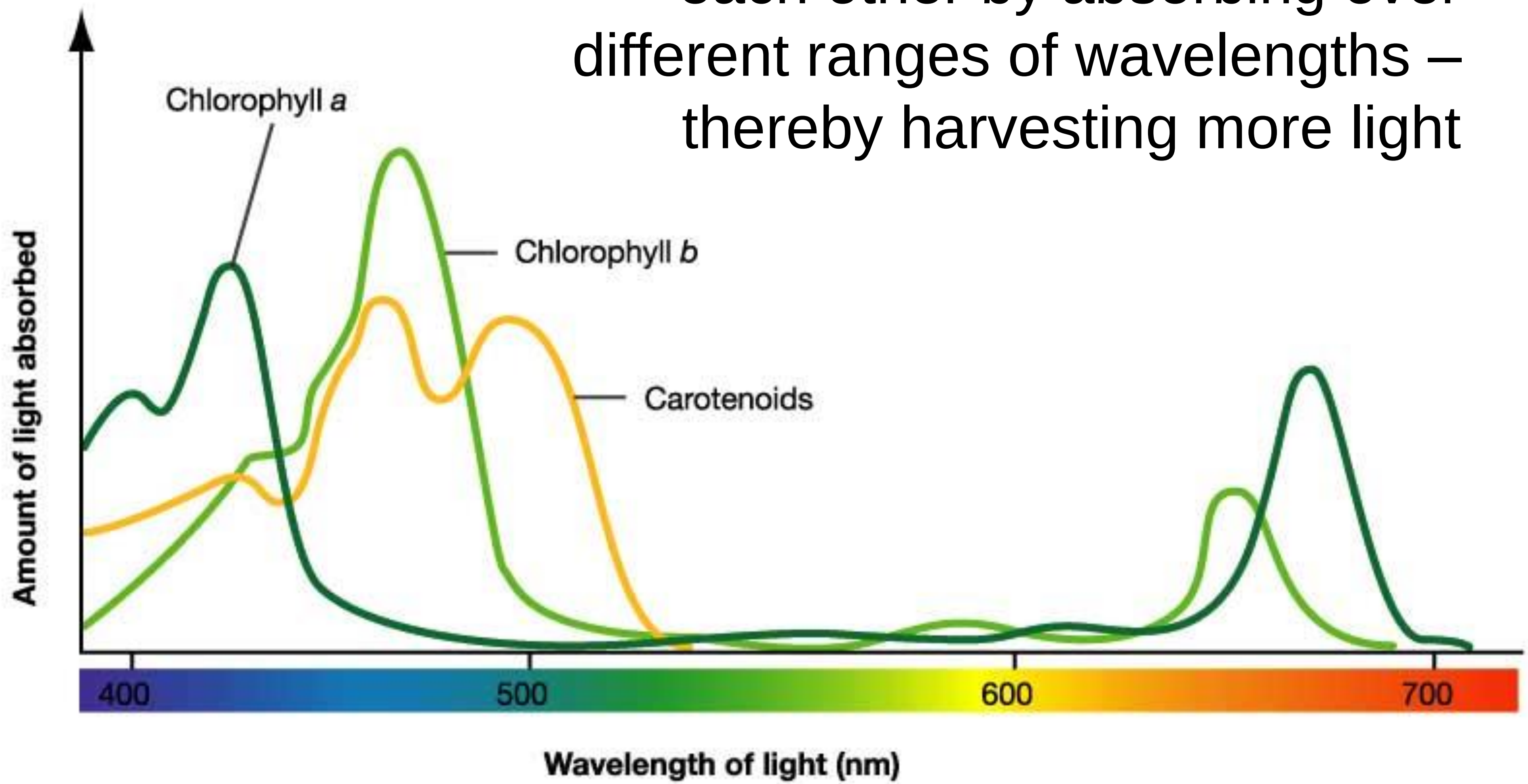
*which shows* ***the relative absorption at particular wavelengths***



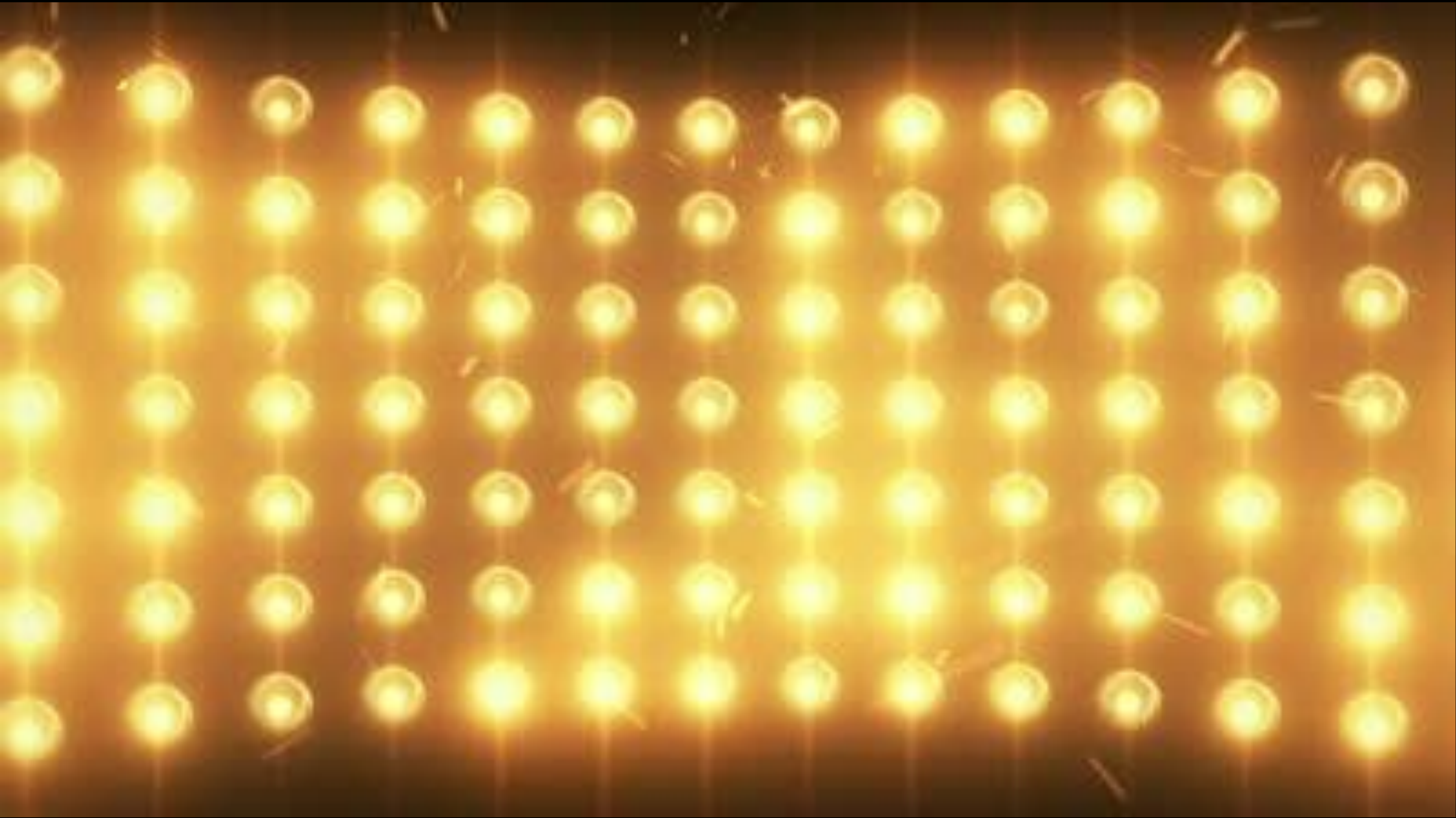
Relative absorption of light
chlorophyll b
chlorophyll a
carotene
400
blue
500
600
red
700
Wavelength / nm

# Absorption spectra

Show how the pigments complement each other by absorbing over different ranges of wavelengths – thereby harvesting more light



**_Note that absorption spectra display the relative light absorption at different wavelengths but do not indicate the intensity of the light available_**

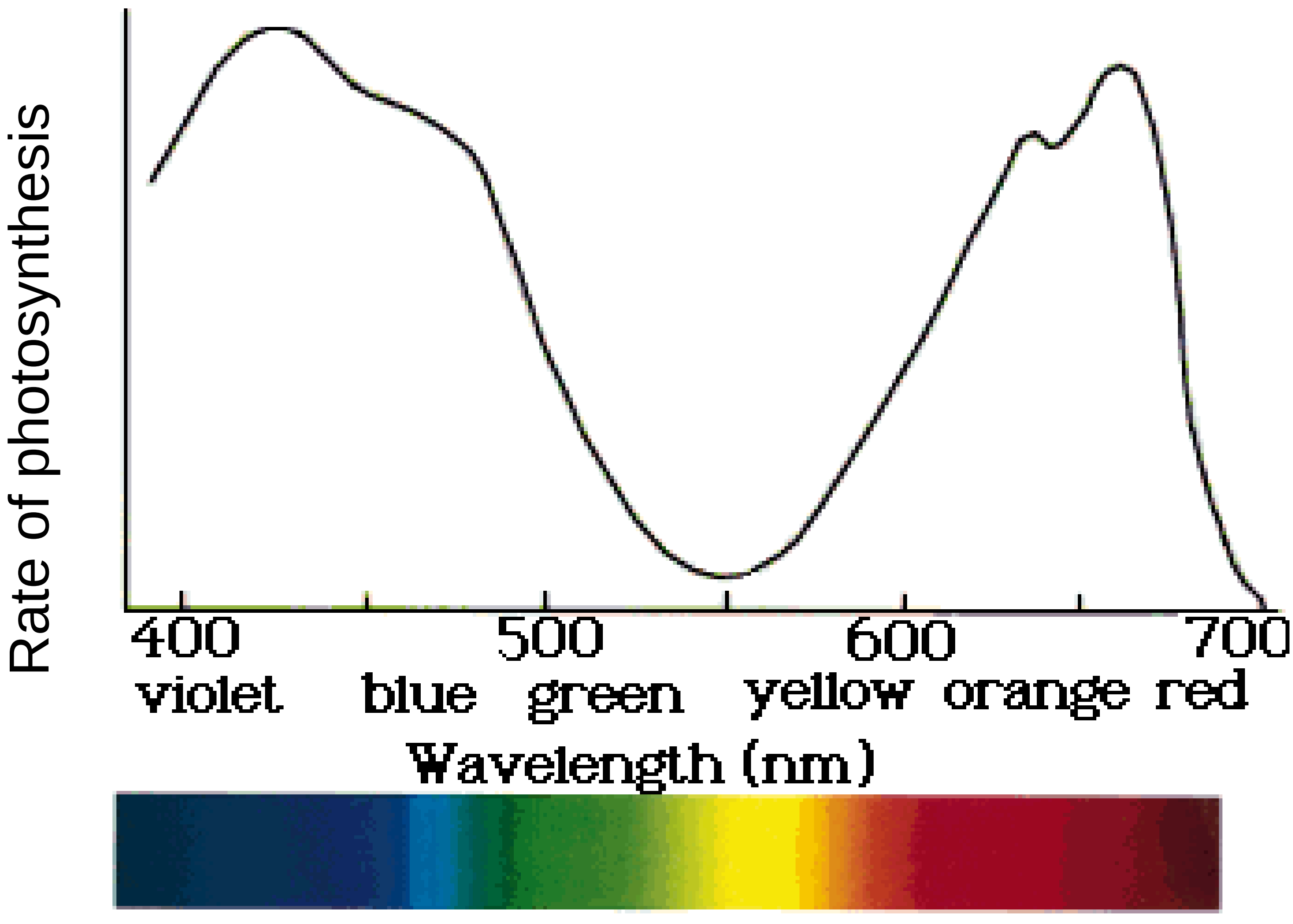


The **rate of photosynthesis** at different wavelengths of light can be represented on a graph called the

