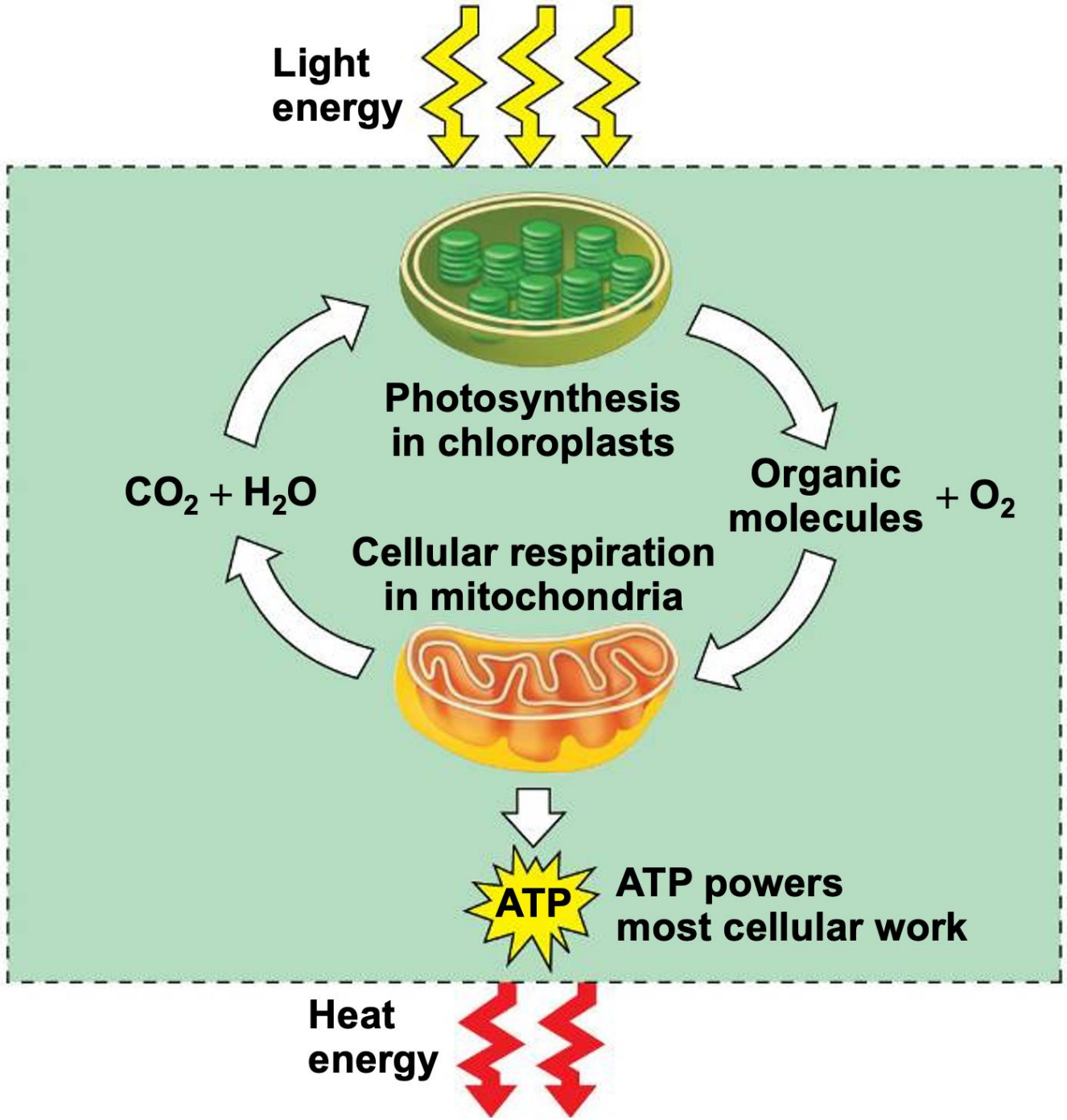
Carbohydrate Metabolism

Outline

Introduction

Respiration

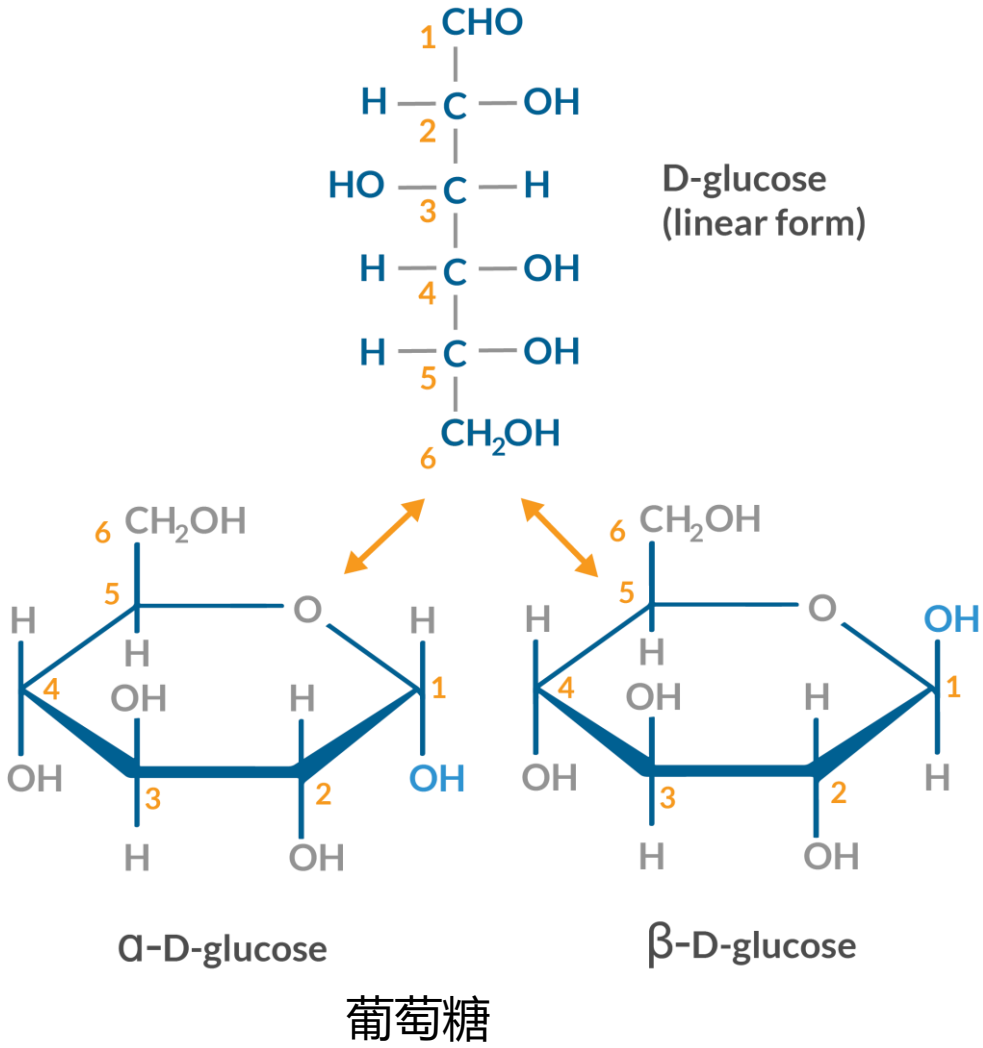
Photosynthesis



Introduction

Definition

Carbohydrate metabolism comprises the enzymatic pathways responsible for the synthesis, degradation, and interconversion of carbohydrate molecules, integrating energy production with biosynthetic demands.



Glucose play as the central metabolic substrate

Introduction

Both processes occur simultaneously but are tightly regulated

Feature	Catabolism	Anabolism
Function	Breakdown	Synthesis
Energy	Produces ATP	Consumes ATP
Example	Glycolysis	Glycogenesis
Redox	$NAD^+ \rightarrow NADH$	NADPH used

Introduction

Biological Significance

Carbohydrates are both fuel and building blocks

1. Energy Production

Glucose to ATP via:

- Glycolysis (cytosol)
- Cellular respiration (mitochondria)

Can function:

- Anaerobically (fast, low yield)
- Aerobically (slow, high yield)

2. Carbon Skeleton Supply

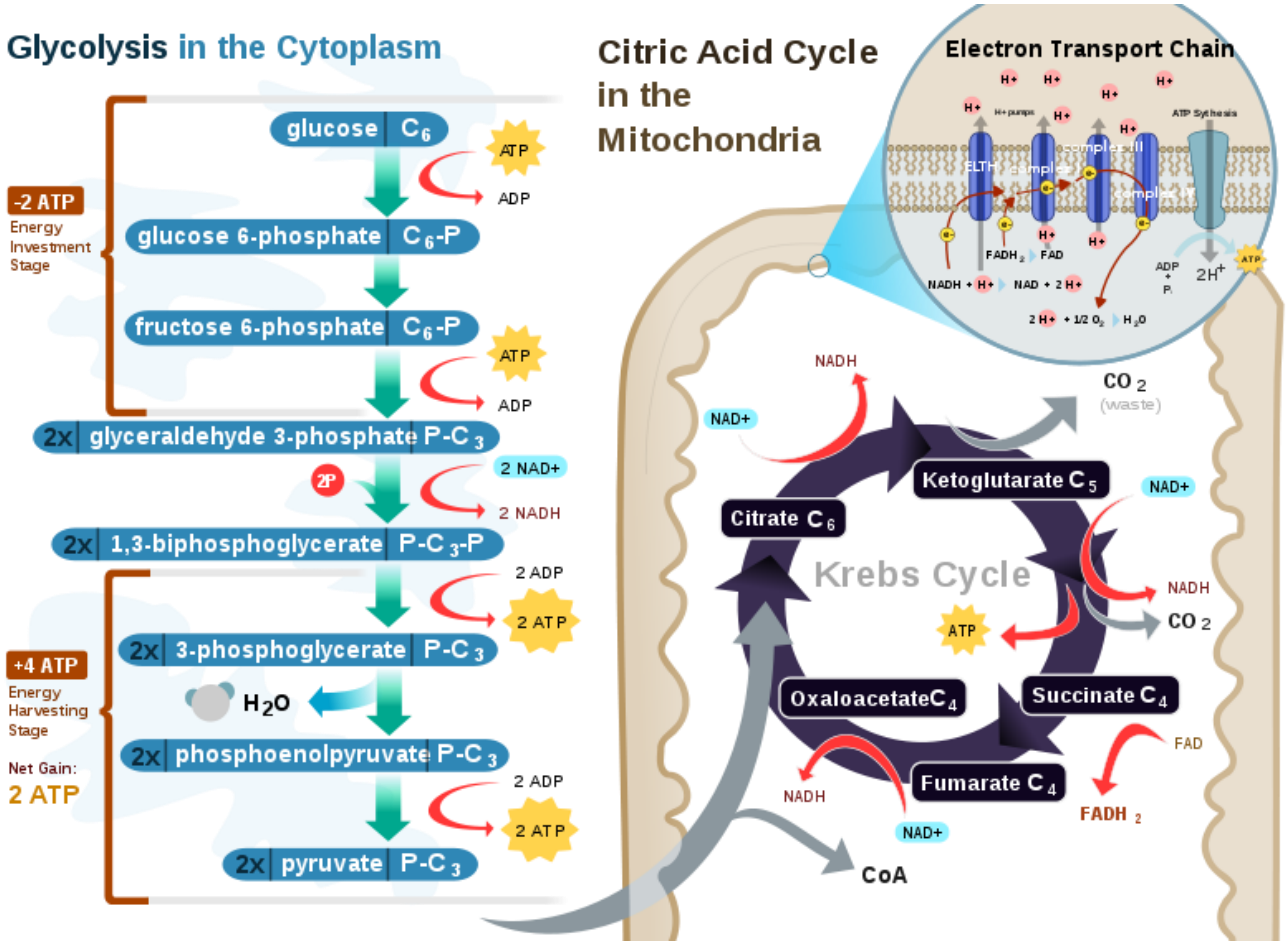
Provides intermediates for:

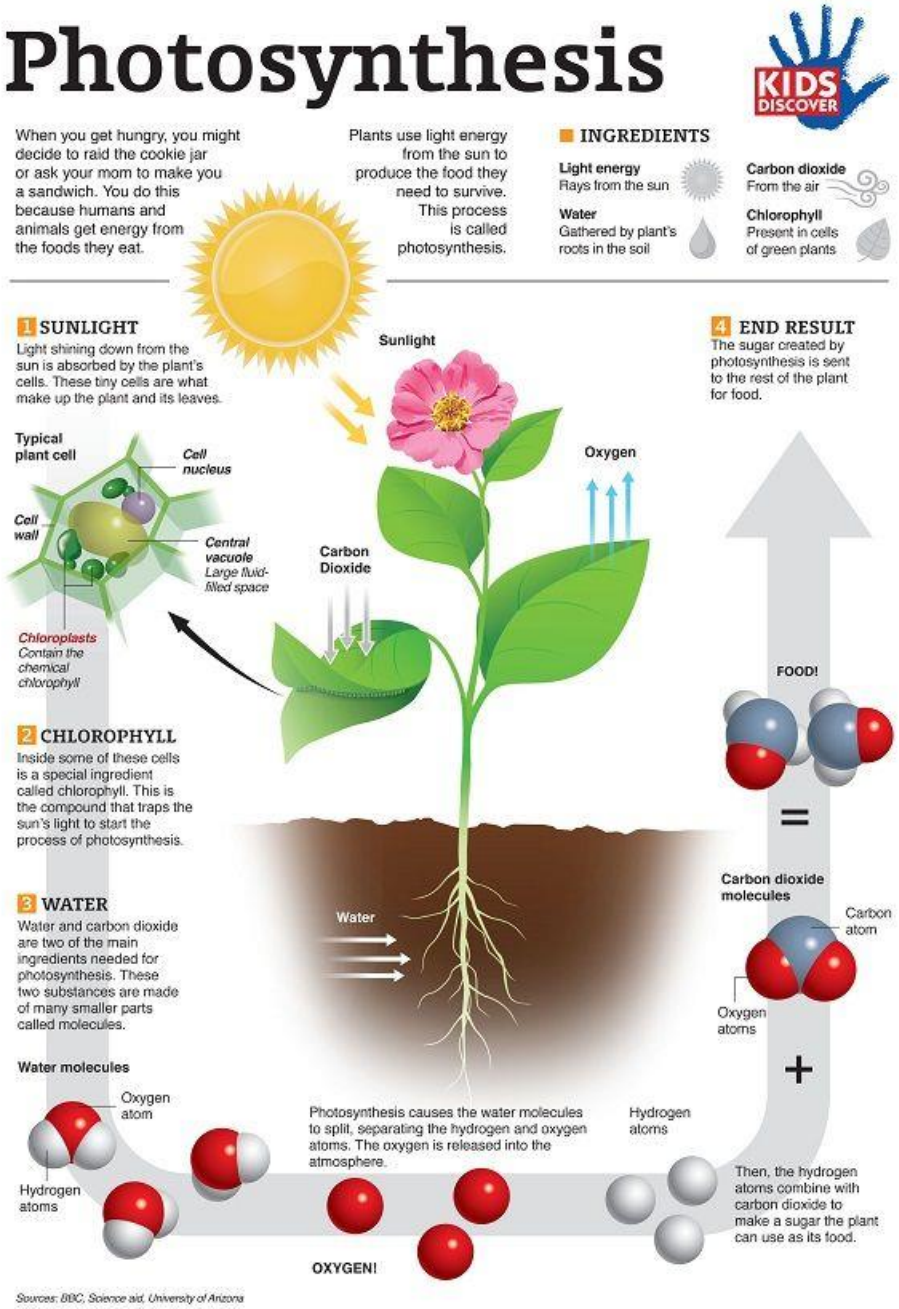
- Amino acids
- Lipids
- Nucleotides

Carbohydrates provide **carbon backbone donors**

Introduction

Respiration



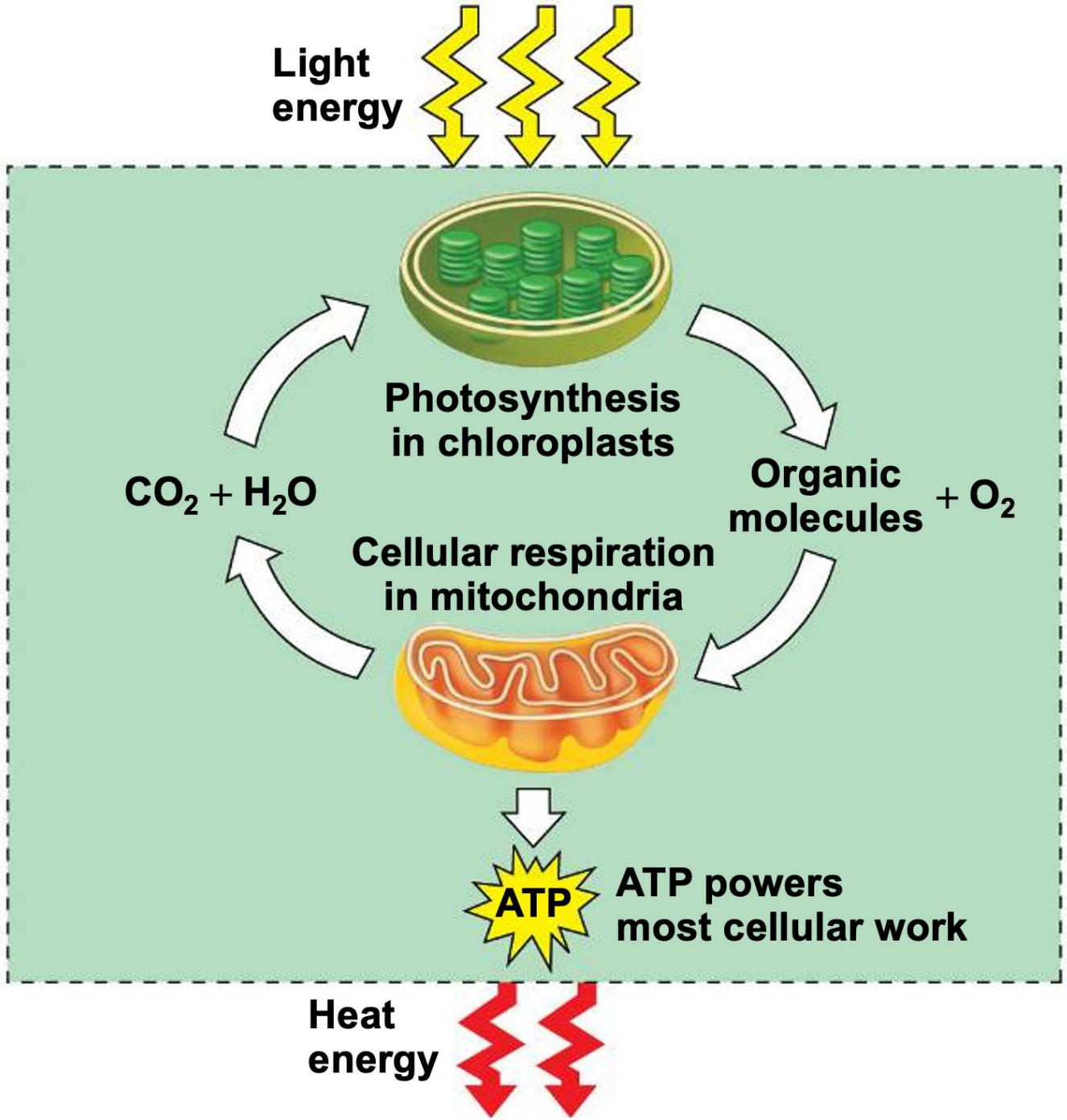


Outline

Introduction

Respiration

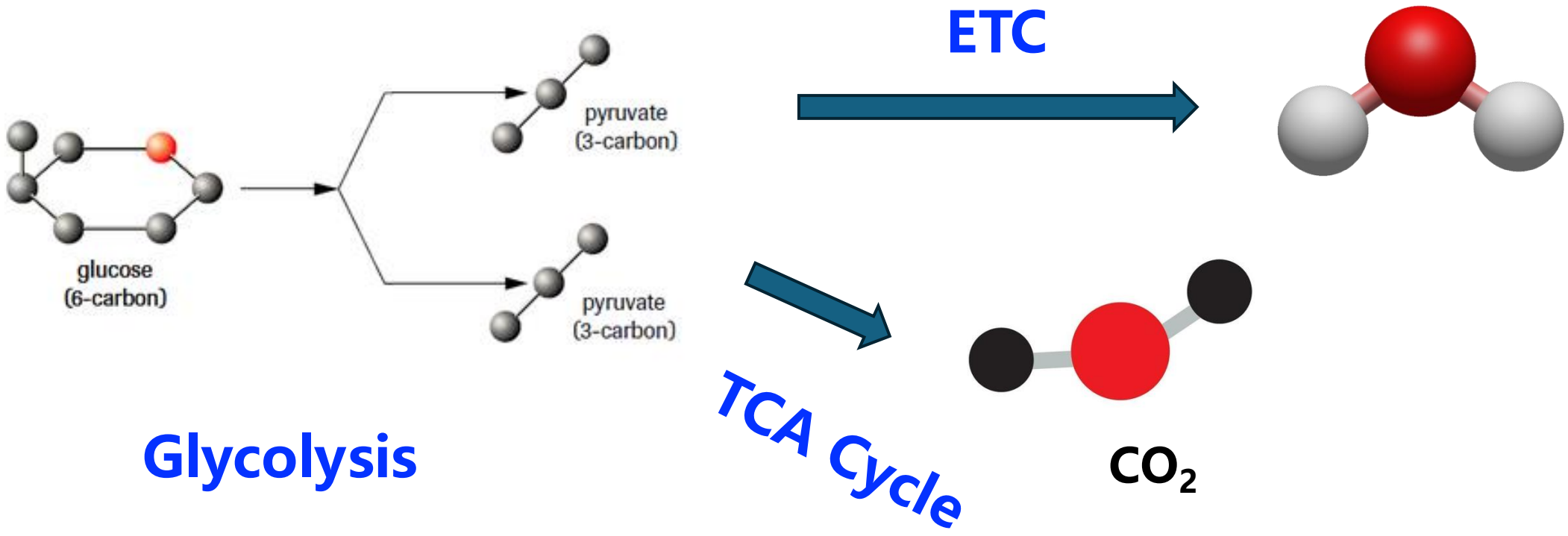
Photosynthesis



Respiration

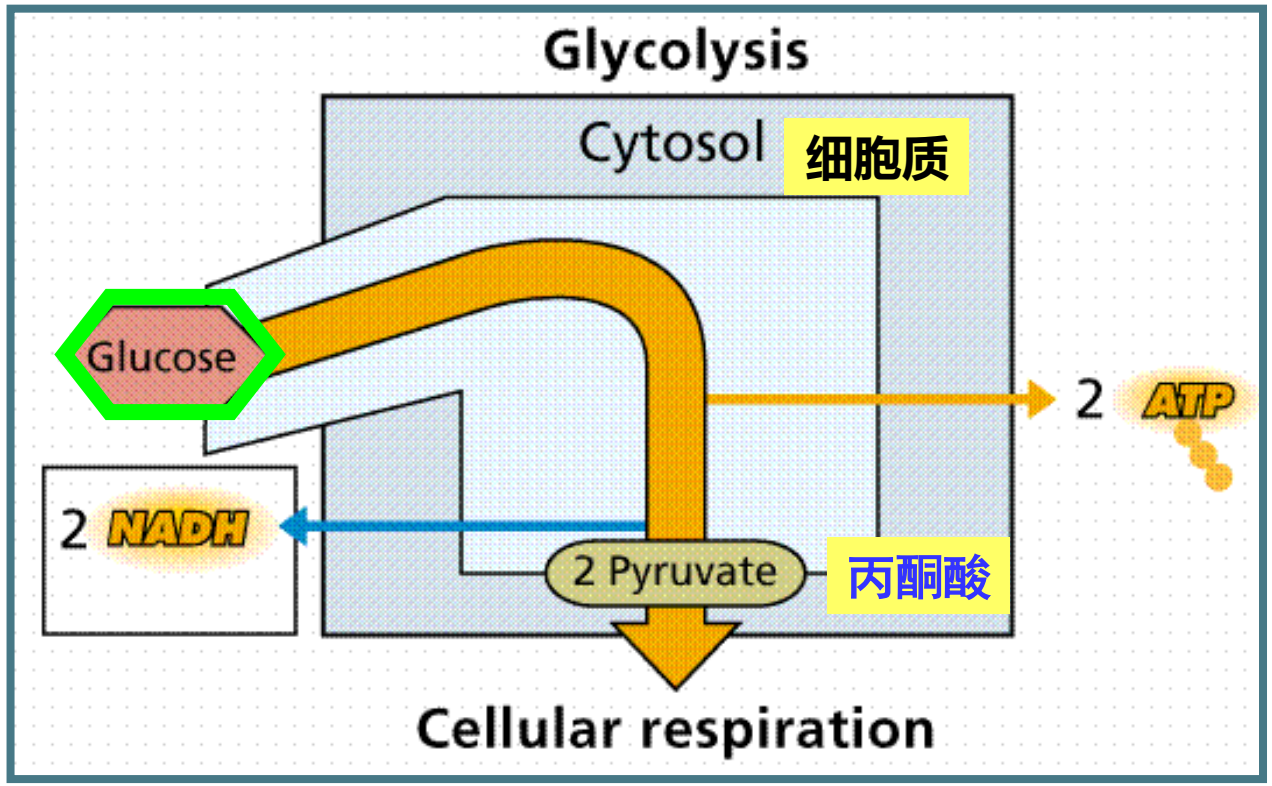
Concept

Respiration refers to the process in which organic molecules within living cells are gradually oxidized, under the catalysis of enzymes, resulting in the release of energy.



Glycolysis/糖酵解

Glycolysis is a cytosolic pathway in which glucose is converted to pyruvate, yielding ATP and NADH.



$$G \rightarrow 2Pyruvate + 2NADH + 2H^{+} + 2ATP$$

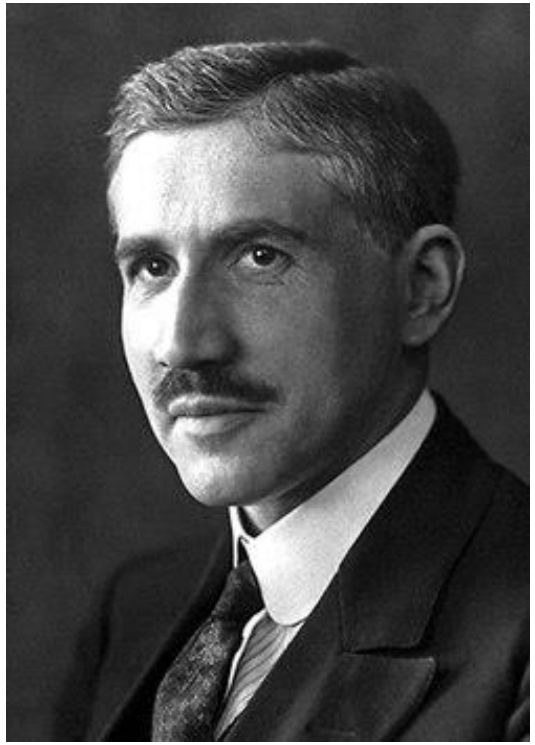
Glycolysis/糖酵解

It also known as the Embden–Meyerhof Pathway (EMP).



Eduard Buchner

First analyzed glucose by the non-cellular fermentation experiments during the 1890s.