# Action spectrum

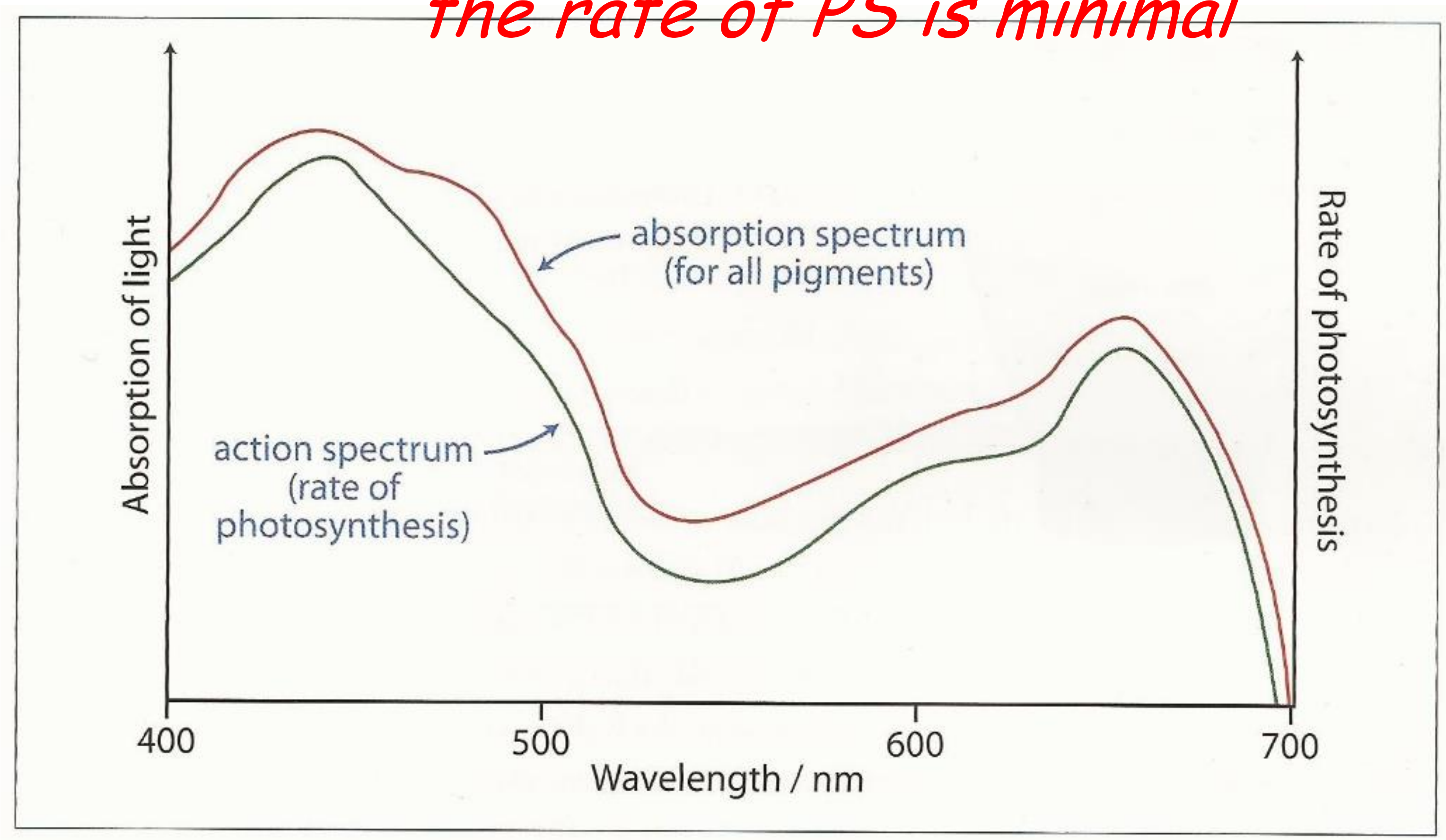
which shows **wavelength of light** which promotes the highest rate of photosynthesis

# action spectrum



By **comparing the absorption spectra** for the different photosynthetic pigments **to the action spectrum** it can be seen that the maximum rates of photosynthesis coincides with the wavelengths at which the pigments absorb light best.

*Where the pigments don't absorb light (yellow/green) the rate of PS is minimal*



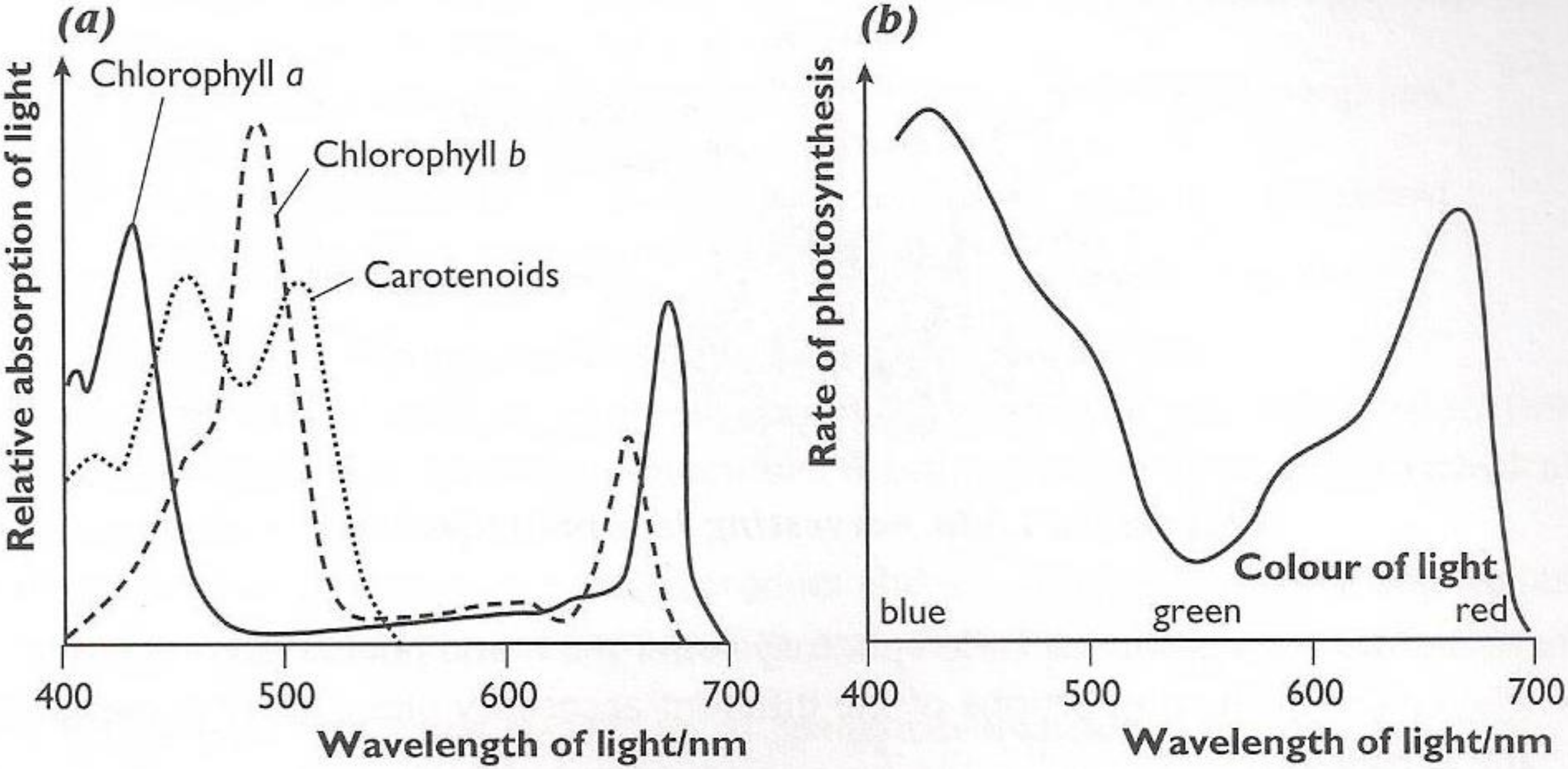
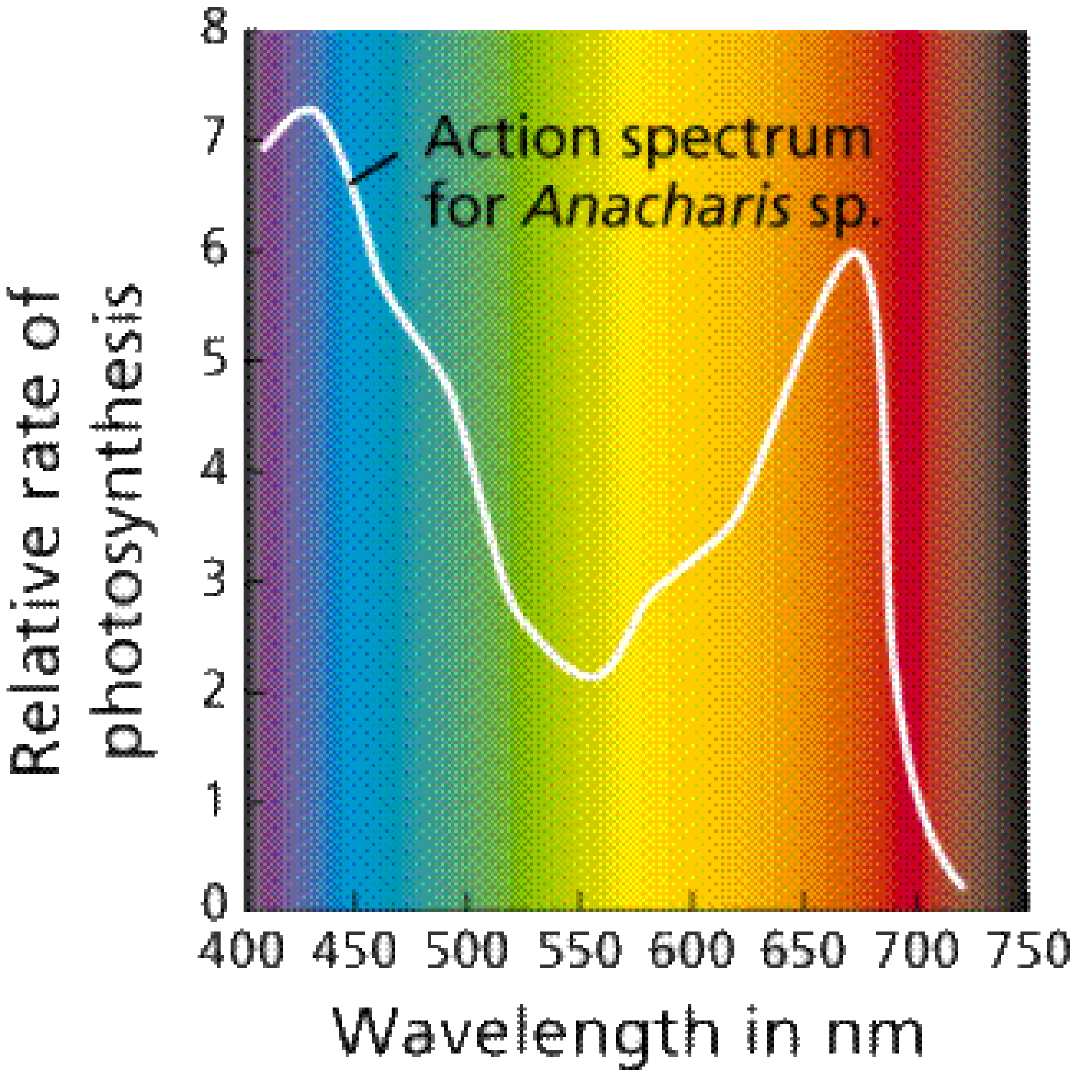
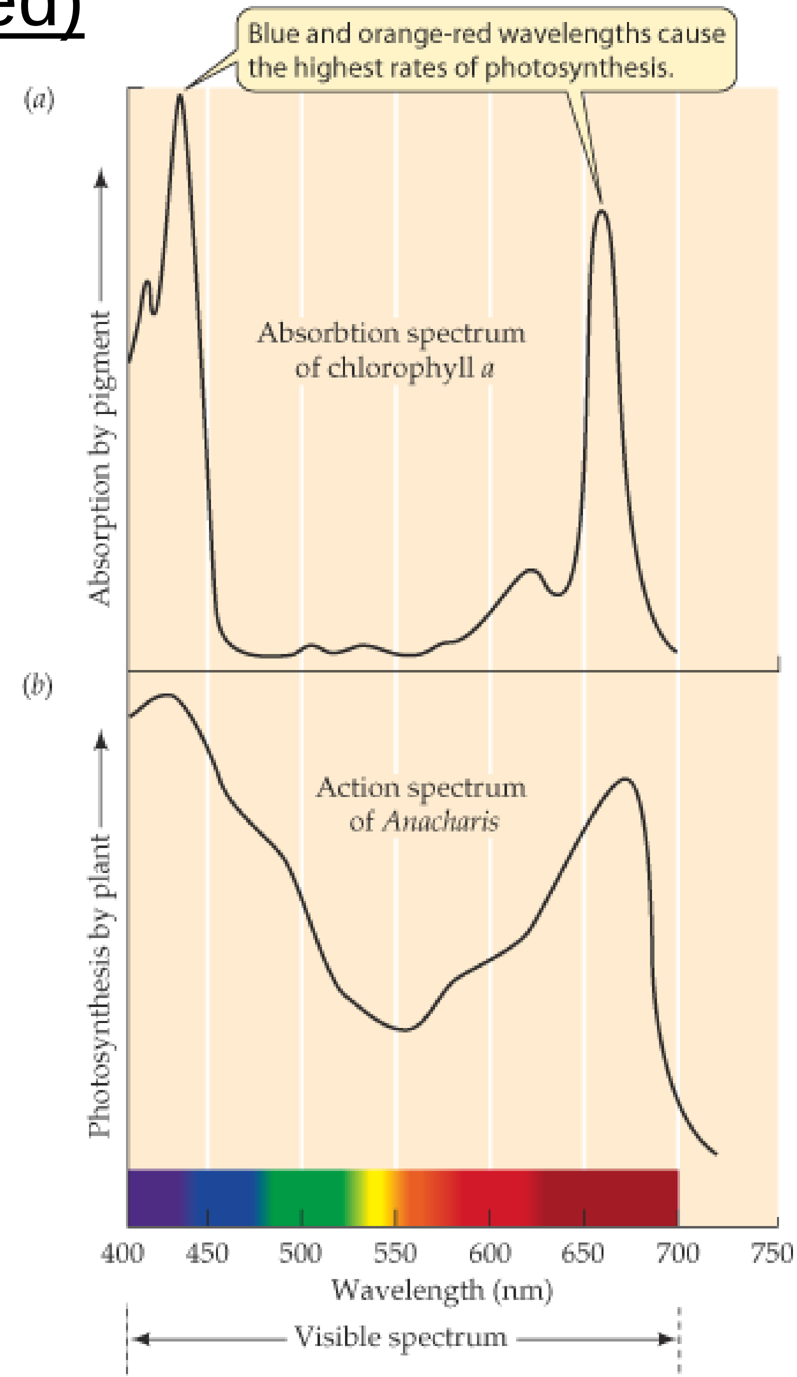
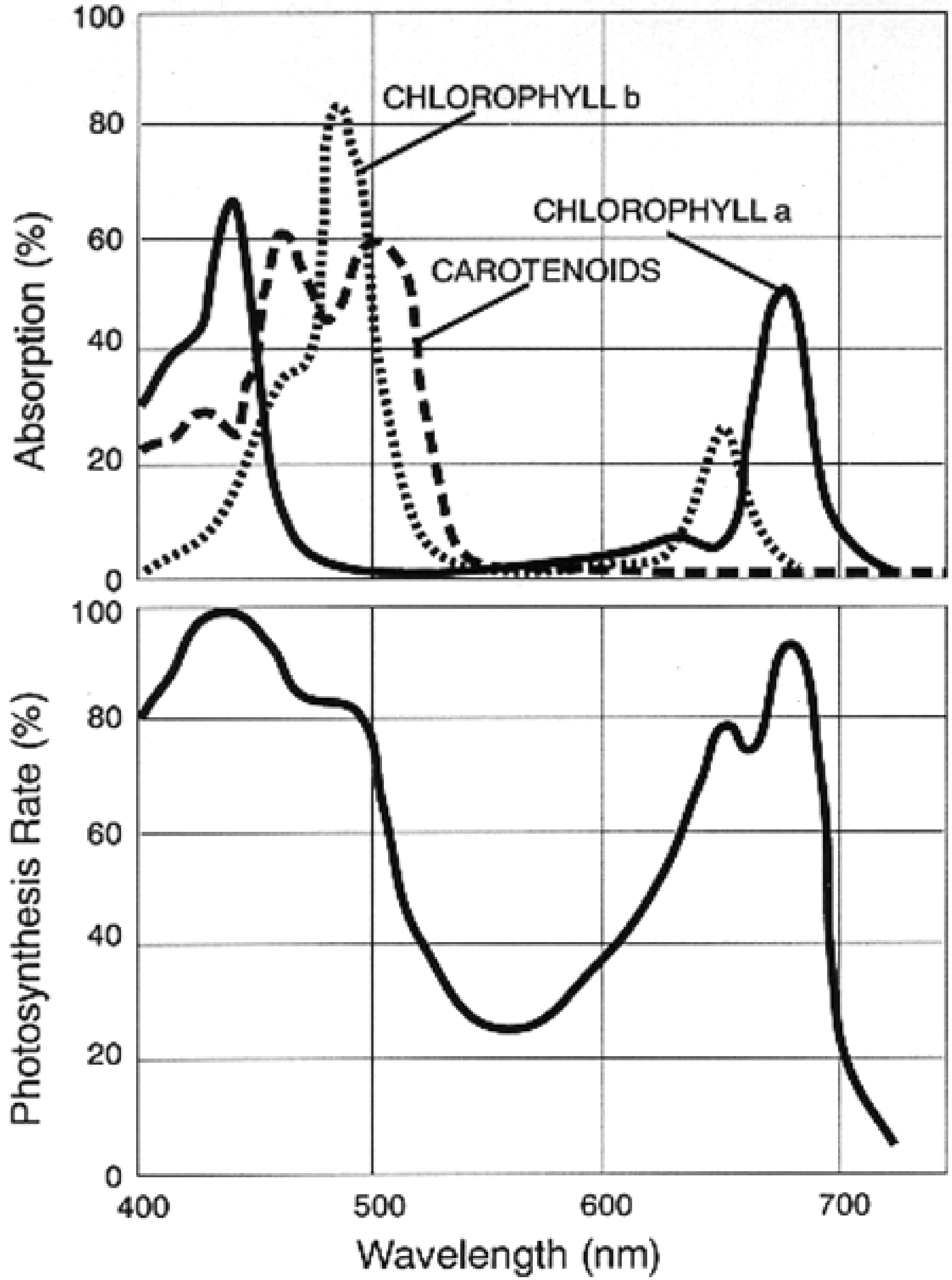



***Figure 11 (a) The absorption spectrum for photosynthetic pigments (b) The action spectrum for photosynthesis***

# *e.g. Elodea / Anacharis* (pondweed)

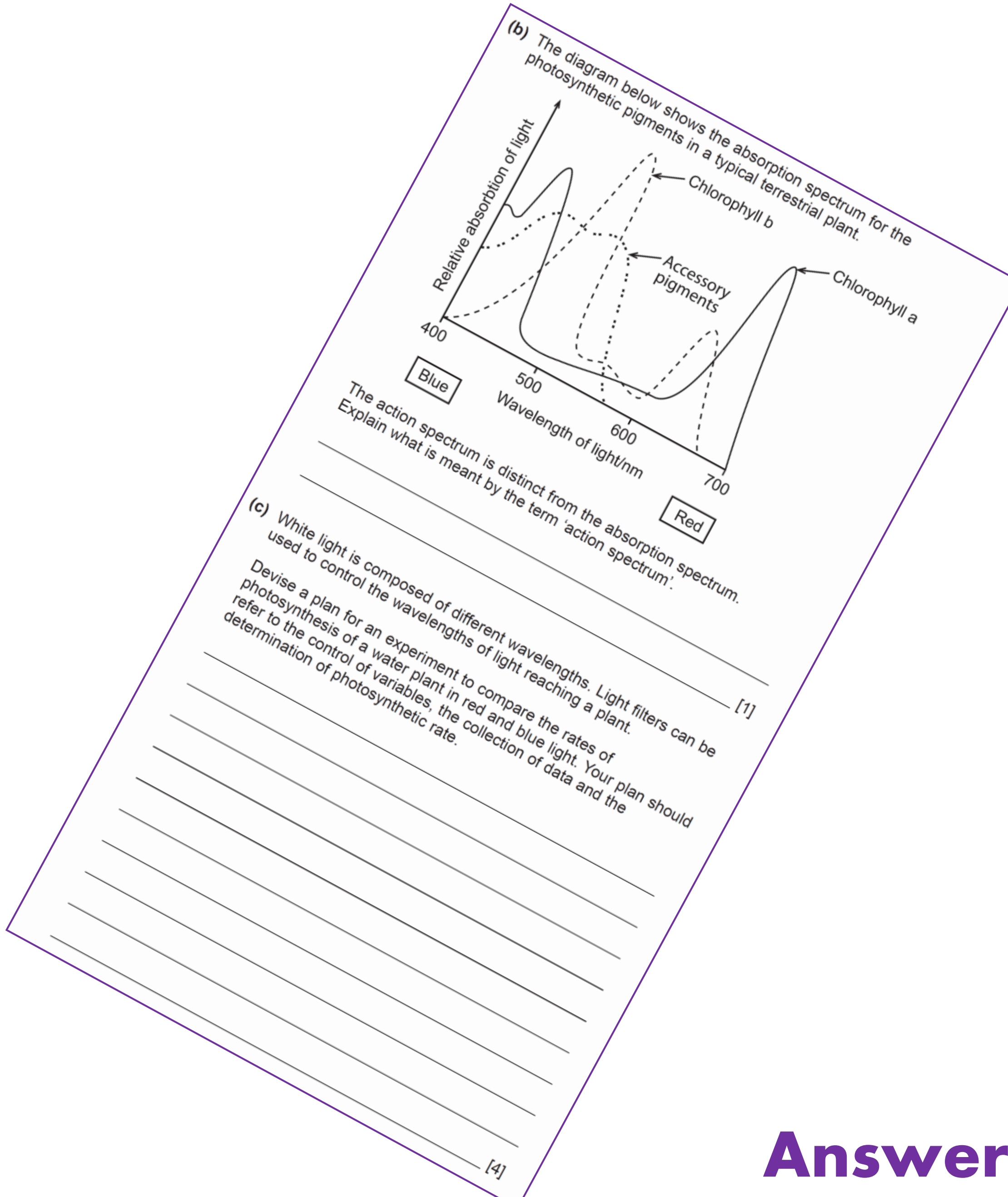




CHLOROPHYLL b
CHLOROPHYLL a
CAROTENOIDS
Absorption (%)
100
80
60
40
20
0
Photosynthesis Rate (%)
100
80
60
40
20
0
400
500
600
700
Wavelength (nm)

# TRY A PPQ!



**(b)** The diagram below shows the absorption spectrum for the photosynthetic pigments in a typical terrestrial plant.



The action spectrum is distinct from the absorption spectrum. Explain what is meant by the term 'action spectrum'.

.......................................................................................................... [1]

**(c)** White light is composed of different wavelengths. Light filters can be used to control the wavelengths of light reaching a plant.

Devise a plan for an experiment to compare the rates of photosynthesis of a water plant in red and blue light. Your plan should refer to the control of variables, the collection of data and the determination of photosynthetic rate.

.......................................................................................................... [4]

# Answers...

**(b)** Action spectrum shows the rate of photosynthesis across the range of wavelengths; [1]

**(c)** **Any four from**

- use red and blue filters to provide red and blue light respectively
- measure length/volume of oxygen bubble (using Audus apparatus)
- over a defined period of time
- calibration of scale using syringe/bore diameter
- hydrogen carbonate solution supplies $CO_2$ (ensures $CO_2$ not limiting)
- water bath to maintain temperature/method of controlling light intensity
- replication (at least 3 times) to improve reliability/allow statistical analysis

[4]

Complete questions 1, 4 and 6 on p308 in Froggy…

## 5.2.6 Practical Work:

*Refer to the use of the Audus apparatus in 2.1 (b):*

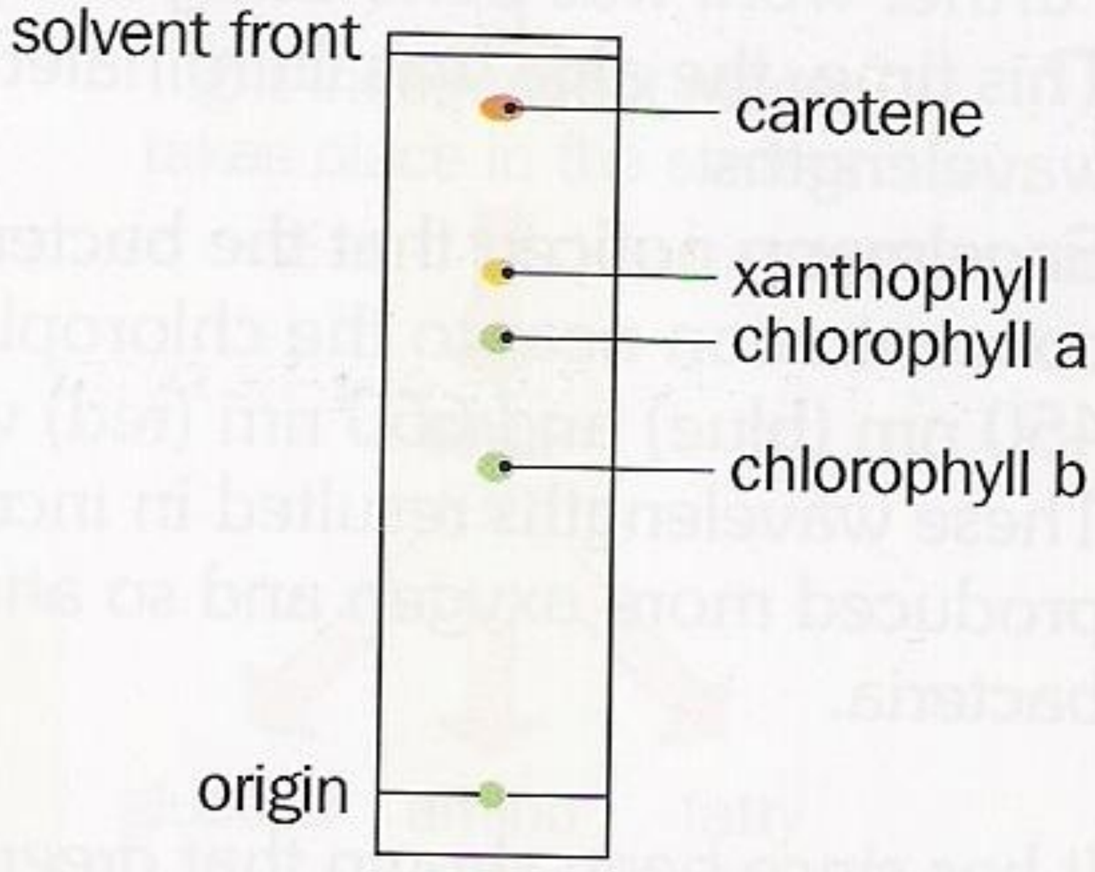
- *the effect of light intensity and* $CO_2$ *concentration on the rate of photosynthesis;*