In the 1920s Otto **Meyerhof** linked together some of the many individual pieces of glycolysis discovered by others



1930s, Gustav **Embden** proposed a detailed, step-by-step outline of glycolysis

Glycolysis/糖酵解

I. Chemical Reactions of the Glycolysis

II. Physiological Significance of the Glycolysis

III. Regulation of the Glycolysis

Chemical Reactions of the Glycolysis

Overview

Glycolysis consists of **10 enzymatic steps**

Occurs in the **cytosol**

Can be divided into **three phases**:

1. **Energy Investment (2 ATP consumed)**
2. **Cleavage (C6 breaks into 2 C3)**

} **Investment phase**

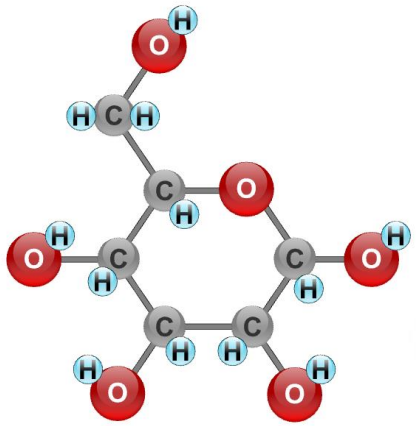
3. **Energy Payoff (4 ATP + 2 NADH produced)** **Payoff phase**

己糖的磷酸化（消耗2分子ATP）、**磷酸己糖的裂解**、**3-磷酸甘油醛生成丙酮酸**

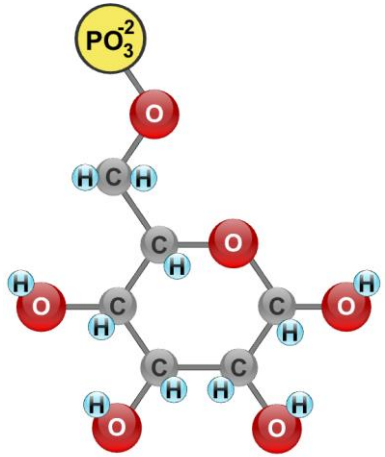
Chemical Reactions of the Glycolysis

Phase 1: Energy Investment

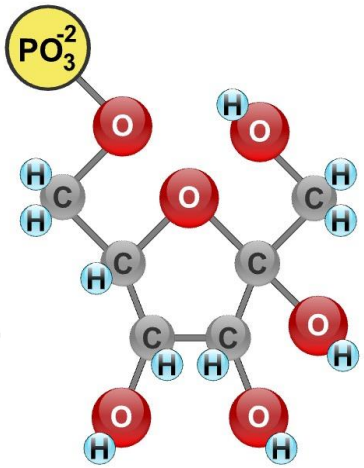




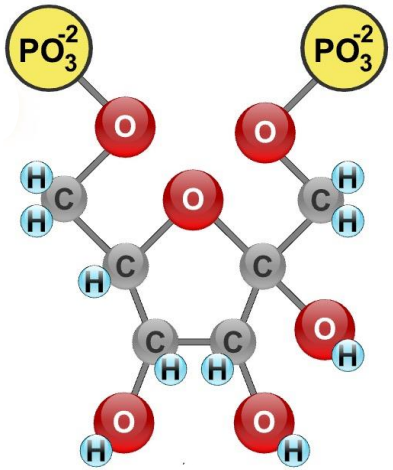
Glucose



Glucose 6-phosphate



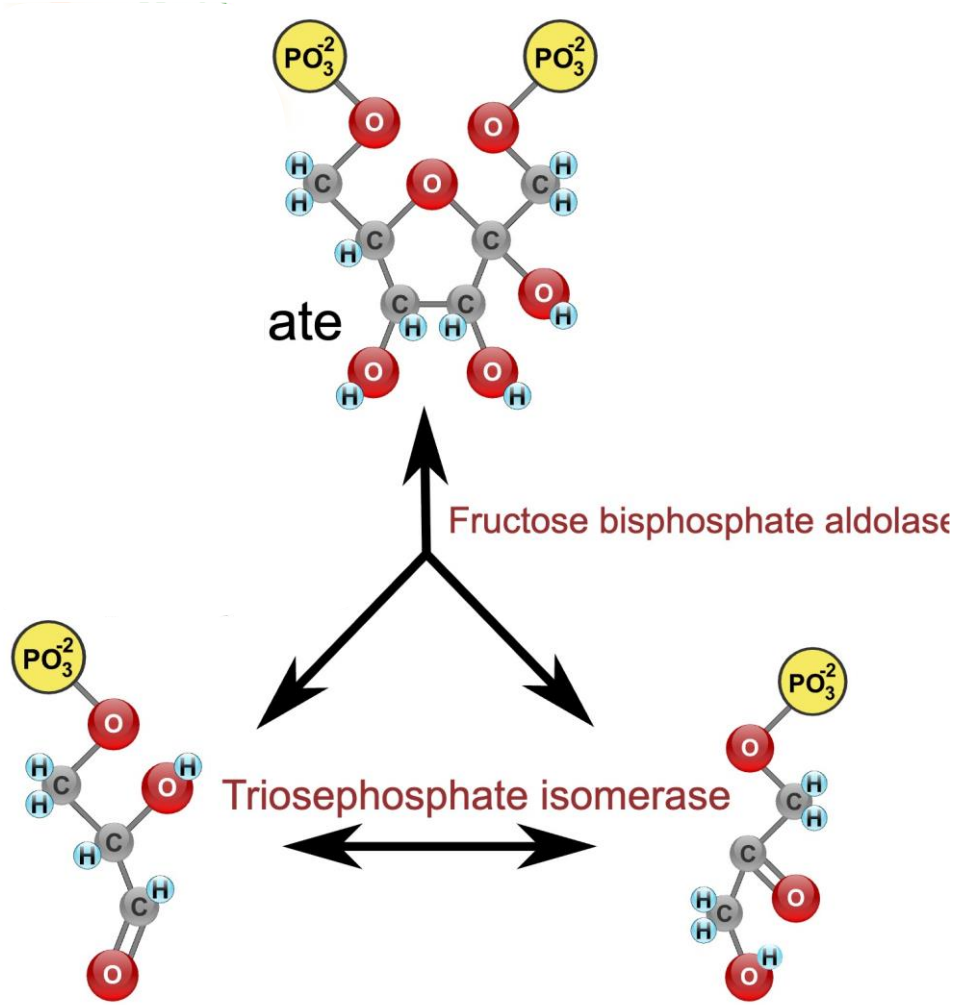
Fructose 6-biphosphate



Fructose 1,6-biphosphate

Chemical Reactions of the Glycolysis

Phase 2: Cleavage (C6 breaks into 2 C3)



1,6-二磷酸果糖 F-1,6-P

醛缩E

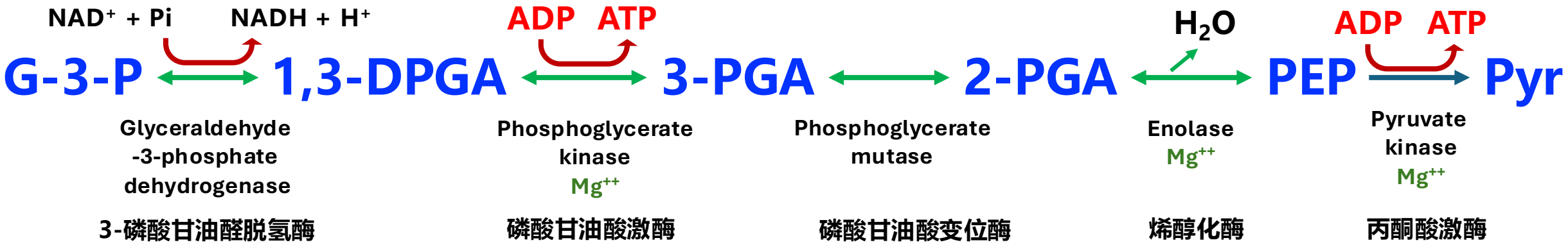
磷酸二羟丙酮 DHAP (96%)

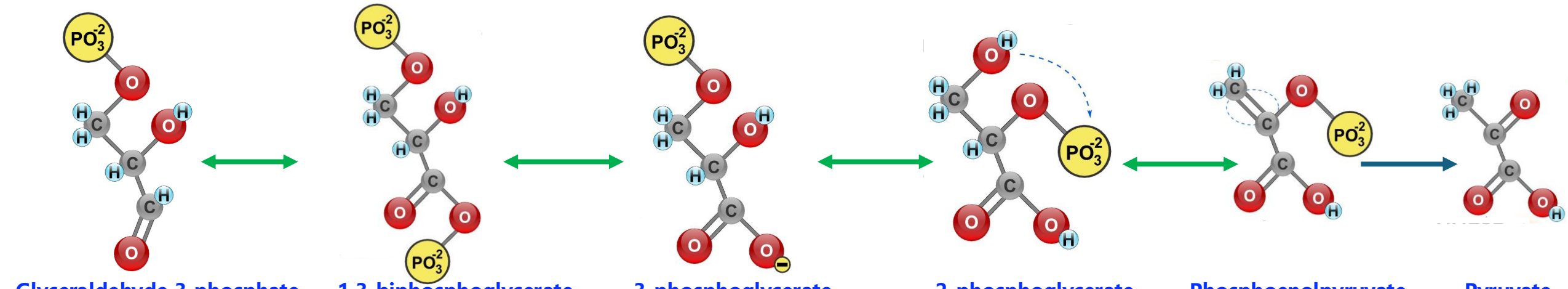
磷酸丙糖异构E

甘油醛3-磷酸 G-3-P (4%)