*Carry out paper chromatography of plant pigments:*

- *preparation and running of the chromatogram;*
- *calculation of* $R_f$ *values;*

*Demonstrate the role of hydrogen acceptors using redox indicator (such as DCPIP).*

# Chromatography of plant pigments



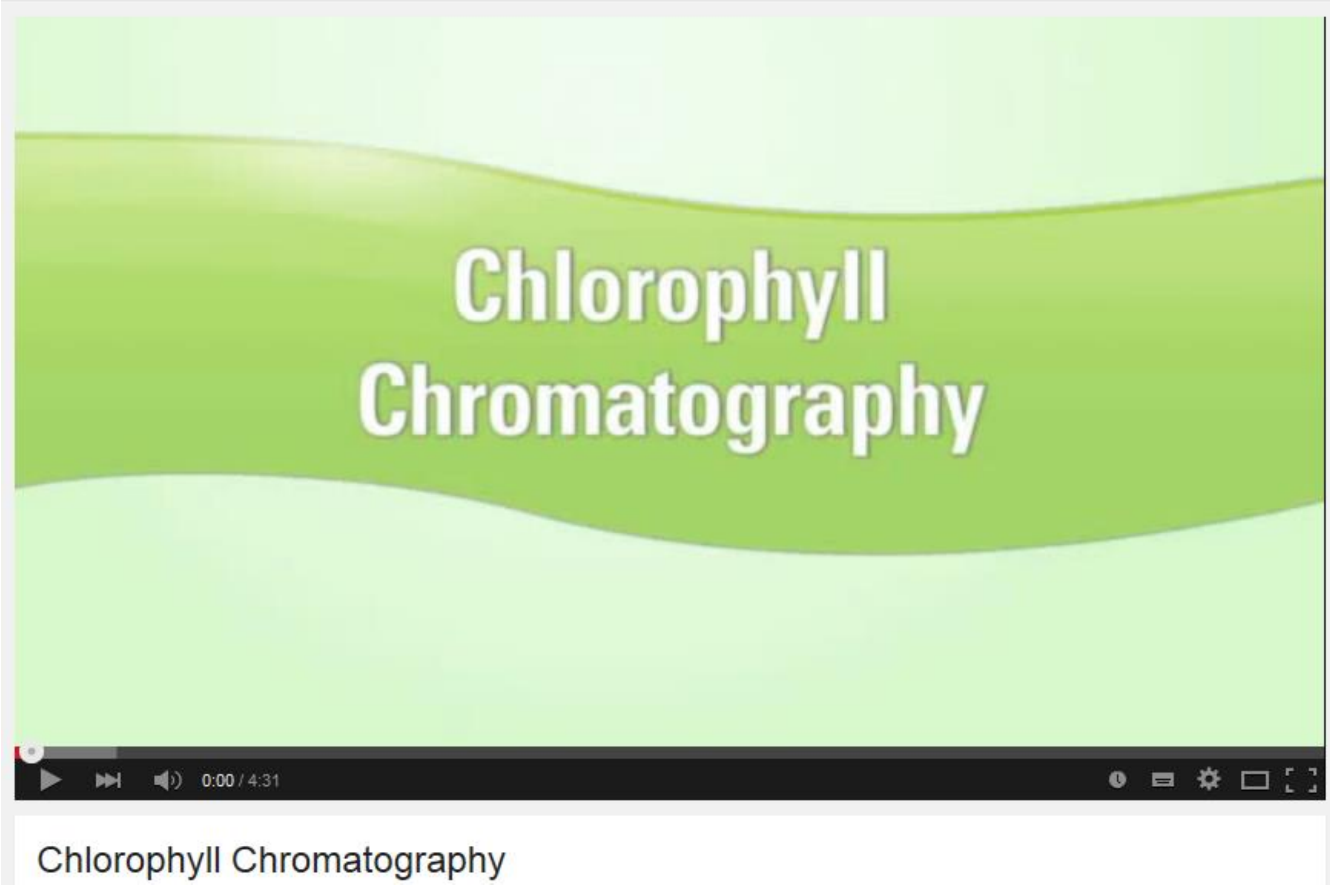

*Separation of plant pigments by chromatography*

## Separating photosynthetic pigments

Photosynthetic pigments can be separated by **chromatography**.

- First, the pigments are extracted by grinding up a leaf, using a pestle and mortar, with a solvent such as propanone.
- The extract is then 'spotted' onto the origin line of a piece of chromatography paper.
- The chromatogram is placed into a glass tank containing a solvent.
- The solvent gradually rises up the chromatography paper and the different pigments separate out depending upon their relative solubility in the solvent and their adhesion to the chromatography paper.
- When the solvent front comes close to the top, the paper is taken out and dried.
- The Rf value for each pigment can then be worked out, and the pigment can be identified. Work out the Rf value of each pigment.

$$\text{Rf value} = \frac{\text{distance travelled by pigment}}{\text{distance travelled by solvent front}}$$




https://www.youtube.com/watch?v=jiPd5CkCkkU

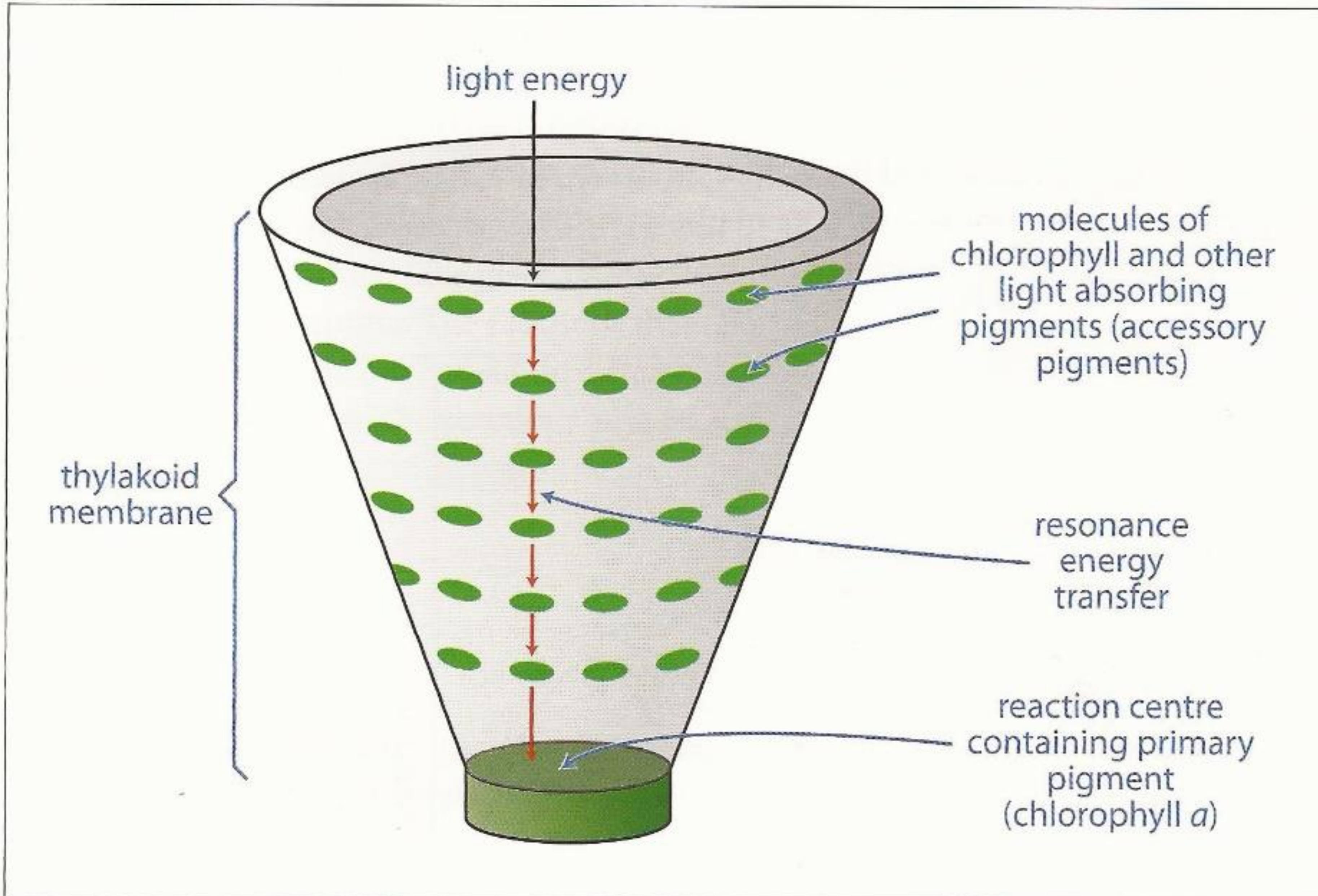
# PHOTOSYNTHESIS

# – the biochemistry

5.2.2 Understand the light-dependent stage of photosynthesis:

- photoactivation of photosystem I (PSI) and photosystem II (PSII) resulting in the passage of electrons from PSII to PSI (the Z-scheme) coupled with the production of ATP (photophosphorylation) (Cyclic photophosphorylation NOT required);
- the final acceptor of PSI electrons as $NADP^+$ (with $H^+$ from the dissociation of water) producing reduced NADP (NADPH);
- the replacement of PSII electrons from hydroxyl ions ($OH^-$) resulting from the dissociation of water with the concomitant release of oxygen.

# THE LIGHT-DEPENDENT REACTION


light energy
molecules of chlorophyll and other light absorbing pigments (accessory pigments)
thylakoid membrane
resonance energy transfer
reaction centre containing primary pigment (chlorophyll *a*)

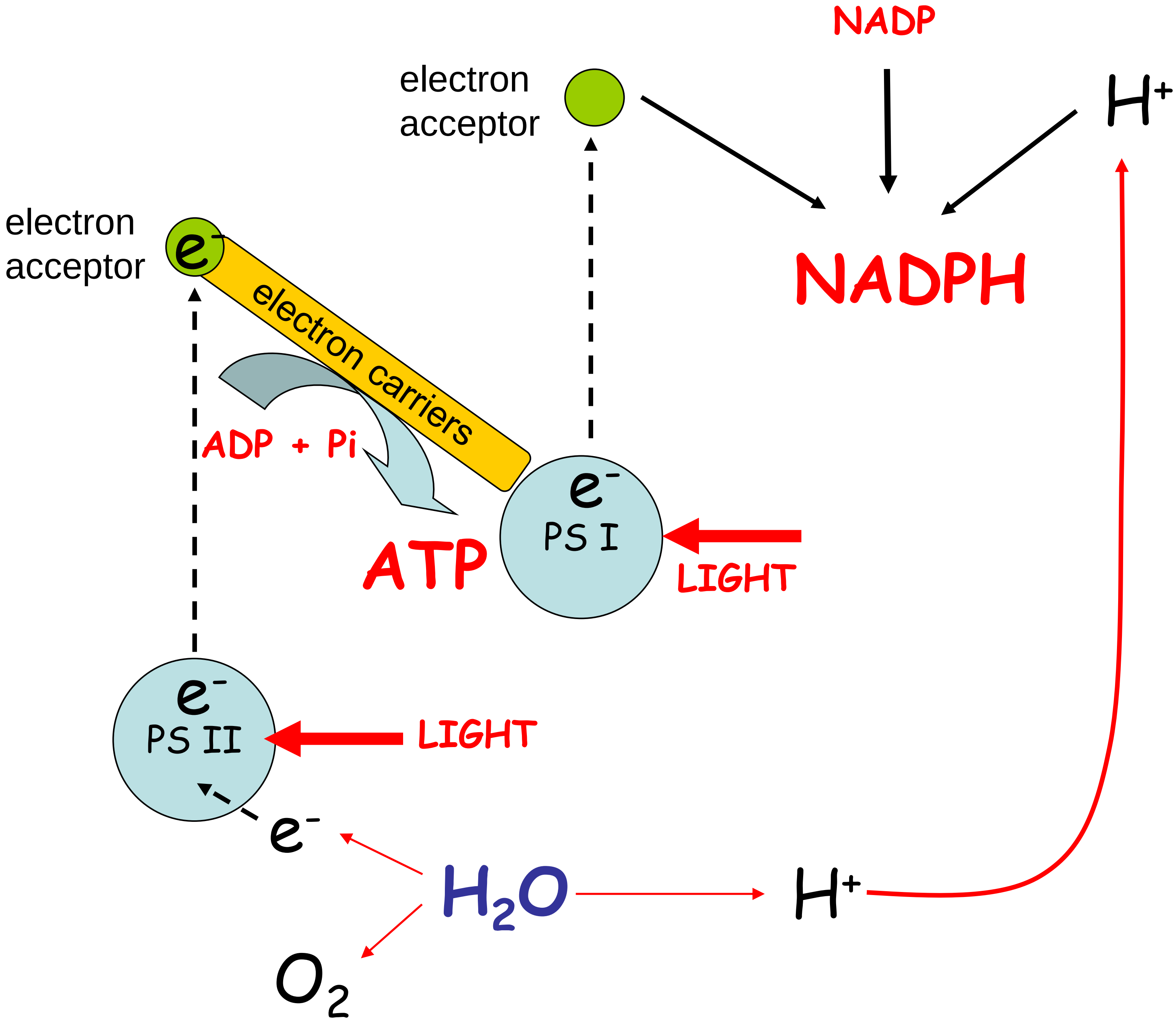
notes from girls books about the arrangement of the molecules in antenna complex

- When the chlorophyll a molecule in the reaction centre of an antenna complex receives sufficient energy, **electrons** are emitted and are taken up by an **electron acceptor**.
- The antenna complexes form units called **photosystems**.
- Two photosystems exist:
- **PSII** the chlorophyll a molecules has an absorption peak of **680nm**.
- **PSI** the chlorophyll a molecule has an absorption peak of **700nm**.

- The electrons leaving **PSII are picked up** by an electron acceptor and passed to an **electron carrier chain** containing **cytochromes** which are at successively lower energy levels.
- As the electrons are passed along the chain **ATP** is made from ADP and Pi in a process called **photophosphorylation**.
- The electrons leaving **PSI** are picked up by an electron acceptor and combine with **NADP**, and **hydrogen ions** to form **reduced NADP** (NADPH)

- The **electrons leaving PSI** are **replaced by electrons** at the end of the electron carrier chain, that originated **from PSII**.
- The **electrons leaving PSII** are **replaced by the splitting of water** into electrons, hydrogen ions and oxygen.
- This process requires light energy and is known as **photolysis**.
- The **hydrogen ions** are used in the process of **reducing NADP** and
- The **oxygen** is either used in **respiration** or **released** from the cell and diffuses out of the stomata.

- The electron pathway and reactions of the light dependent stage, is summarised as a diagram, and described as the **z-scheme**, due to the shape of the graph produced as the electrons change energy levels.



NADP
electron acceptor
H+
electron acceptor
e-
electron carriers
NADPH
ADP + Pi
e-
PS I
ATP
LIGHT
e-
PS II
LIGHT
e-
H2O
H+
O2

# The products of the light dependent reaction are:

**ATP**

**NADPH**

**oxygen**

ATP and NADPH are both required for the light independent stage of PS

# Summary

- Light is needed for the photoactivation of PSI and PSII.
- The electrons from PSI join with NADP and H+ to form NADPH (needed in LI reaction)
- The electrons in PSI are replaced by electrons from PSII
- As electrons are passed from PSII to PSI ATP is formed (needed in LI reaction)
- The electrons in PSII are replaced by electrons released from the photolysis of water.

CCEA SPEC

# light independent reaction

- $CO_2$ fixation in a C3 plant in terms of reaction with ribulose bisphosphate (5C) producing 2 molecules of glycerate phosphate (3C) which is reduced by NADPH to a triose phosphate with the consumption of ATP
- The recycling of 5/6 of the triose phosphate to regenerate ribulose bisphosphate
- The utilisation of the remaining 1/6 in the synthesis of 6C sugars and other compounds

The light independent reaction takes place in the stroma of the chloroplast.

It is dependent upon the products of the light dependent reaction:

**energy from ATP &**

**H from NADPH**

The LI reaction results in **carbon dioxide fixation** as it is reduced to organic carbohydrate.

- The American Calvin showed the reaction to be a cyclical series of steps requiring specific enzymes, therefore it is often called the **Calvin Cycle**.
- As it is not dependent on light it used to be called the dark reaction, but it also occurs in the presence of light.

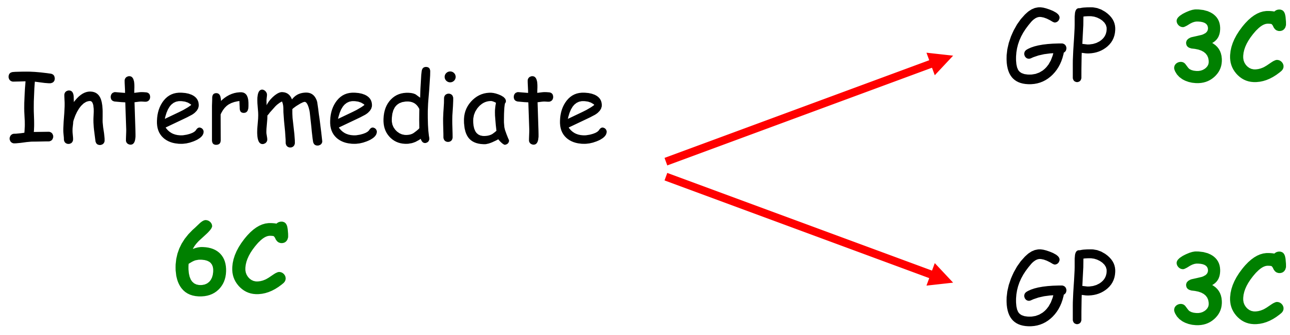
- As it involves compounds containing 3 carbon atoms it is also referred to as the **C3 pathway**.

**$CO_2$** diffuses into the chloroplast where it combines with the 5C sugar **ribulose bisphosphate** (RuBP).

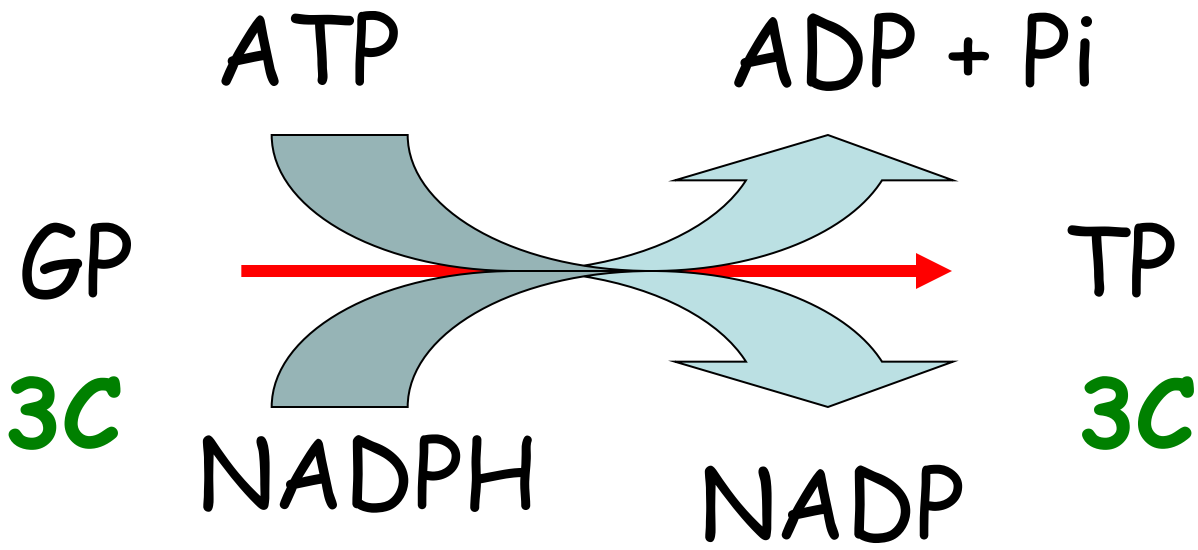
The reaction is catalysed by **RuBP carboxylase** (rubisco) and forms a 6C intermediate product.

$$\underset{\textbf{5C}}{\text{RuBP}} + \underset{\textbf{1C}}{CO_2} \longrightarrow \underset{\textbf{6C}}{\text{Intermediate}}$$

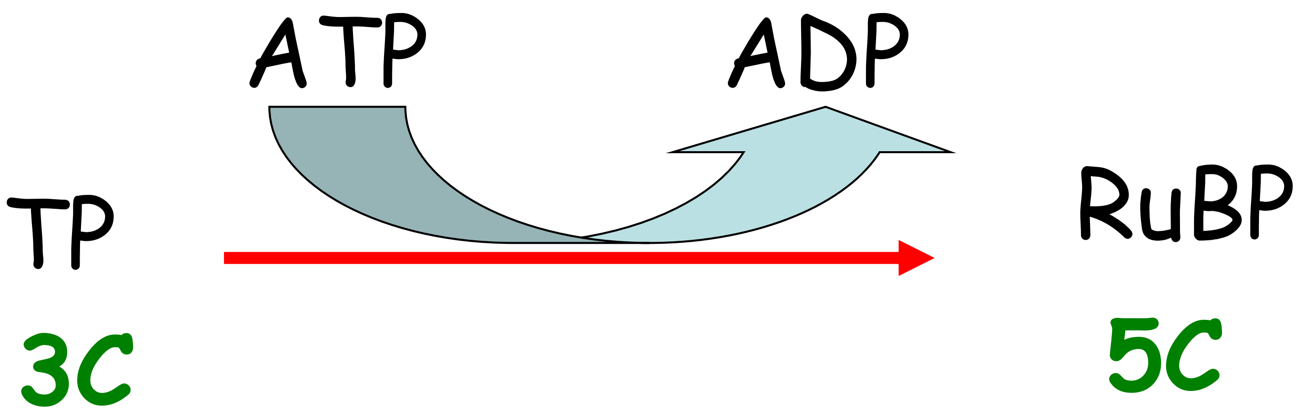
This 6C compound is unstable and immediately breaks down to form **two 3C molecules of glycerate phosphate (GP).**



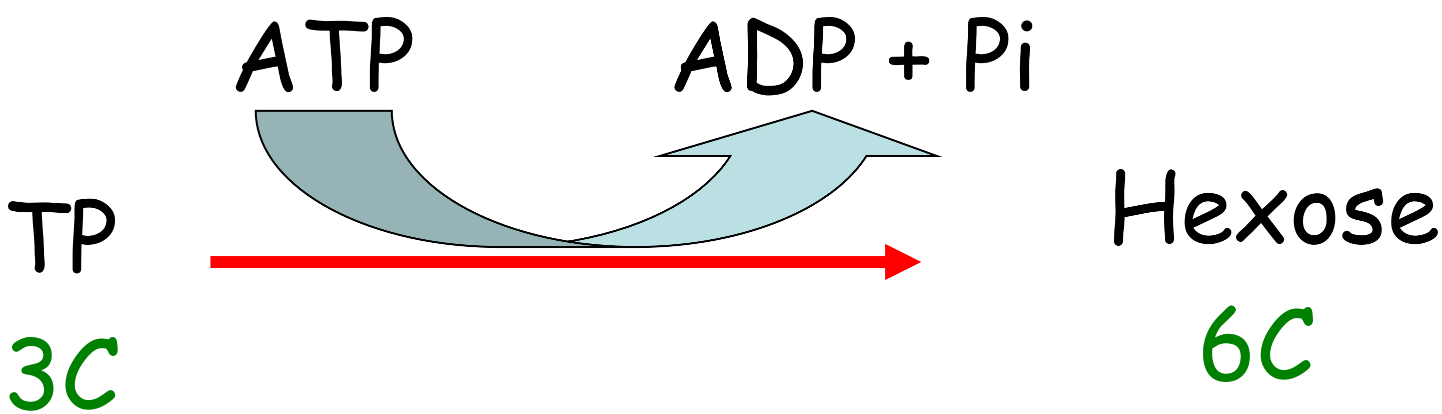
Each GP molecule is **reduced** by **NADPH** (from LDR) forming two molecules **triose phosphate** (TP). This reaction uses energy from ATP.