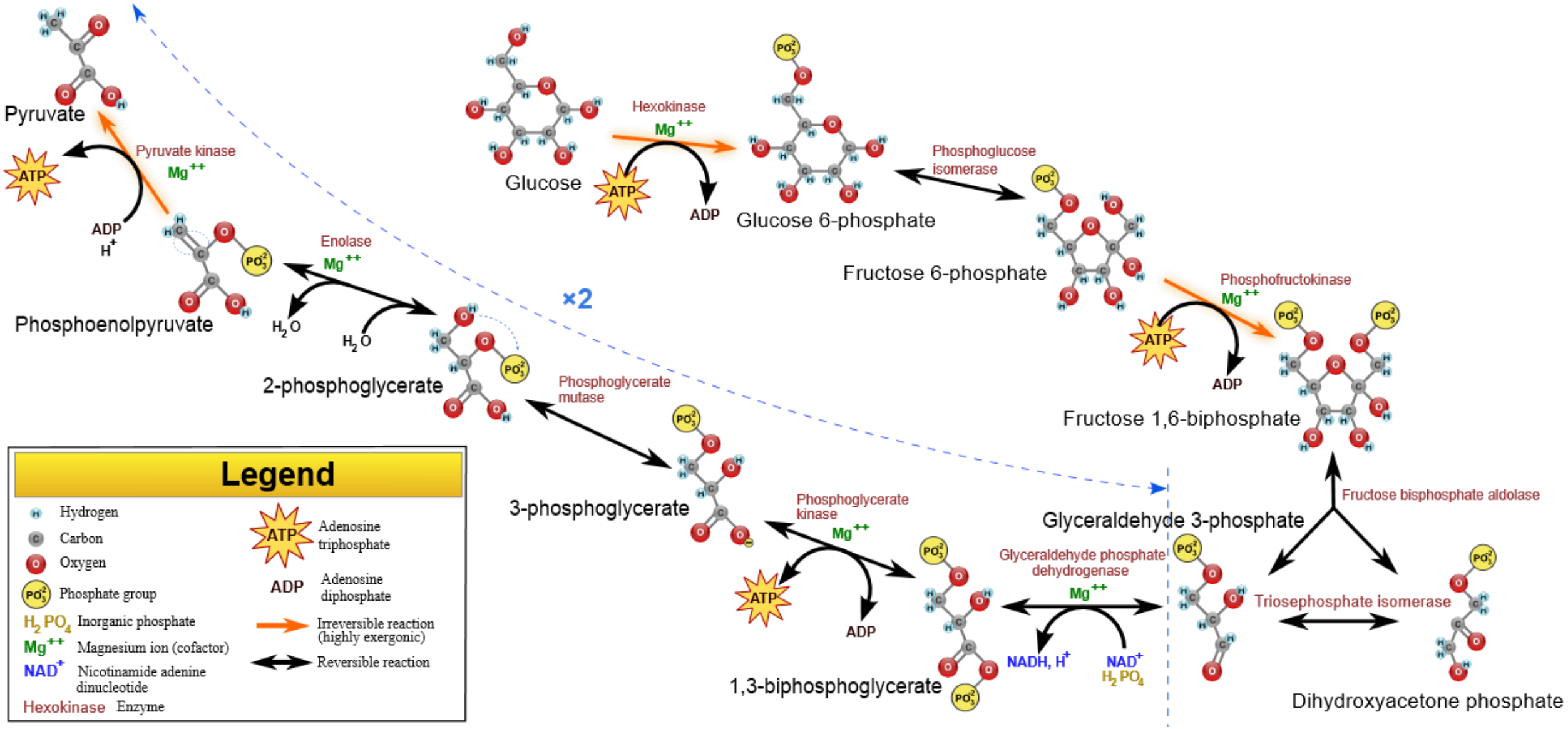
Chemical Reactions of the Glycolysis

Phase 3: Energy Payoff



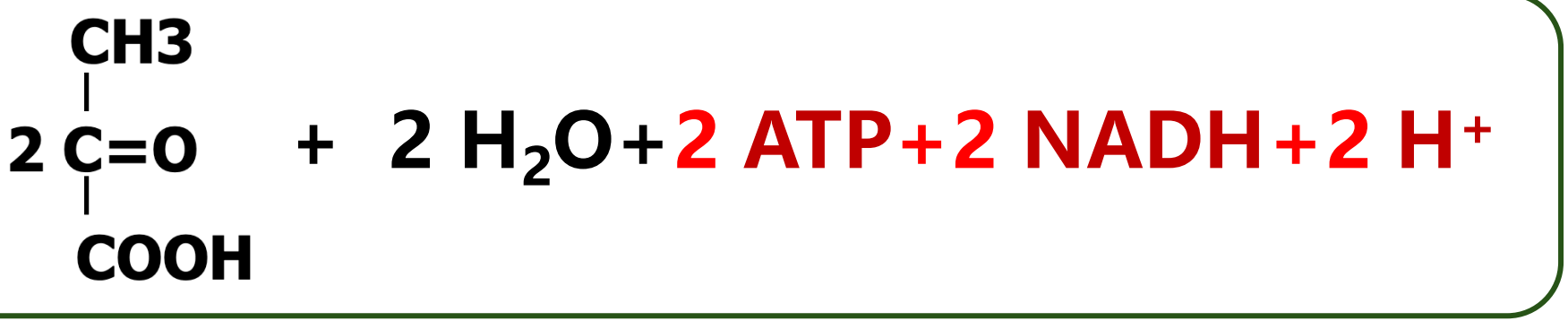


Overview of Glycolysis



Overview of Glycolysis

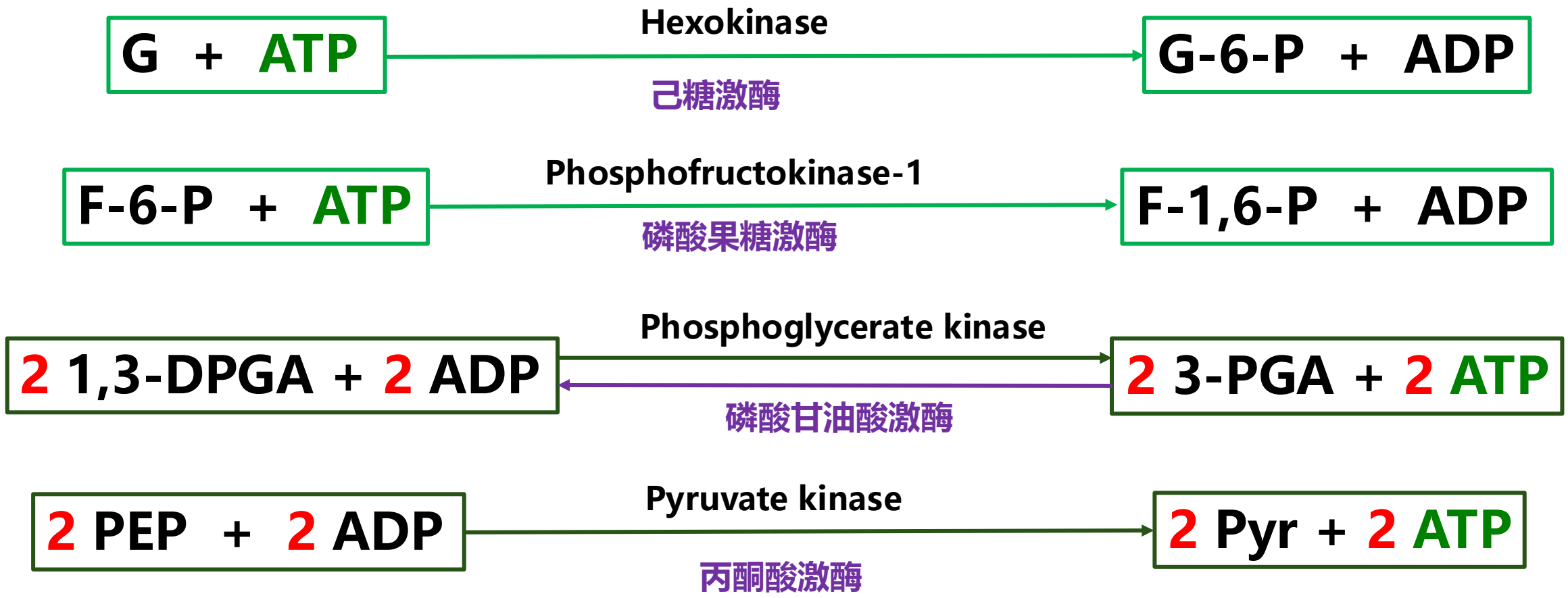
$$G + 2\,Pi + 2\,NAD^{+} + 2\,ADP$$



Key Features of Glycolysis

1. Phosphoryl Transfer Reactions (Kinases)

磷酸基团转移反应



Key Features of Glycolysis

2. Isomerization Reactions (Isomerases)

异构反应

(1) Phosphoglucose isomerase

Glucose–6–phosphate (G–6–P) ⇔ Fructose–6–phosphate (F–6–P)

(2) Triose phosphate isomerase

Dihydroxyacetone phosphate (DHAP) ⇔ Glyceraldehyde–3–phosphate (G–3–P)

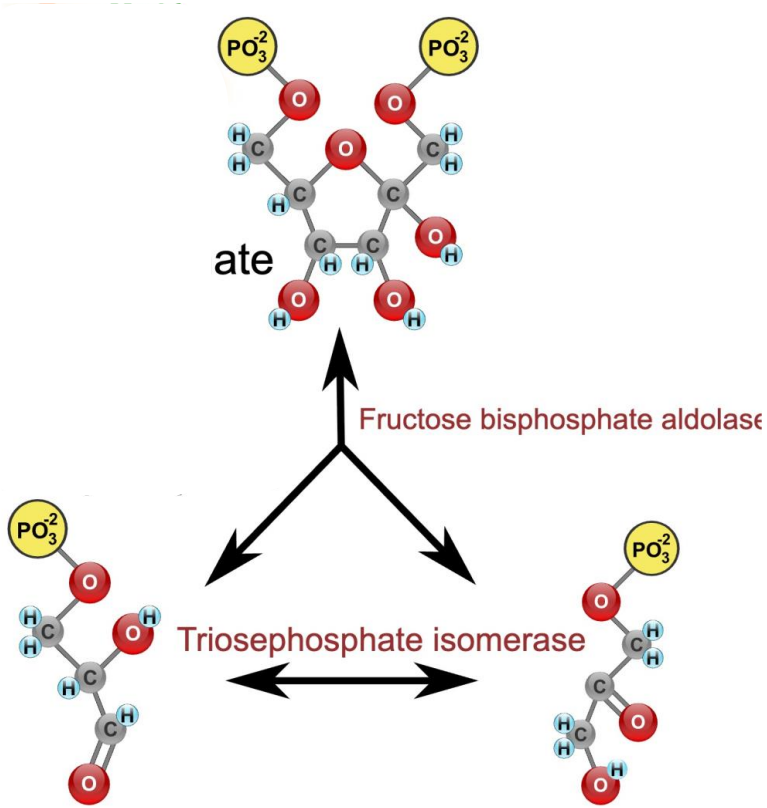
(3) Phosphoglycerate mutase

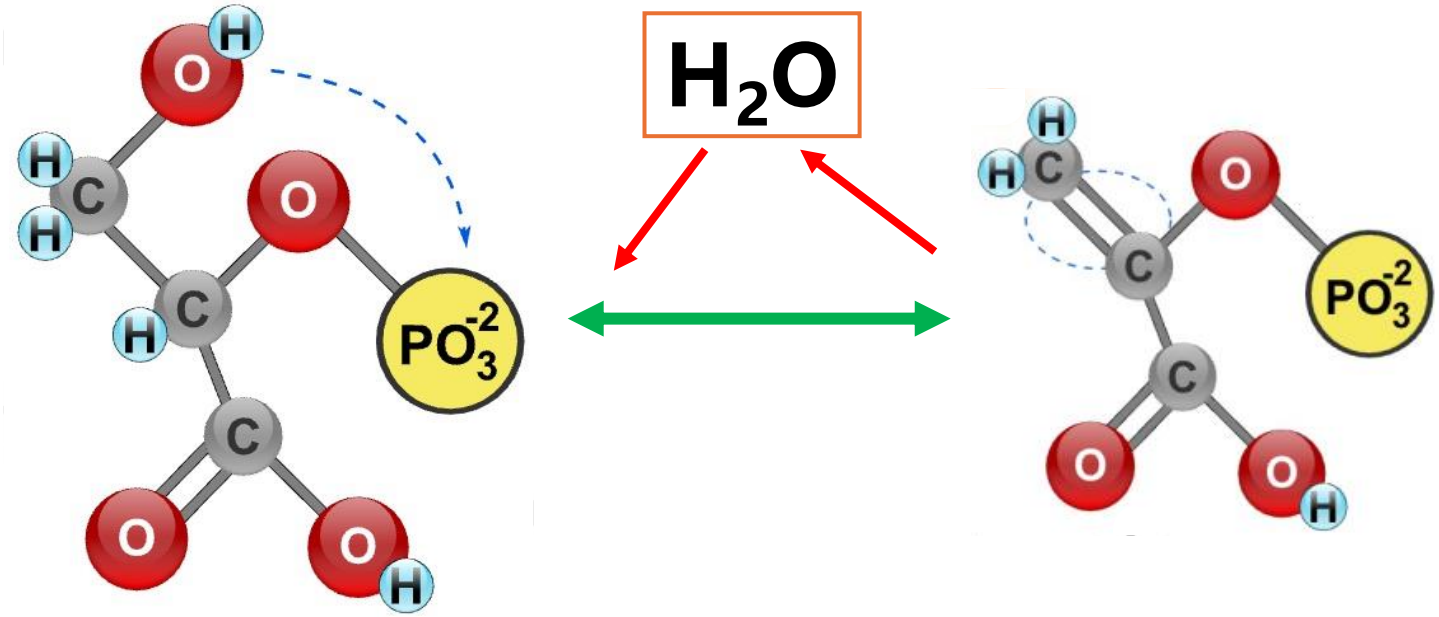
2 3–phosphoglycerate ⇔ 2 2–phosphoglycerate

Key Features of Glycolysis

3. Cleavage and Dehydration Reactions

裂合反应

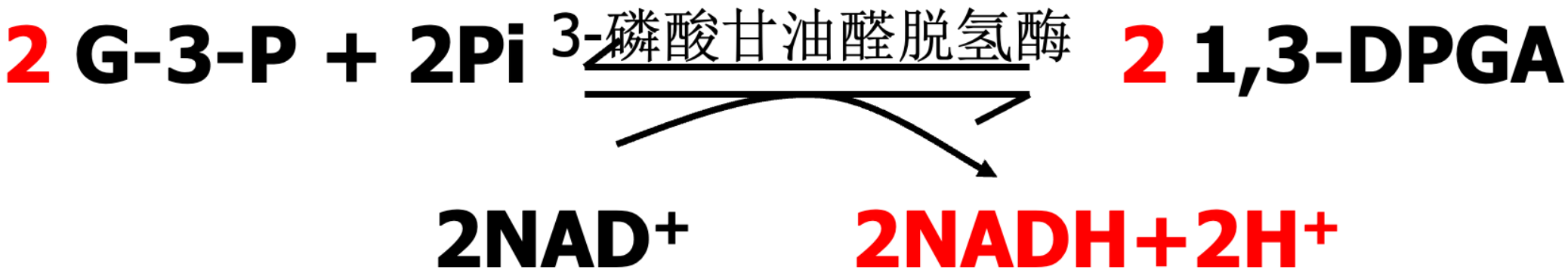




Key Features of Glycolysis

4. Oxidation–Reduction Reaction

氧化还原反应



Physiological Roles of Glycolysis

1. Source of Cellular Energy

One glucose yields **2 ATP**

Under **anaerobic conditions**:

Glycolysis is the **primary source of ATP** (e.g., muscle during intense exercise)

Under **aerobic conditions**:

NADH is oxidized via the **electron transport chain** can produce **~3–5 additional ATP**

生物能量的来源之一

2. Source of Metabolic Intermediates

Glycolytic intermediates serve as precursors for:

Pyruvate → Acetyl-CoA → Lipid synthesis

3-carbon intermediates → Amino acids

中间产物是合成其它物质的原料

3. Link to Gluconeogenesis

Glycolysis contains three irreversible steps

Other reactions are reversible

糖异生作提供基本途径

Physiological Roles of Glycolysis

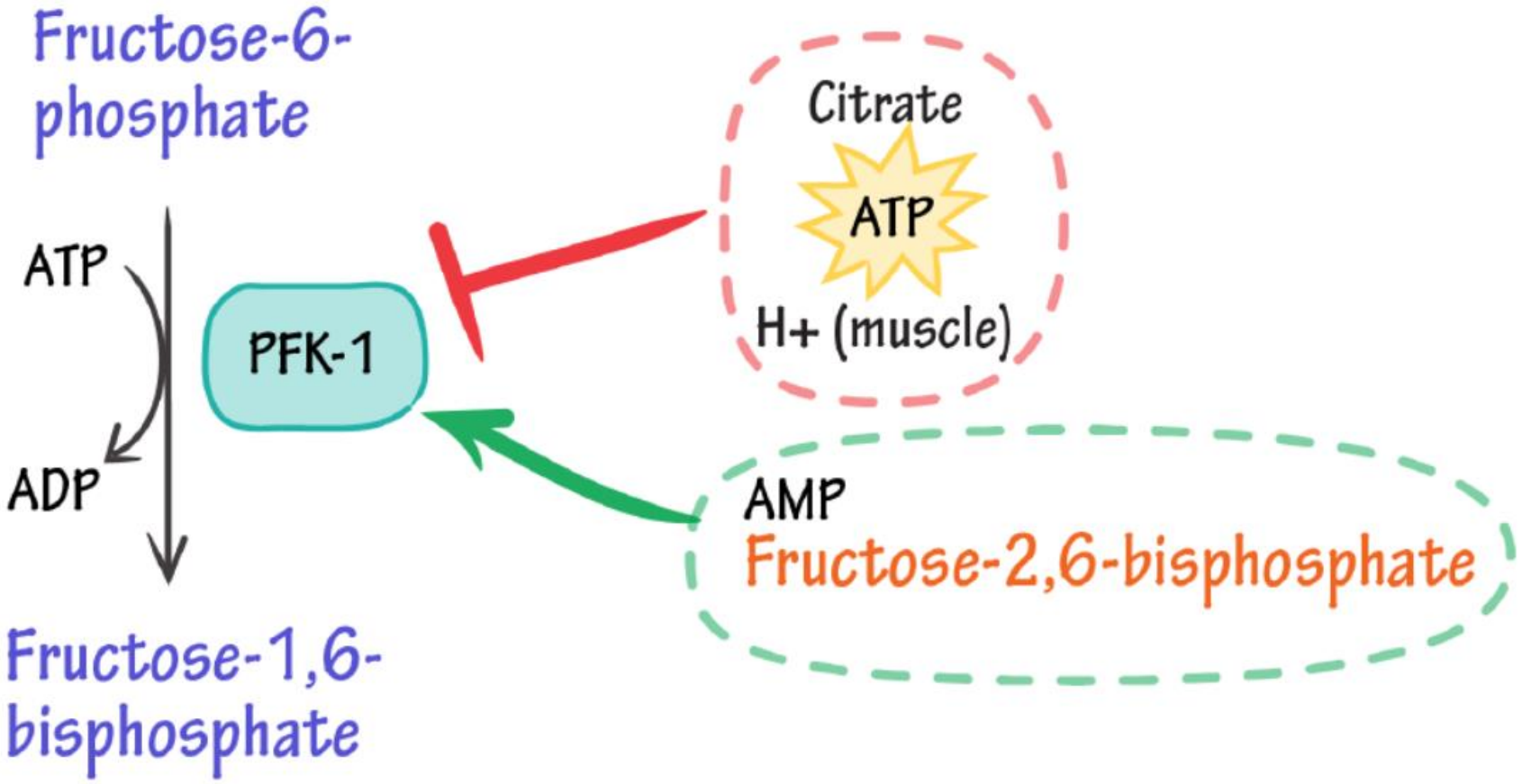
Three Irreversible Steps (Key Control Points)/三个不可逆反应