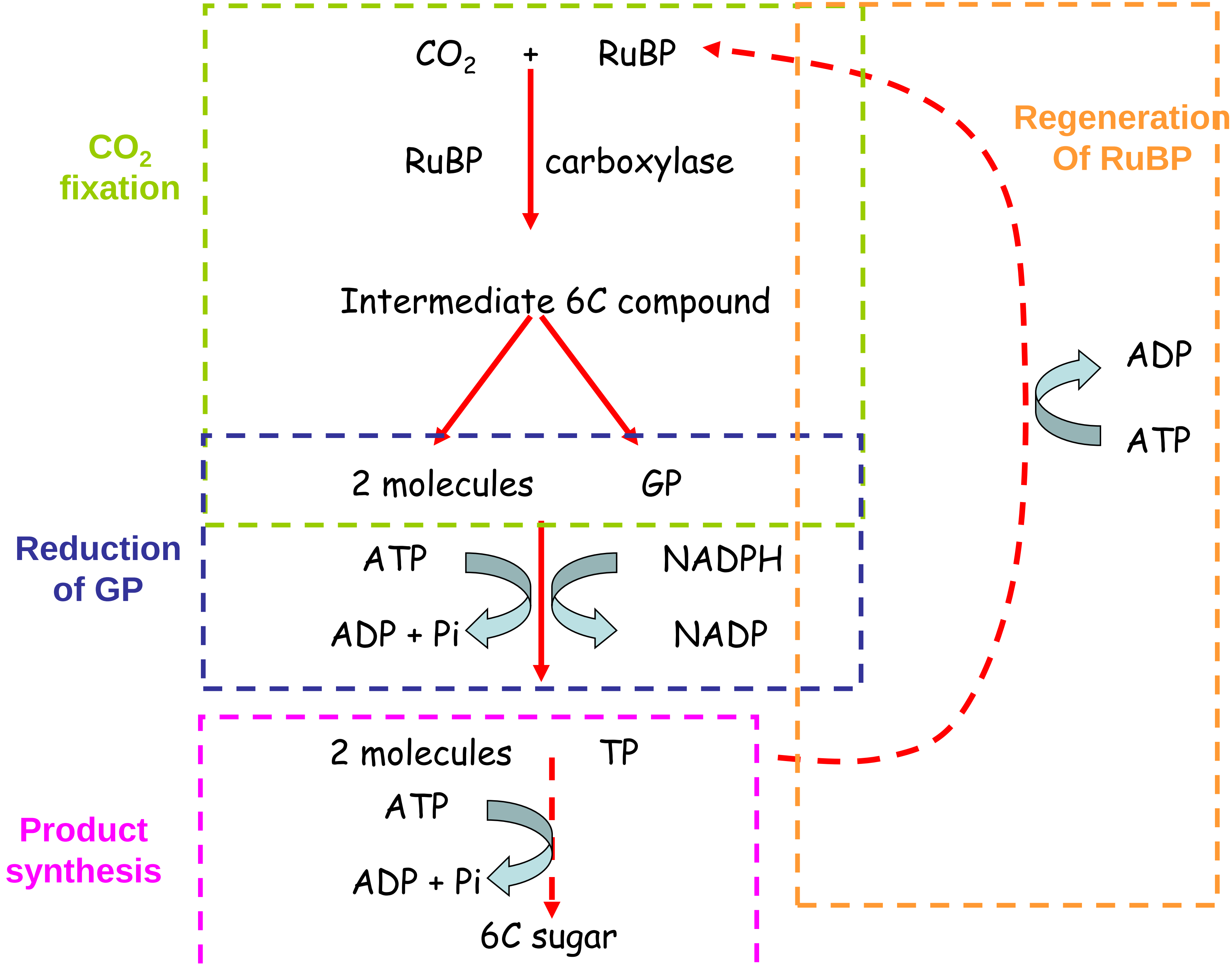


5 out of every 6 molecules of TP are used in the recycling of RuBP which allows the cycle to continue. ATP provides the energy and phosphate needed for this reaction.

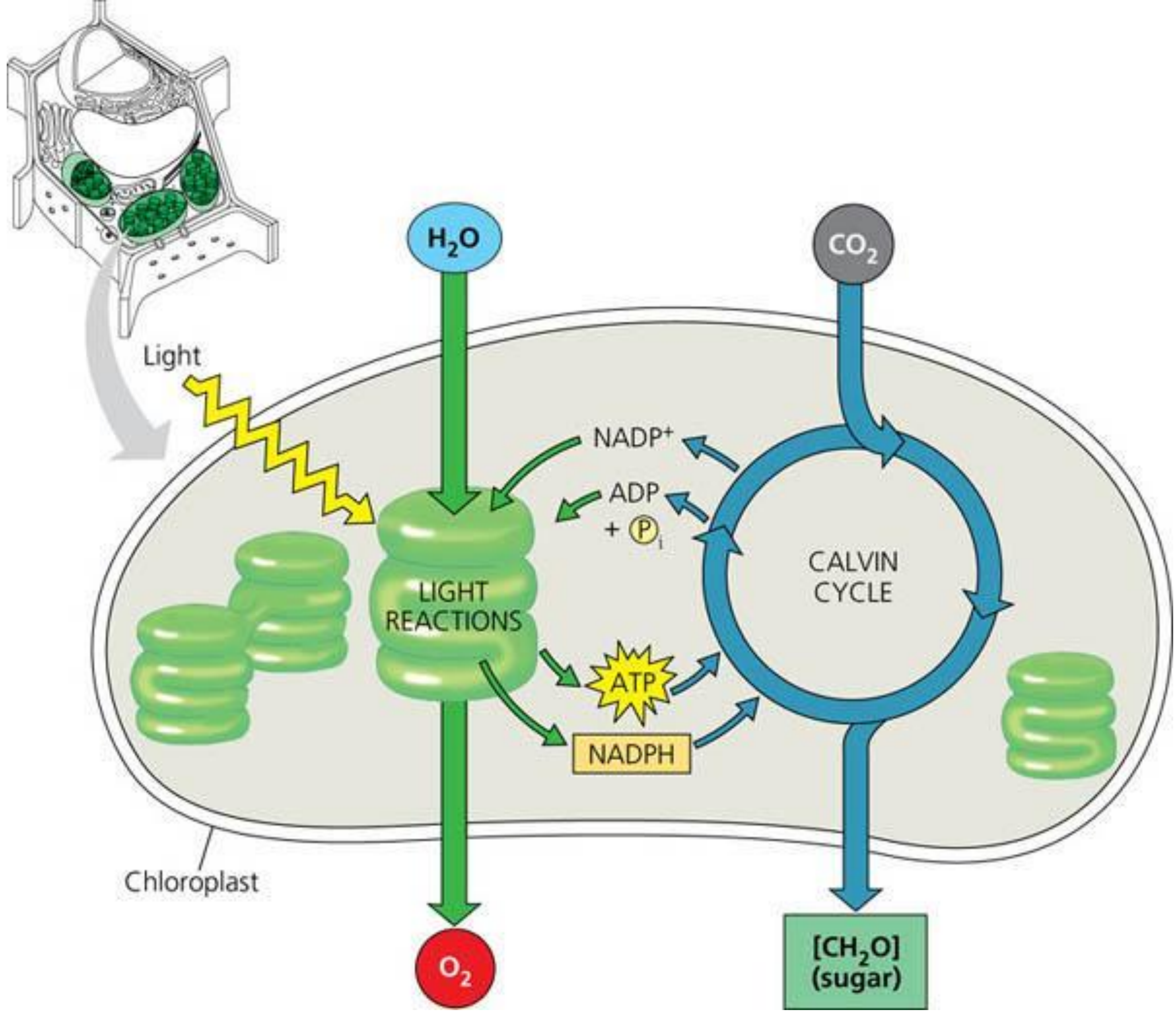


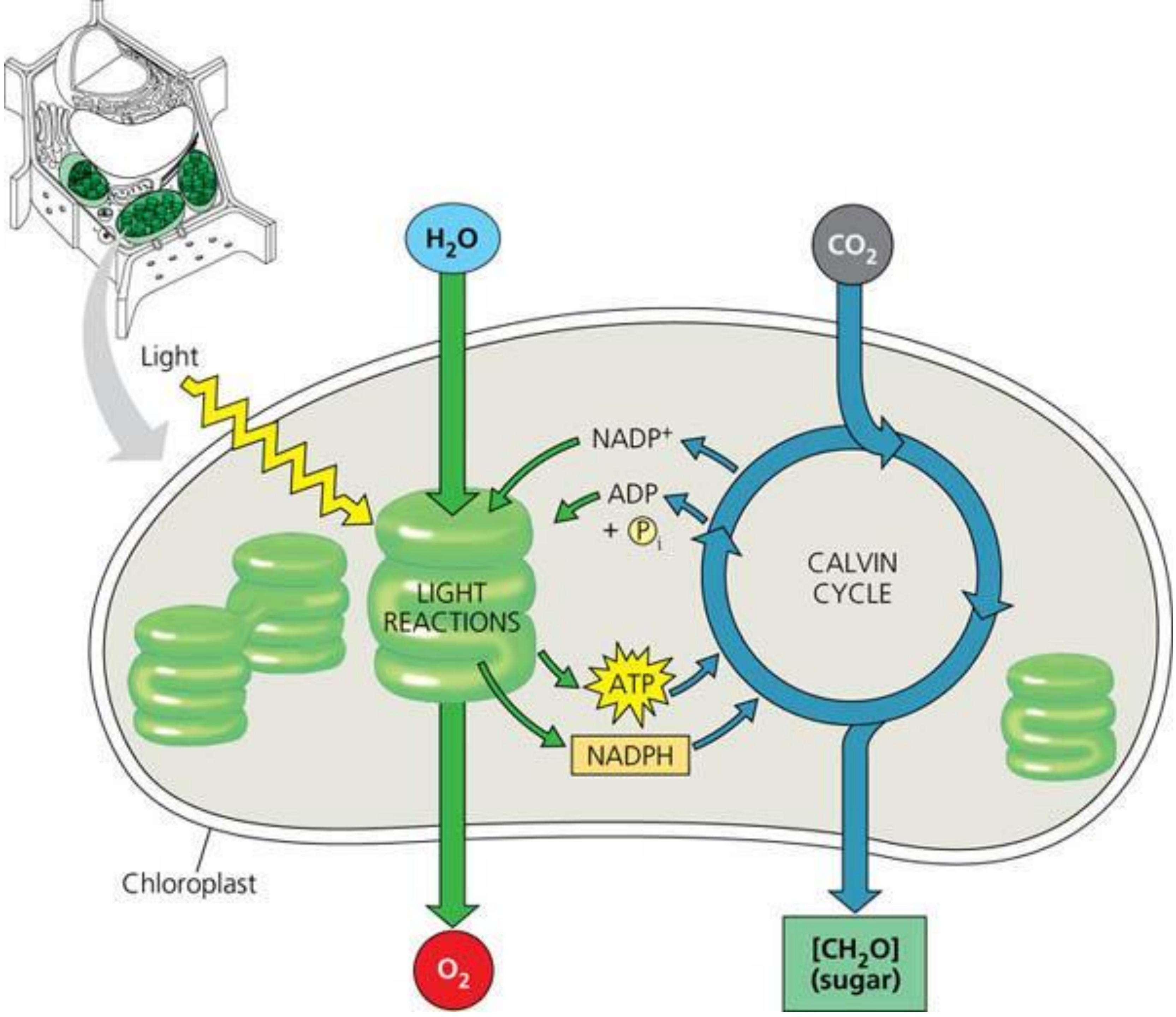
The remaining **one sixth** of the TP is converted through a series of reactions to **hexose sugars**, glucose using ATP. This is the product of the reaction. Glucose is converted to other carbohydrates e.g. sucrose, starch, cellulose, glycerol, fatty acids and amino acids (with addition of nitrate).