Glycolysis is regulated by cellular energy status (ATP/AMP ratio)

Enzyme	Activators	Inhibitors
PFK-1 磷酸果糖激酶-1 *Rate-limiting step*	AMP, ADP, Fructose-2,6-bisphosphate	ATP, Citrate, H^+
Hexokinase 己糖激酶	—	Glucose-6-phosphate
Pyruvate kinase 丙酮酸激酶	Fructose-1,6-bisphosphate	ATP, Alanine, Acetyl-CoA

Physiological Roles of Glycolysis

High ATP decreases the affinity of PFK for fructose-6-phosphate, reducing the rate of glycolysis



Fate of Pyruvate / 丙酮酸去向

Pyruvate produced from glycolysis has **two major metabolic fates**:

1. Anaerobic Conditions

Lactate fermentation

Alcohol fermentation

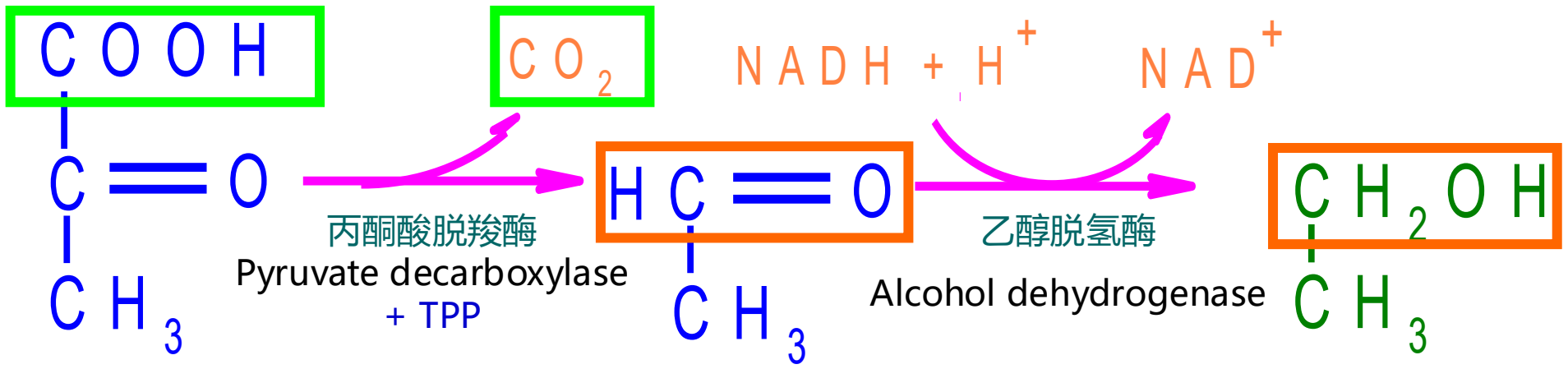
2. Aerobic Conditions

Pyruvate enters the mitochondrial matrix

Converted to acetyl-CoA

Enters the TCA cycle

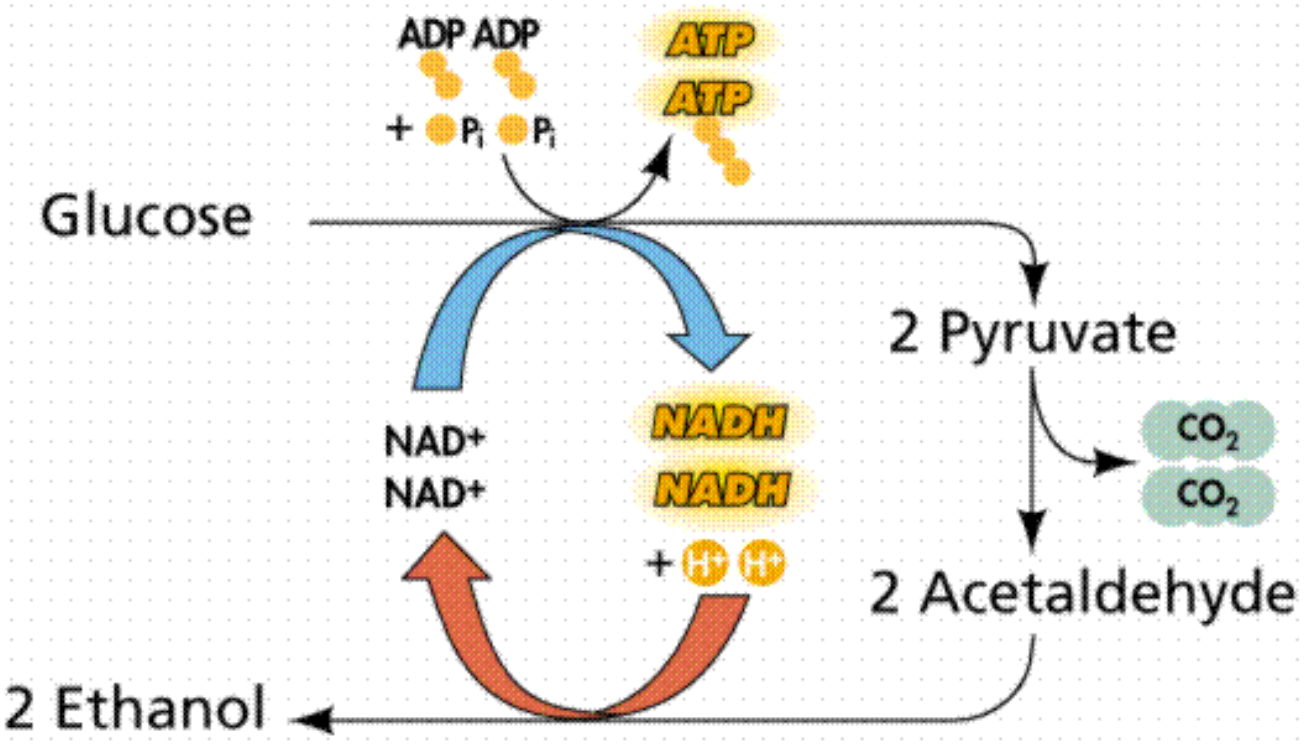
Fate of Pyruvate / 丙酮酸去向



TPP：焦磷酸硫胺素
/Vitamin B1

Alcohol fermentation

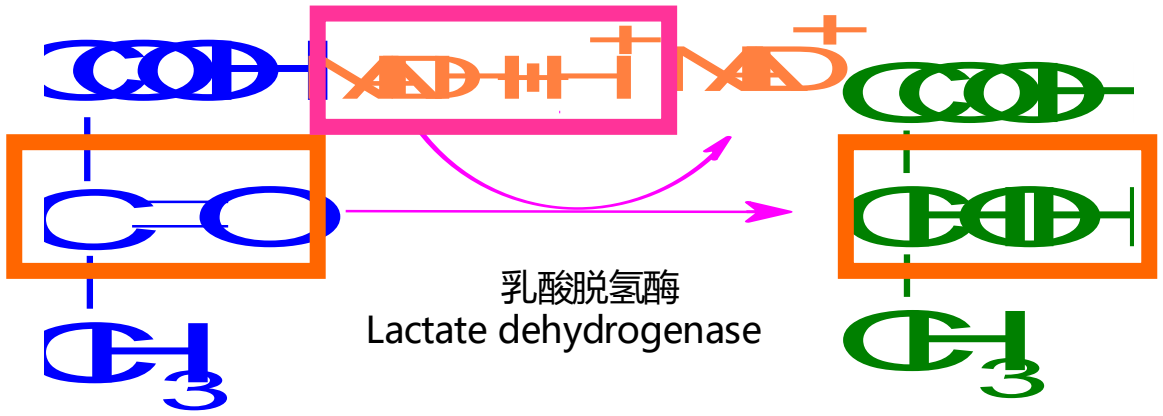
酒精发酵



Fate of Pyruvate / 丙酮酸去向

Lactate fermentation

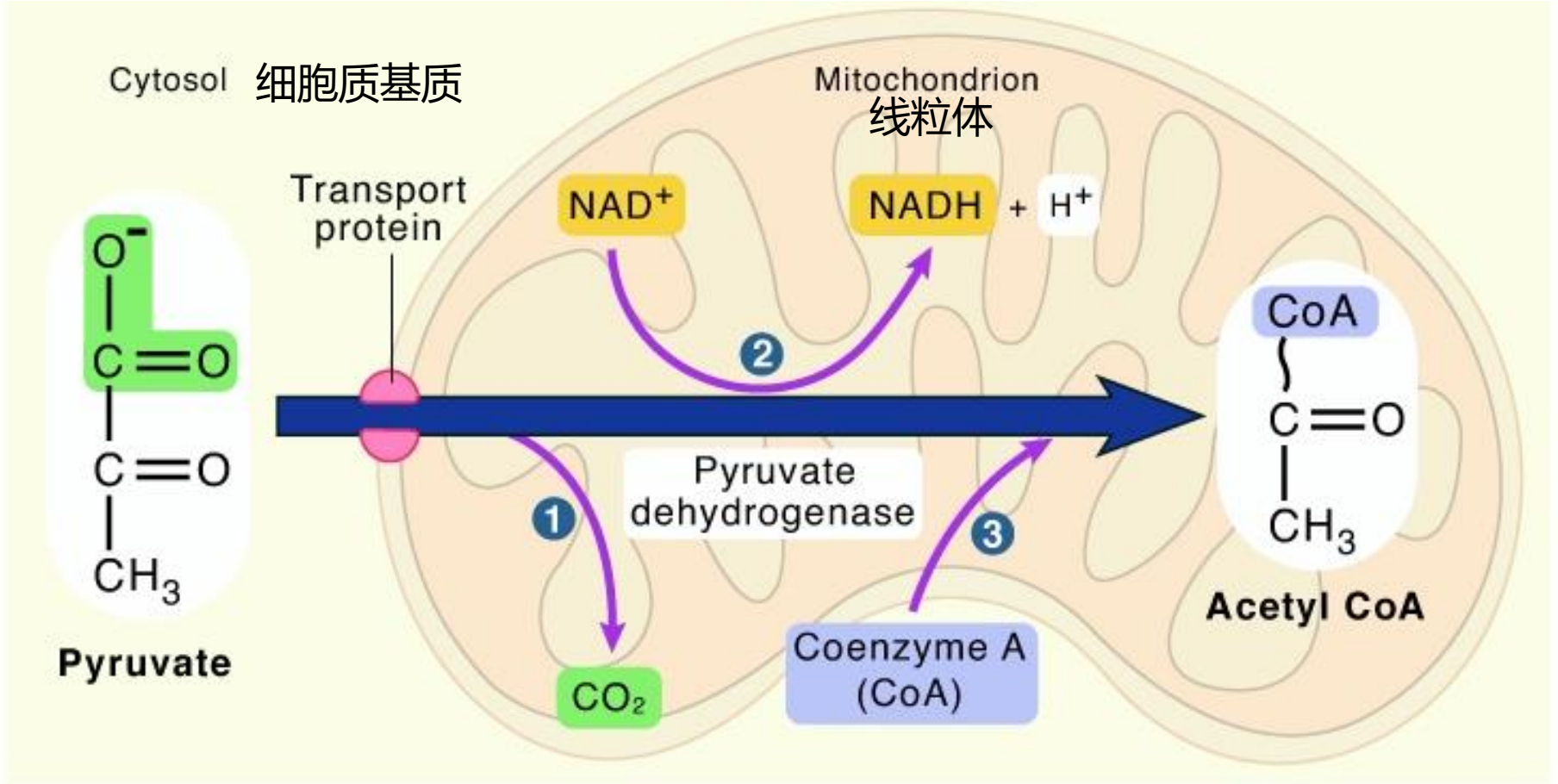
乳酸发酵





Fate of Pyruvate / 丙酮酸去向

Pyruvate Oxidation /有氧降解



Fate of Pyruvate / 丙酮酸去向

Pyruvate Oxidation /有氧降解

Pyruvate + CoA + NAD^+

Pyruvate dehydrogenase complex (PDH)

丙酮酸脱氢酶系

TCA

乙酰辅酶A

Acetyl-CoA + CO_2 + NADH

PDH Complex Components

E1: Pyruvate dehydrogenase（丙酮酸脱氢酶）

E2: Dihydrolipoyl transacetylase （二氢硫辛酰转乙酰基酶）

E3: Dihydrolipoyl dehydrogenase（二氢硫辛酰脱氢酶）

Cofactors

TPP (Vitamin B1)

Lipoic acid / 硫辛酸

CoA (Vitamin B5) /辅酶A

FAD (Vitamin B2) / 黄素腺嘌呤二核苷酸

NAD^+ (Vitamin B3)/ 烟酰胺腺嘌呤二核苷酸

TCA cycle / 三羧酸循环

The tricarboxylic acid cycle (TCA cycle), also known as the citric acid cycle/柠檬酸循环, Krebs cycle, Szent–Györgyi–Krebs cycle, is a series of biochemical reactions that release the energy stored in nutrients through acetyl-CoA oxidation.

Nobel Prize in Physiology or Medicine 1953



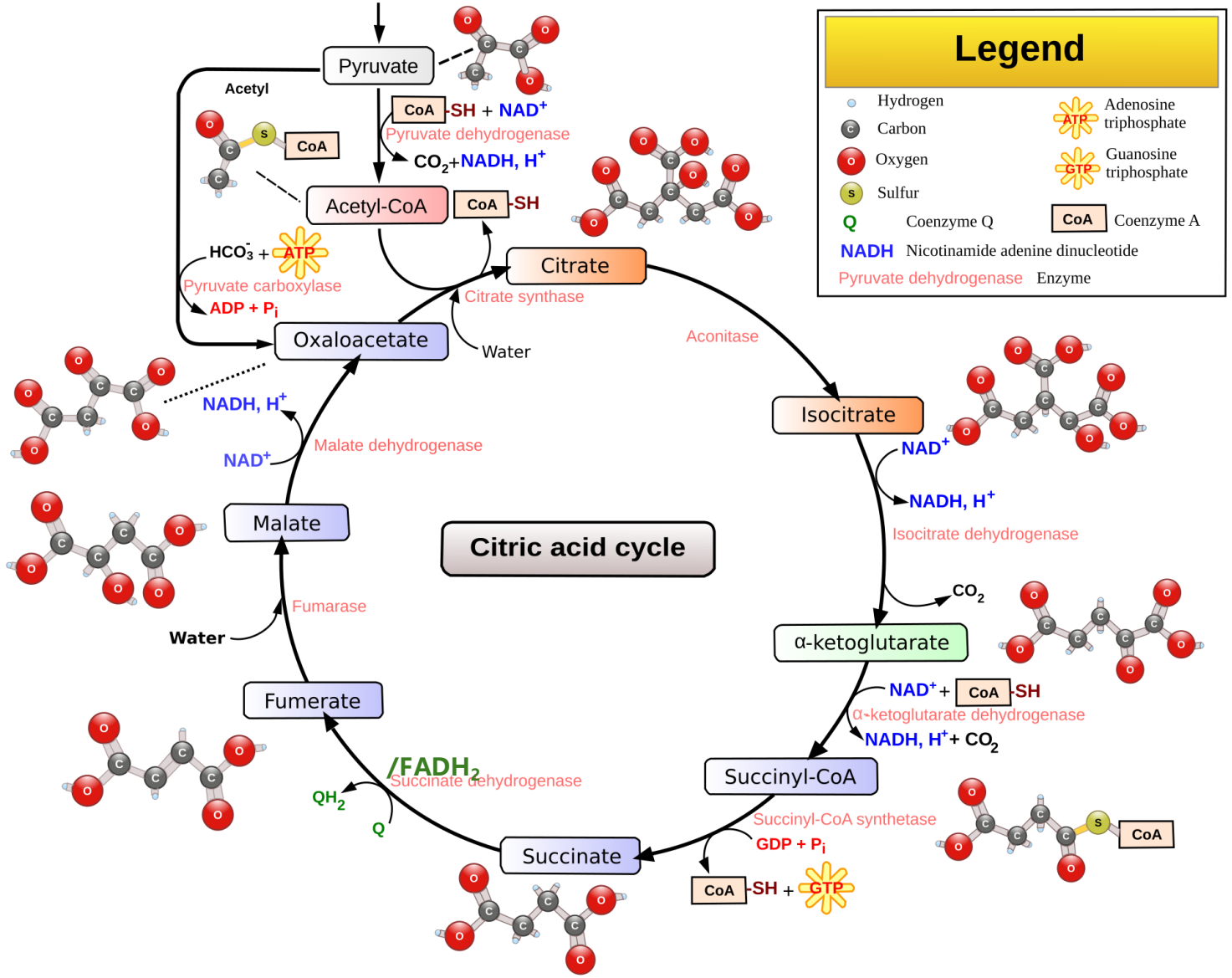
Photo from the Nobel Foundation archive.
Hans Adolf Krebs

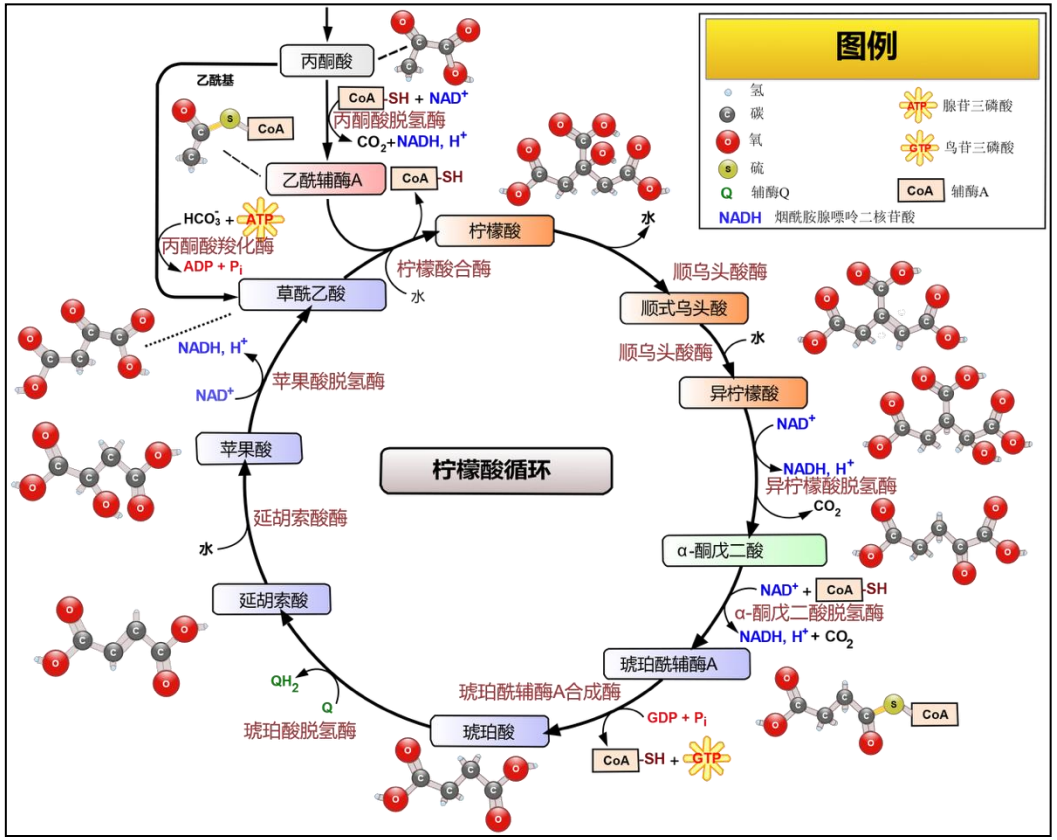


Photo from the Nobel Foundation archive.
Fritz Albert Lipmann

The Nobel Prize in Physiology or Medicine 1953 was divided equally between Hans Adolf Krebs "for his discovery of the citric acid cycle" and Fritz Albert Lipmann "for his discovery of co-enzyme A and its importance for intermediary metabolism"

TCA cycle / 三羧酸循环





TCA cycle / 三羧酸循环

$$\text{Acetyl-CoA} + 3\ NAD^+ + FAD + GDP + Pi$$

$$2CO_2 + CoASH + 3\ NADH + 3H^+ + FADH_2 + GTP$$

Complete Oxidation of Carbon (Two carbons from acetyl-CoA generate 2 CO_2)

Generation of Reducing Equivalents (3 NADH + 1 $FADH_2$)

1 GTP (≈ ATP equivalent) per cycle

Four Oxidation Steps

- 3 NAD^+-dependent reactions
- 1 FAD-dependent reaction

TCA cycle / 三羧酸循环

Four Oxidation Steps

A. Isocitrate/异柠檬酸 → α-Ketoglutarate/ α-酮戊二酸

Enzyme: **Isocitrate dehydrogenase** /异柠檬酸脱氢酶

Produces: **CO_2 ,NADH, H^+**

B. α-Ketoglutarate → Succinyl-CoA / 琥珀酰CoA

Enzyme: **α-Ketoglutarate dehydrogenase complex / α-酮戊二酸脱氢酶系**

Requires: **CoA-SH, NAD^+**

Produces: **CO_2, NADH, H^+**

C. Succinate → Fumarate

Enzyme: Succinate dehydrogenase

Produces: $FADH_2$

D. Malate → Oxaloacetate

Enzyme: Malate dehydrogenase

Produces: NADH + H^+

TCA cycle / 三羧酸循环

Energy Yield of the TCA Cycle

1. Substrate-Level Phosphorylation

$$\text{Succinyl–CoA} + \text{GDP} + P_i \rightarrow \text{Succinate} + \text{GTP} + \text{CoA–SH}$$

Enzyme: **Succinyl-CoA synthetase**

GTP ≈ ATP equivalent

2. Total Energy Yield (per Acetyl-CoA)

3 NADH → 3 × 2.5 ATP = 7.5 ATP

1 $FADH_2$ → 1 × 1.5 ATP = 1.5 ATP

1 GTP → 1 ATP

10 ATP per cycle

TCA cycle / 三羧酸循环

Physiological Roles of the TCA Cycle

1. Central Pathway of Energy Metabolism

Major pathway for **oxidation of carbohydrates**

Final common pathway for:

- **Lipids** (via acetyl-CoA)
- **Proteins** (via amino acid catabolism)

2. Amphibolic Pathway/物质代谢枢纽

TCA cycle is both:

- **Catabolic** (energy production)
- **Anabolic** (biosynthesis)

3. Source of Carbon Skeletons

Pyruvate → glucose (gluconeogenesis)

Acetyl-CoA → fatty acids

α-Ketoglutarate → amino acids

Oxaloacetate → amino acids / glucose

TCA cycle / 三羧酸循环

Allosteric Regulation

Enzyme	Activators	Inhibitors
Citrate synthase 柠檬酸合成酶	—	ATP, NADH, citrate, succinyl-CoA
Isocitrate dehydrogenase 异柠檬酸脱氢酶	ADP	ATP, NADH
α-Ketoglutarate dehydrogenase	—	NADH, succinyl-CoA, ATP

Isocitrate dehydrogenase plays as the rate-limiting step enzyme

Summary of TCA

What is the TCA Cycle?

Central pathway in the **mitochondrial matrix**

Oxidizes **acetyl-CoA → CO_2**

Key Features

Occurs in mitochondria

Requires oxygen indirectly

Generates reducing equivalents (NADH, $FADH_2$)

Regulation by Key Enzymes:

Citrate synthase

Isocitrate dehydrogenase (rate-limiting)

α-Ketoglutarate dehydrogenase

Core Functions

1. Energy Production (Indirect)

- 3 NADH + 1 $FADH_2$ + 1 GTP per cycle

2. Complete Oxidation of Carbon

3. Metabolic Hub (Amphibolic)

- Integrates metabolism of Carbohydrates, Lipids, Proteins

4. Source of Biosynthetic Precursors

- Amino acids (α-KG, OAA)
- Fatty acids (acetyl-CoA)
- Gluconeogenesis (OAA)

Anaplerotic Reactions of the TCA Cycle

Anaplerotic Reactions（回补反应）

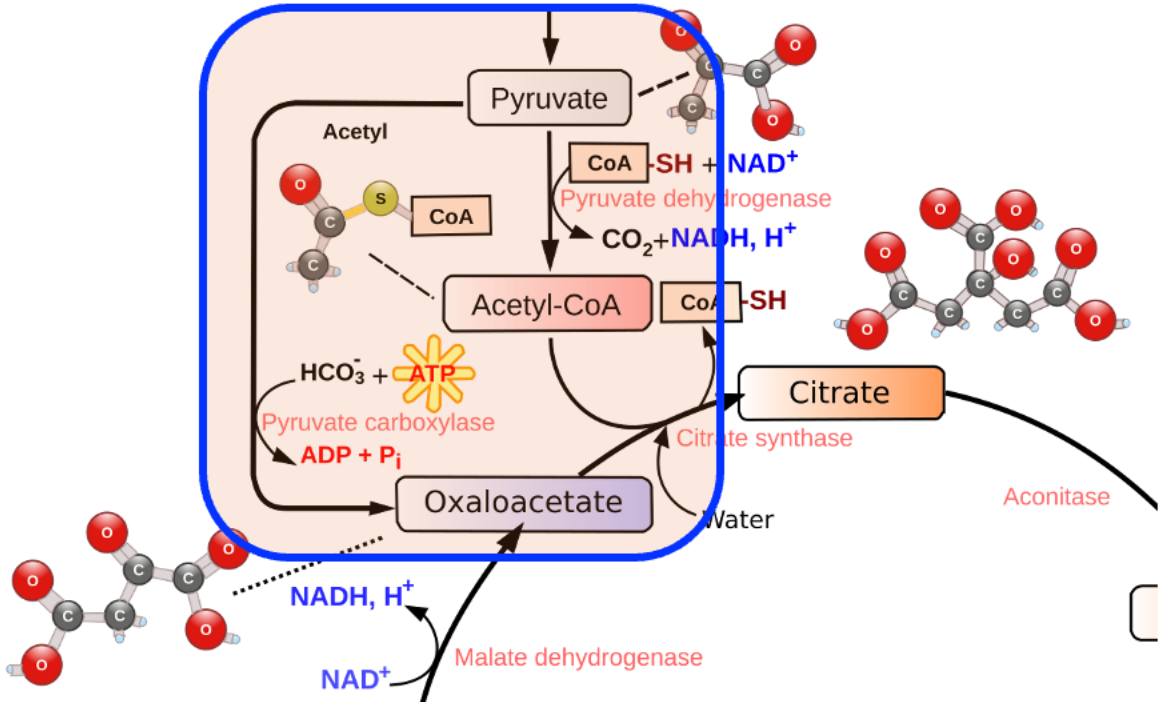
Purpose: Replenish oxaloacetate (OAA) in the TCA cycle

$$\text{Pyruvate} + CO_2 + \text{ATP} \xrightarrow{\text{Pyruvate carboxylase}\ \text{丙酮酸羧化酶}} \text{Oxaloacetate (OAA)} + \text{ADP} + \text{Pi}$$