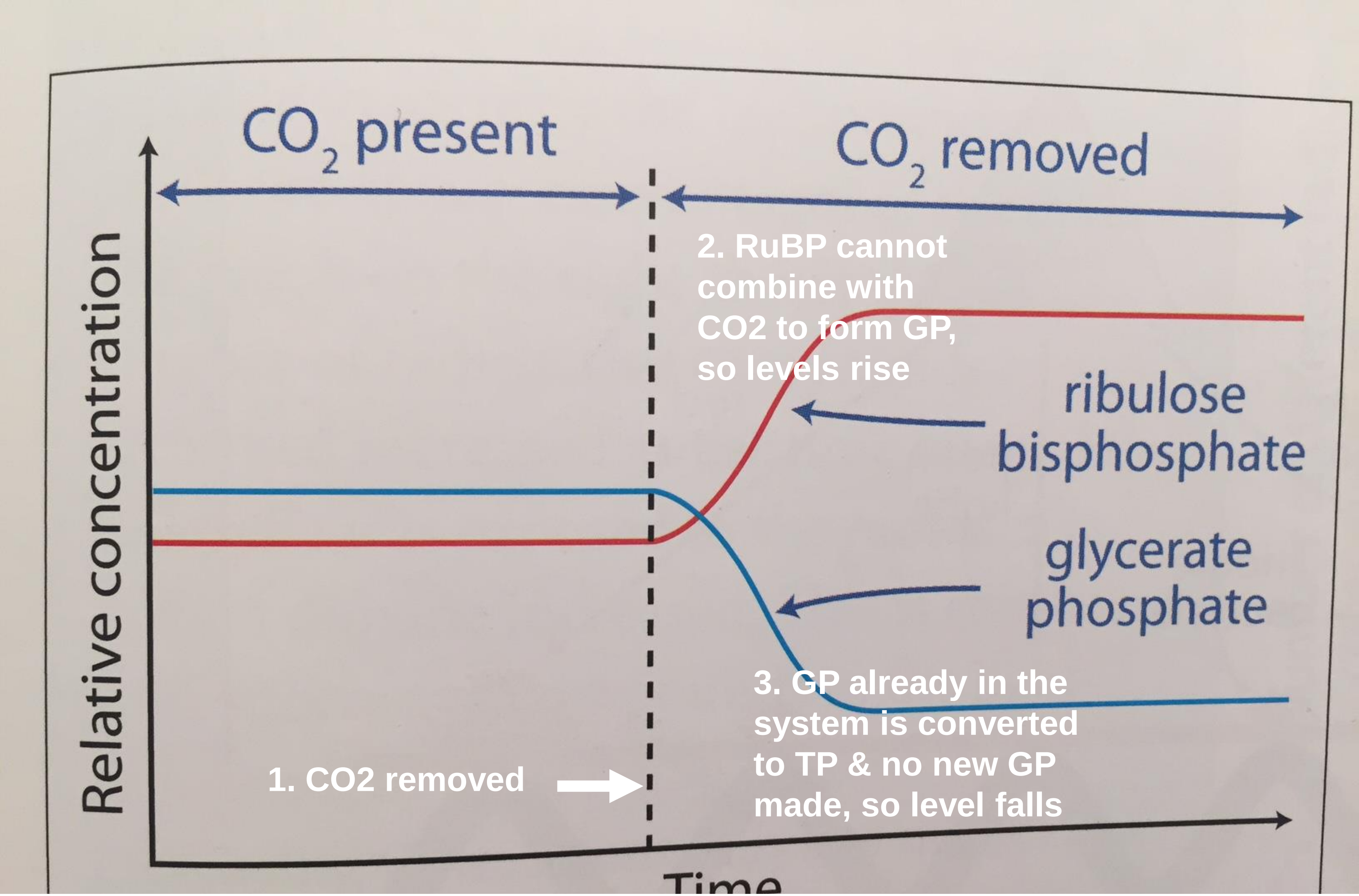

CO2 + RuBP
RuBP carboxylase
Intermediate 6C compound
2 molecules GP
ATP
ADP + Pi
NADPH
NADP
2 molecules TP
ATP
ADP + Pi
6C sugar
ADP
ATP
CO2 fixation
Reduction of GP
Product synthesis
Regeneration Of RuBP

- 2 molecules of TP are needed to make one hexose sugar.
- 6 cycles of the LI reactions only creates one molecule of ATP for hexose production
- Therefore 12 cycles are needed to produce 2 molecules to make one hexose sugar.


H2O
CO2
Light
NADP+
ADP
+ Pi
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
Chloroplast
O2
[CH2O] (sugar)

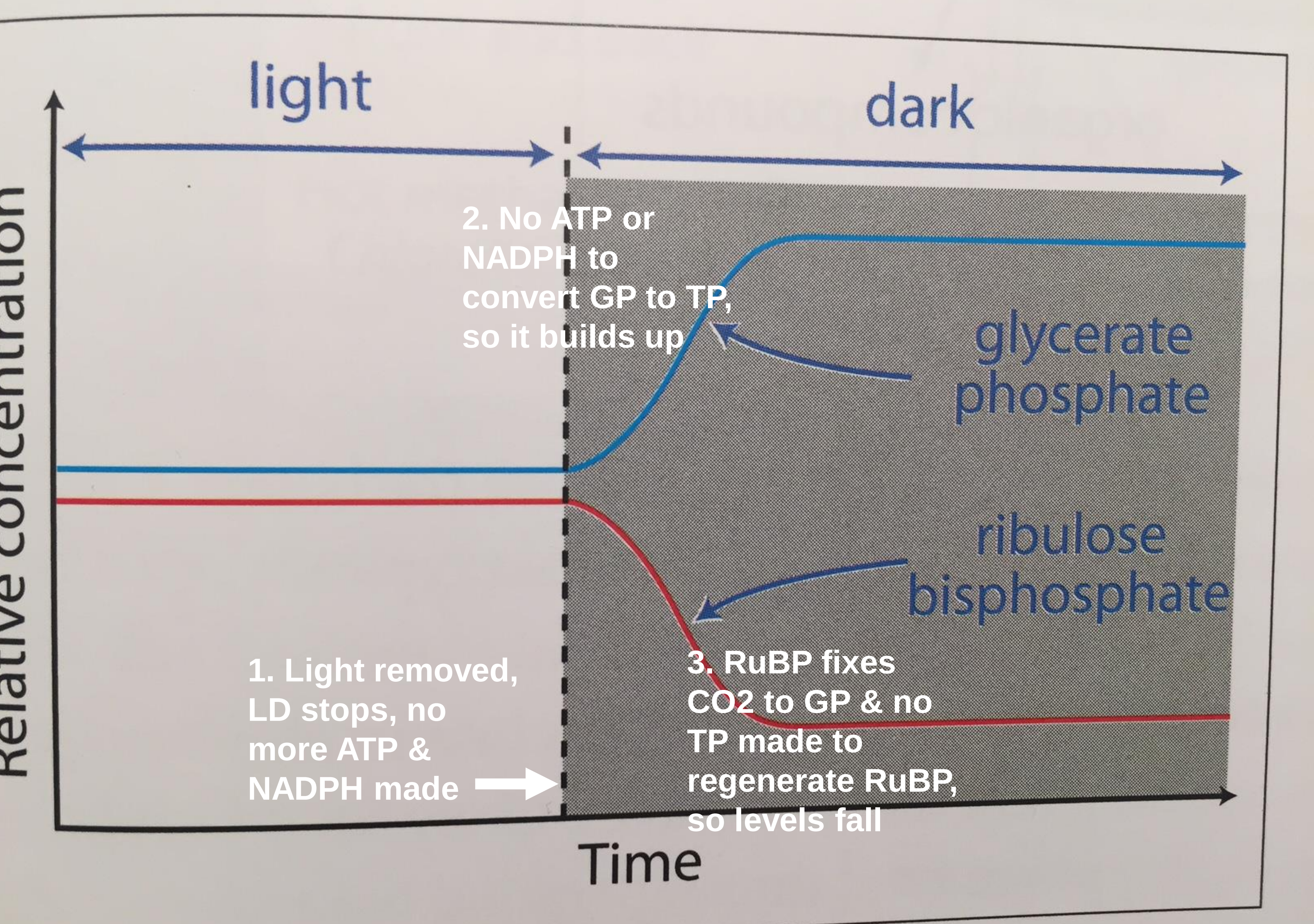


$H_2O$
$CO_2$
Light
NADP+
ADP
+ Pi
LIGHT
REACTIONS
CALVIN
CYCLE
ATP
NADPH
Chloroplast
$O_2$
$[CH_2O]$
(sugar)




The effect of the presence and absence of $CO_2$ on the concentrations of GP and RuBP

# The effect of light & darkness on the concentrations of GP and RuBP



- http://www.science.smith.edu/departments/Biology/Bio231/calvin.html

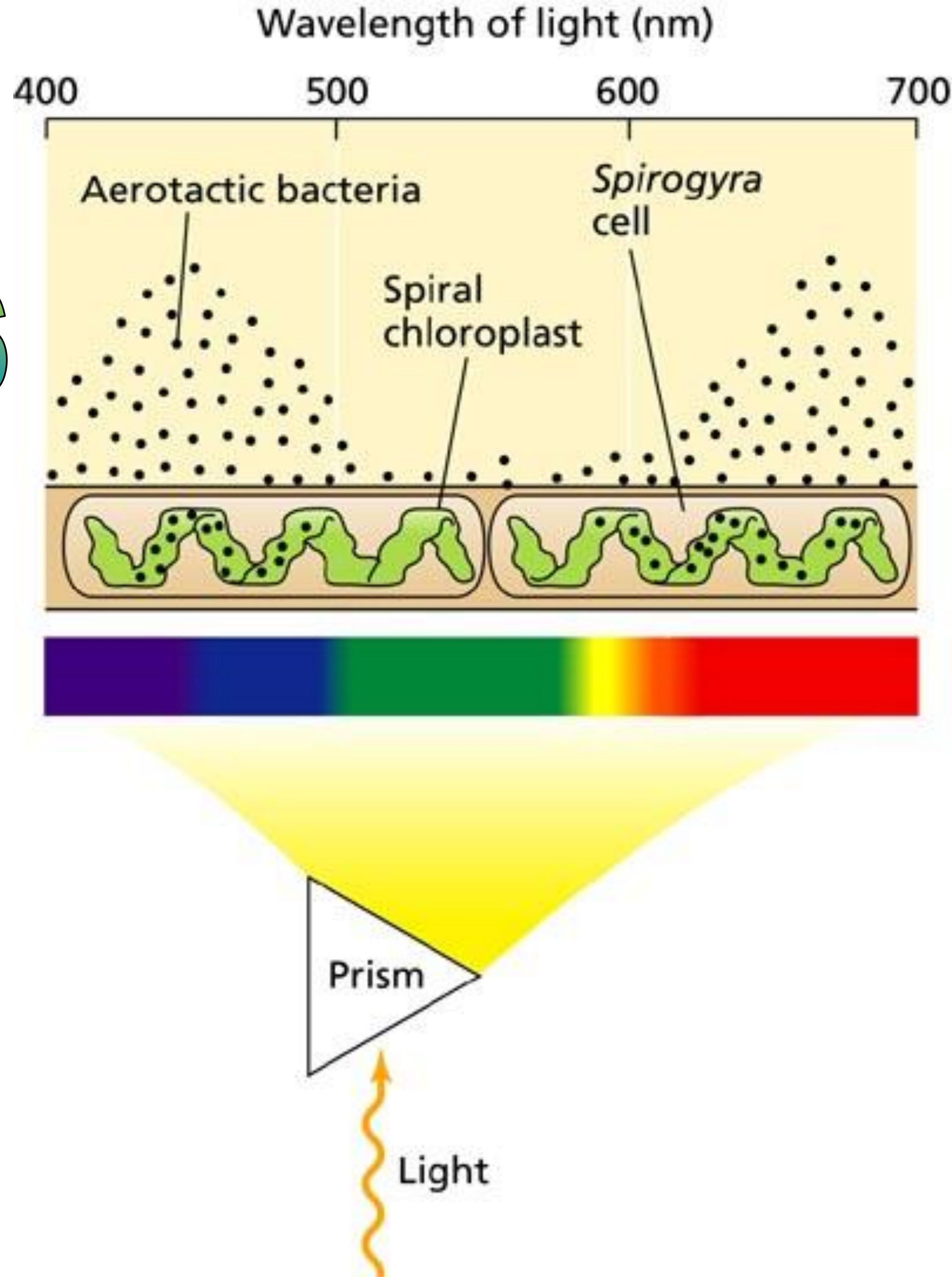
- http://www.yteach.co.uk/page.php/resources/view_all?id=Calvin_cycle_photolysis_of_water_Rubisco_photosystems_membranes_thylakoid_grana_stroma_ribosomes_photophosphorylation_ATP_NADPH_ADP_electrons_molecules_reduction_regeneration_of_RuBP_t_page_10&from=search

- http://highered.mcgraw-hill.com/sites/0070960526/student_view0/chapter5/animation_quiz_1.html

# case studies

Engelmann
& *Spirogyra*
1880s

Showed that most PS occurs in blue & red light. Here most oxygen is released and bacteria gather to use it for respiration.



# case studies

Calvin
& *Chlorella*

Determined the intermediate products of the LI reaction, using radioactively labelled $CO_2$.