Physiological Significance

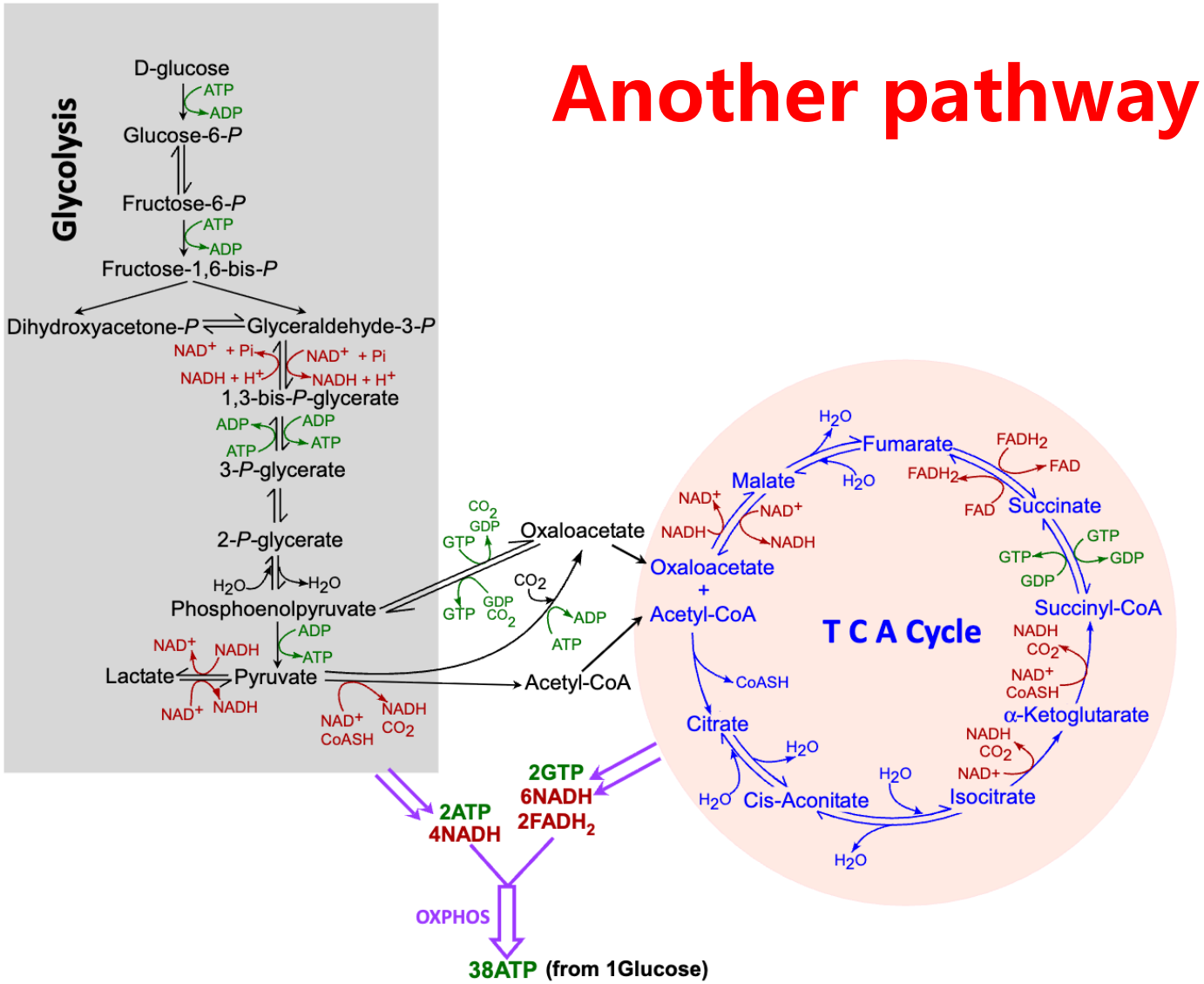
Maintains **TCA cycle function**

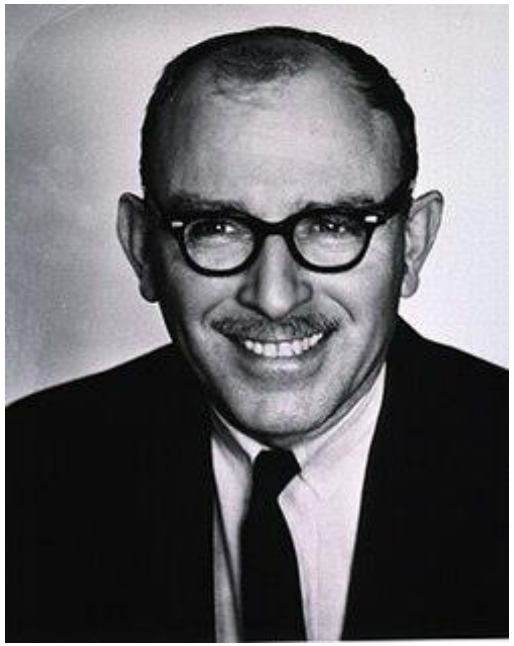
Required when intermediates are used for b**iosynthesis** (amino acids, glucose)



Pentose Phosphate Pathway /磷酸戊糖途径

Another pathways?





Bernard Leonard Horecker

The **pentose phosphate pathway** (**PPP**, also called the phosphogluconate pathway)

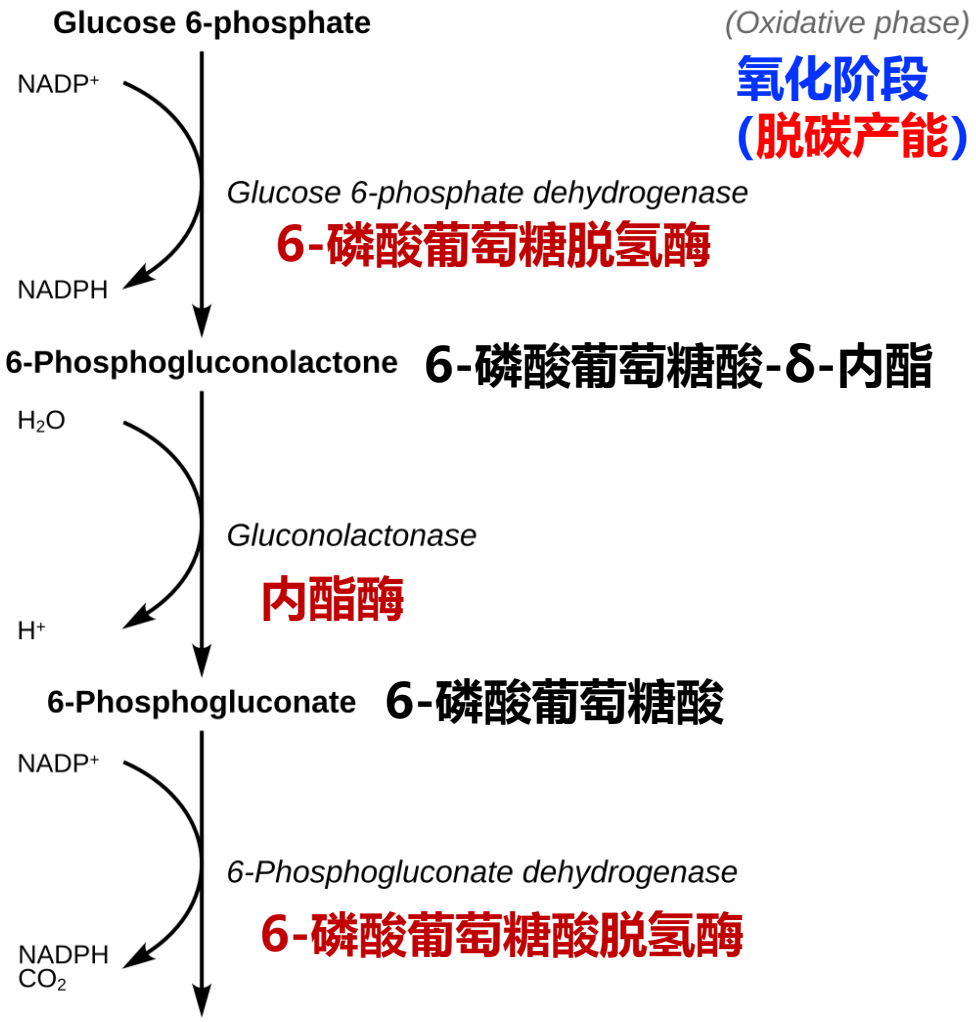
Pentose Phosphate Pathway /磷酸戊糖途径

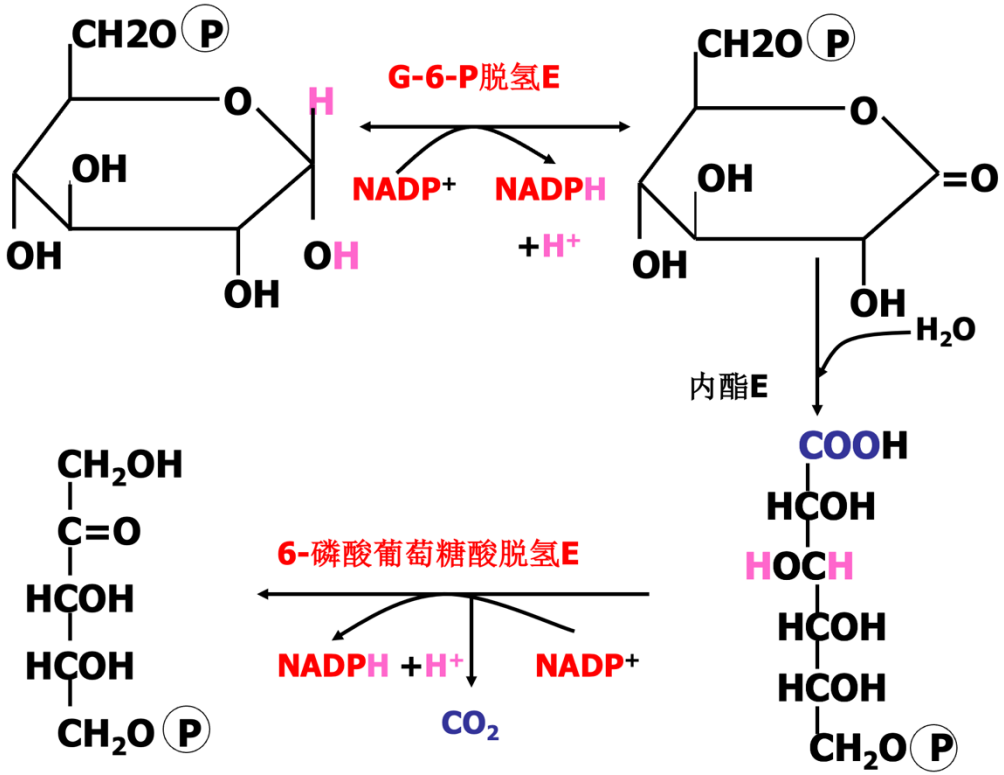
PPP is a metabolic pathway parallel to glycolysis. It generates NADPH and pentoses (five-carbon sugars) as well as ribose 5-phosphate, a precursor for the synthesis of nucleotides.