# external factors affecting rate of PS

The rate of PS is measured by

**Carbon dioxide uptake**

or

**Oxygen production**

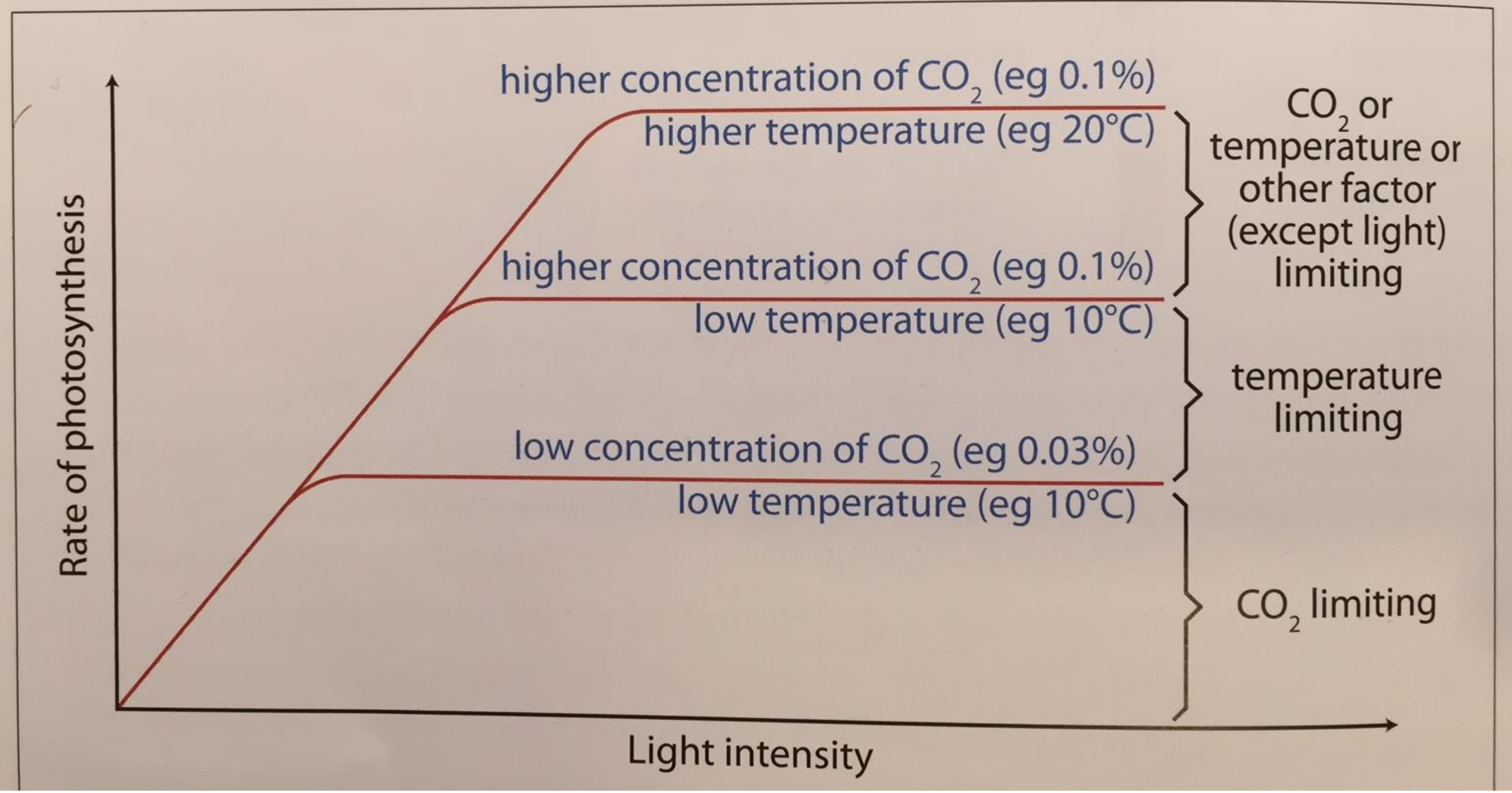
Light intensity, $CO_2$ concentration and temperature are the main factors that affect the rate of PS.

The actual rate is determined by which ever factor is least favourable, ie is the limiting factor

# REMEMBER:

If a factor is limiting, increasing it will increase the rate of PS.

Increasing the rate of other non-limiting factors will not affect the rate of PS.




All 3 graphs show that at low **Light intensity** the rate of PS is low and light is the limiting factor,
IRRESPECTIVE OF THE CO2 CONC OR TEMP.
If LI is limiting , not enough ATP and reduced NADP are produced during the light dependent stage of PS, limiting the LI reaction and therefore carbohydrate production.

Atmospheric **$CO_2$** concentration of 0.04% is below the optimal level for PS in most plants, therefore increasing levels to an optimum of 0.1% leads to higher rates of PS.

If $CO_2$ levels are increased, there is more available for carboxylation of RuBP in the LI stage, more GP is made and therefore more carbohydrate.

**Temperature** can limit the rate of PS if LI and $CO_2$ levels are not limiting.

If temperature is increased, up to an optimum of 25$^{o}$C, the enzyme catalysed reactions of the LI stage of PS occur at a faster rate.

# **REMEMBER**:

If a factor is limiting, increasing it will increase the rate of PS.

Increasing the rate of other non-limiting factors will not affect the rate of PS.

# gross Photosynthesis

The total amount of carbon dioxide fixed as carbohydrate

# net Photosynthesis

The difference between gross PS and carbohydrate used in respiration

## NP = GP - R

- Gross and net PS can be considered in terms of the CO2 consumed or the O2 produced or the organic content of the plant (e.g. mass of starch).

# Compensation point

This is the light intensity at which the **rate of PS is equal to the rate of respiration**.

At this light intensity:

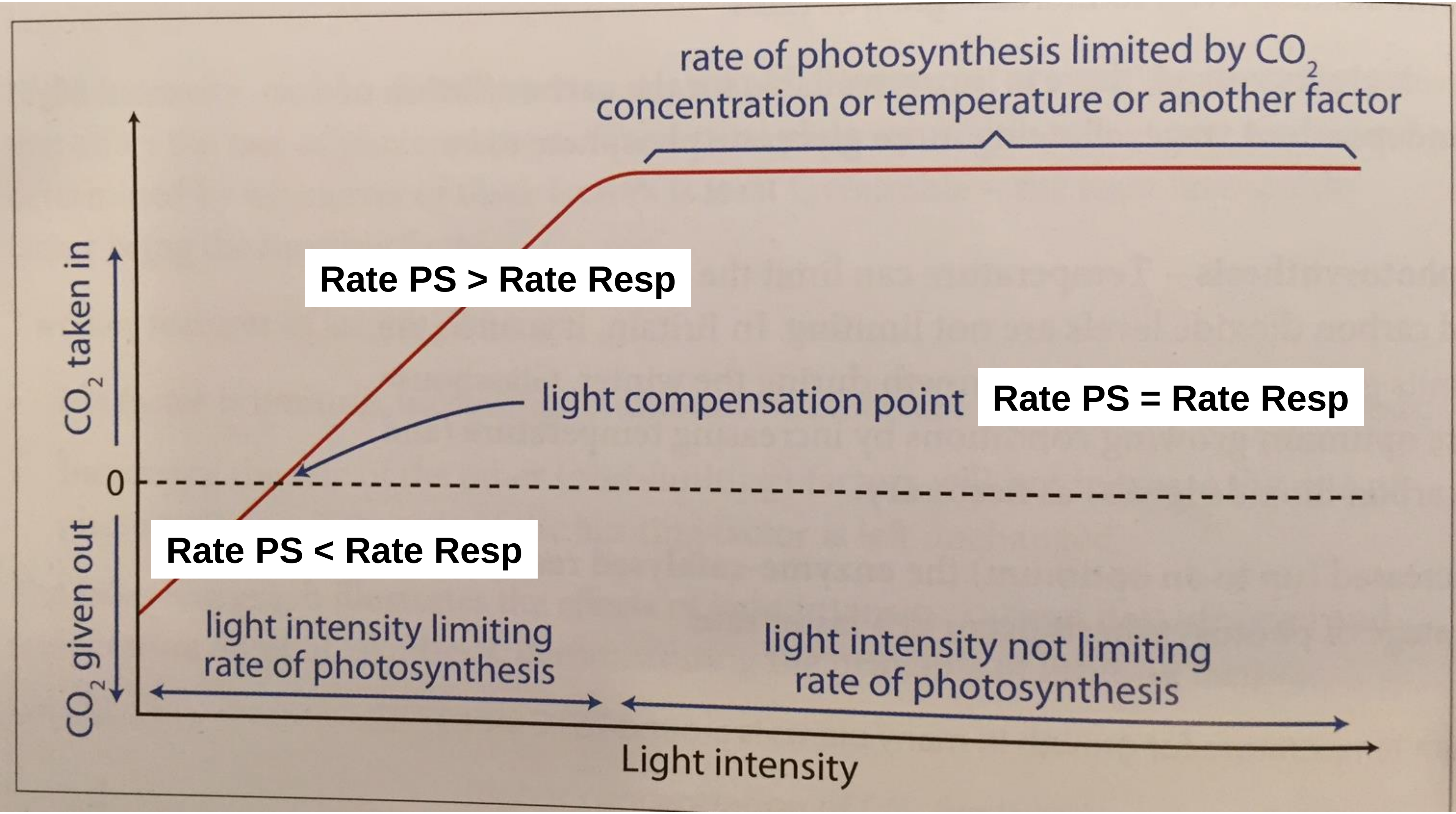
**$CO_2$** produced in **R**espiration = **$CO_2$** used in **PS**

**$O_2$** produced in **PS** = **$O_2$** used in **R**espiration

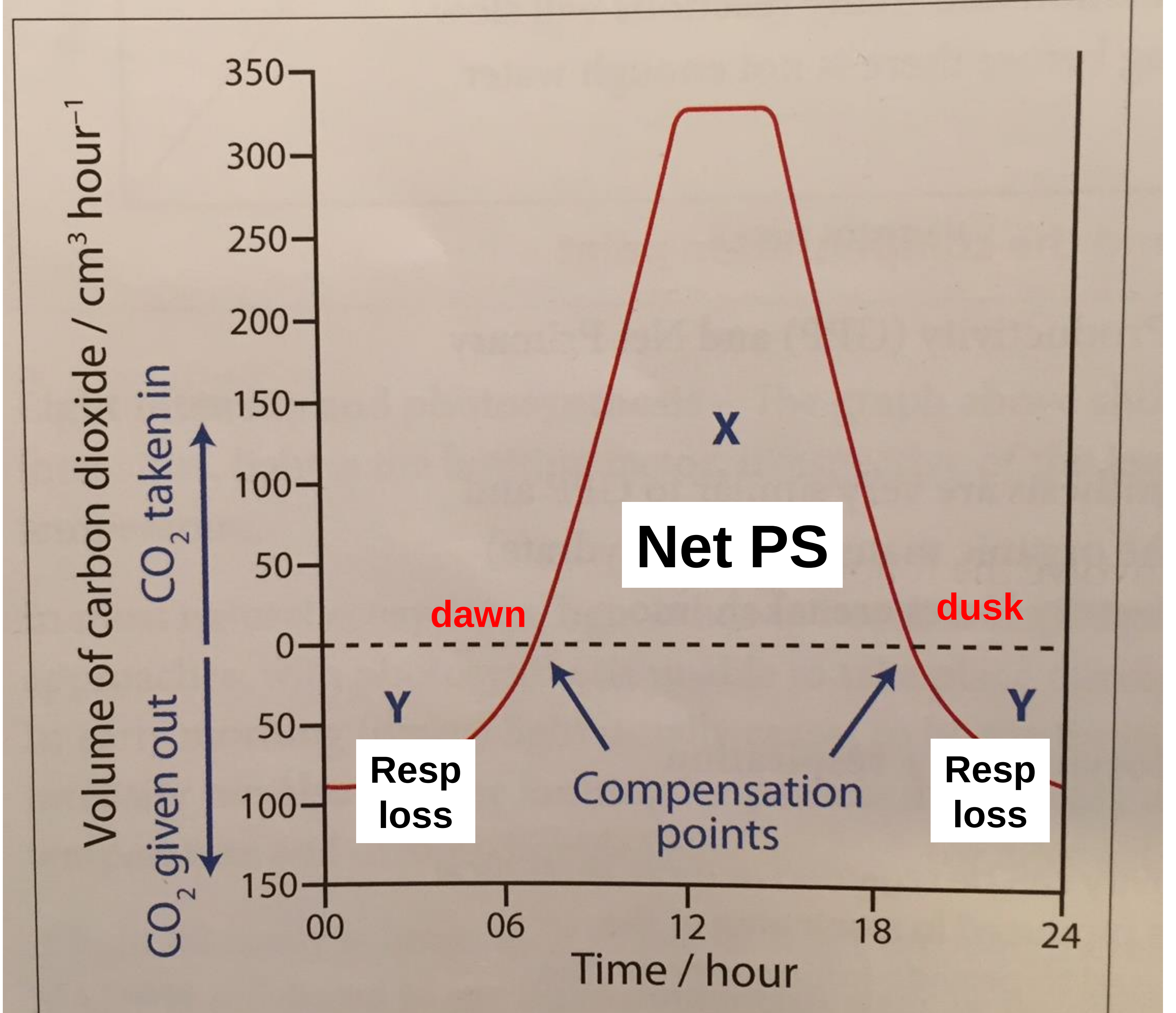
(NB: always compare like with like)

**Therefore there is no gas exchange with the external environment**

And glucose produced in PS = that used in Resp



rate of photosynthesis limited by $CO_2$ concentration or temperature or another factor
Rate PS > Rate Resp
light compensation point
Rate PS = Rate Resp
Rate PS < Rate Resp
$CO_2$ taken in
0
$CO_2$ given out
light intensity limiting rate of photosynthesis
light intensity not limiting rate of photosynthesis
Light intensity


Volume of carbon dioxide / cm³ hour⁻¹
CO2 taken in
CO2 given out
350
300
250
200
150
100
50
0
50
100
150
X
Net PS
dawn
dusk
Y
Y
Resp loss
Resp loss
Compensation points
00
06
12
18
24
Time / hour

# Experiments

- Pigment in chlorophyll
- Hill Reaction