Occurs in the **cytosol**

Starts from **glucose-6-phosphate (G6P)**

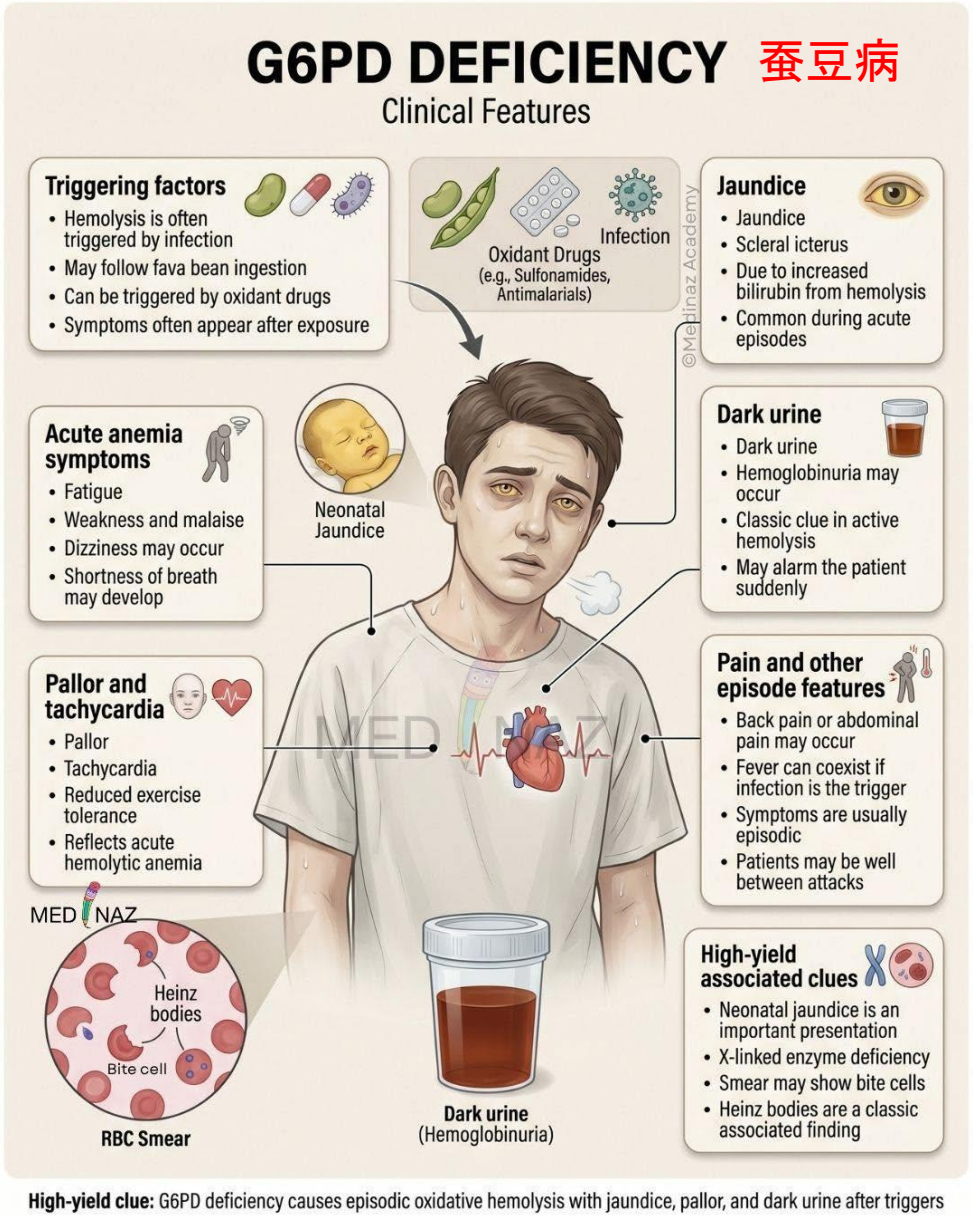
Pentose Phosphate Pathway





Ribulose 5-phosphate 核酮糖-5-磷酸

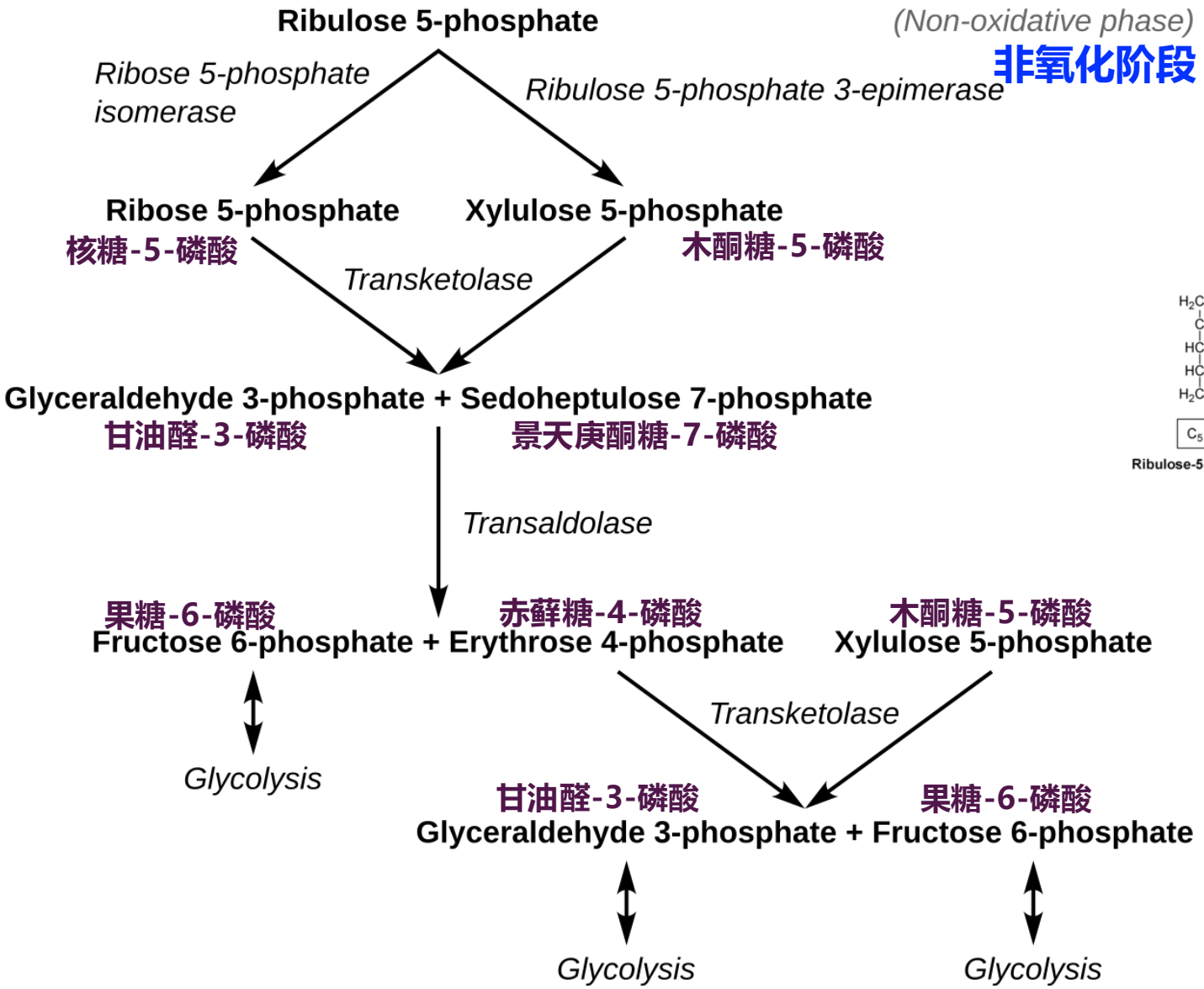
Pentose Phosphate Pathway

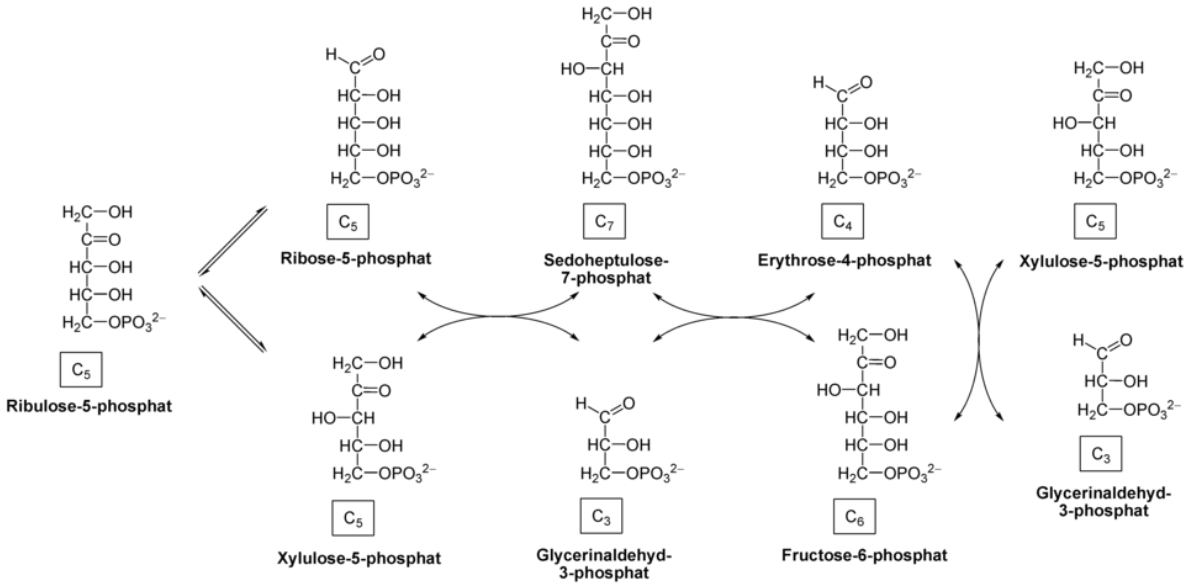


Glucose-6-phosphate dehydrogenase (G6PD) deficiency is a common, inherited X-linked genetic disorder where the body lacks enough G6PD enzyme. This enzyme protects red blood cells from oxidative stress. Without enough of it, red blood cells break down prematurely, leading to hemolytic anemia.

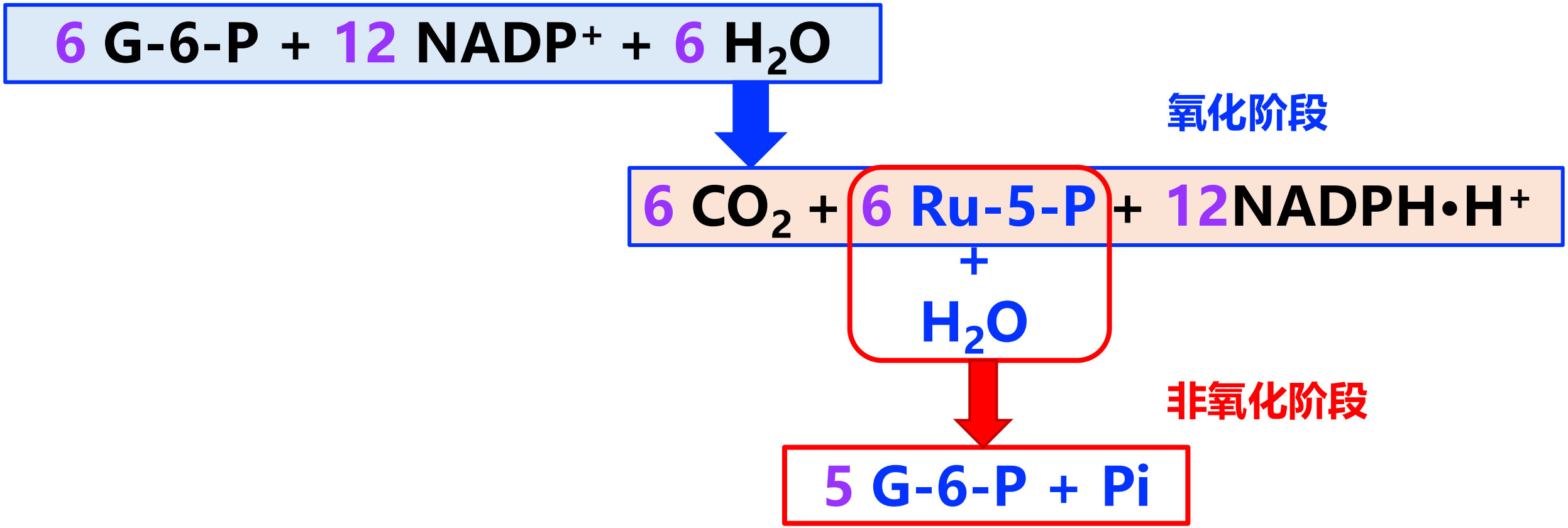
蚕豆中含有高浓度的强氧化物质（如蚕豆嘧啶）。正常人吃蚕豆后，红细胞内的 G6PD 酶会迅速发挥作用，通过戊糖磷酸途径产生大量 NADPH 来中和这些氧化剂。但对于 G6PD 缺乏者，这一途径被堵死了，氧化剂长驱直入，直接摧毁红细胞。

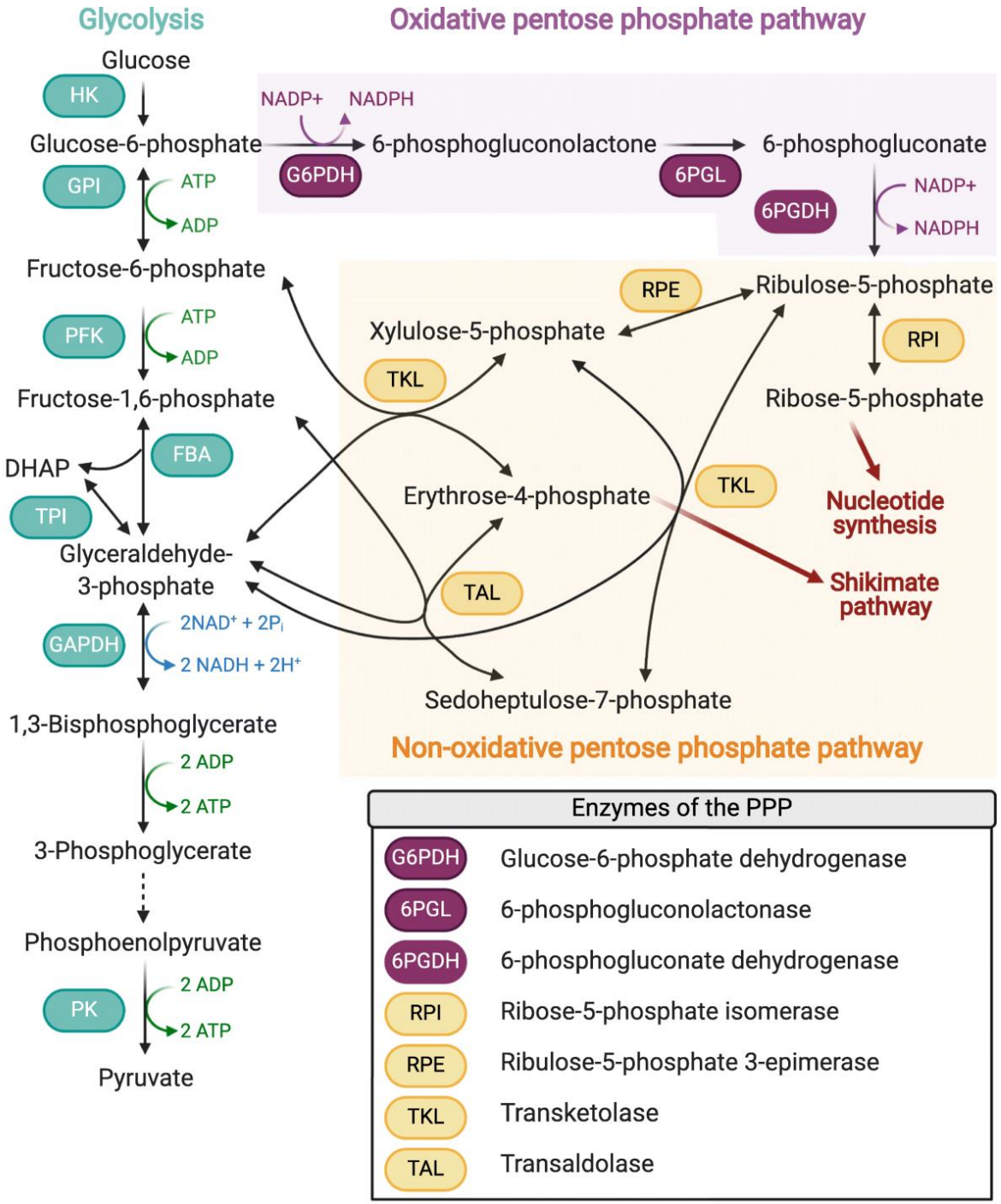
Pentose Phosphate Pathway





Pentose Phosphate Pathway





PPP vs Glycolysis–TCA Pathway

Feature	**PPP**	**Glycolysis**
Location	Cytosol	Cytosol
Starting substrate	Glucose-6-phosphate	Glucose
Oxidation mode	Direct oxidative decarboxylation	Stepwise oxidation
Coenzyme	$NADP^+$	NAD^+
ATP production	None	Yes
Main products	NADPH, Ribose-5-P	ATP, NADH, Pry

Physiological Roles of PPP

1. Production of NADPH (Reducing Power)

Provides **NADPH** for **Fatty acid, Cholesterol, Nucleotide synthesis**

Maintains **redox balance (GSSG → 2 GSH)**

Supports **detoxification and antioxidant defense**

2. Biosynthetic Functions

Ribose-5-phosphate can be used in nucleotide and coenzyme synthesis (NAD^+, FAD)

Erythrose-4-phosphate (E4P) is important for aromatic amino acids (Tyr, Phe, Trp)

3. Metabolic Integration

Intermediates (e.g., **G3P, F6P**) connect with **Glycolysis (EMP)**

4. Special Roles

Provides reducing power for **Nitrate/nitrite reduction (plants, bacteria)**

Linked to **photosynthesis**

Regulation of the PPP

Oxidative Phase (Rate-Limiting Step)

Enzyme: **Glucose-6-phosphate dehydrogenase (G6PD)**

Regulation:

- **Activated by $NADP^+$**
- **Inhibited by NADPH**

Non-oxidative Phase

Reversible reactions

Driven by **substrate availability**

Excess **ribose-5-phosphate (R5P)** can be converted to:

- **Fructose-6-phosphate (F6P)**
- **Glyceraldehyde-3-phosphate (G3P)**

Summary of PPP

What is PPP?

Cytosolic pathway of **glucose-6-phosphate metabolism**

Alternative to glycolysis

Core Functions

NADPH Production

Ribose-5-Phosphate Production

Carbon Rearrangement

Key Features

No ATP production

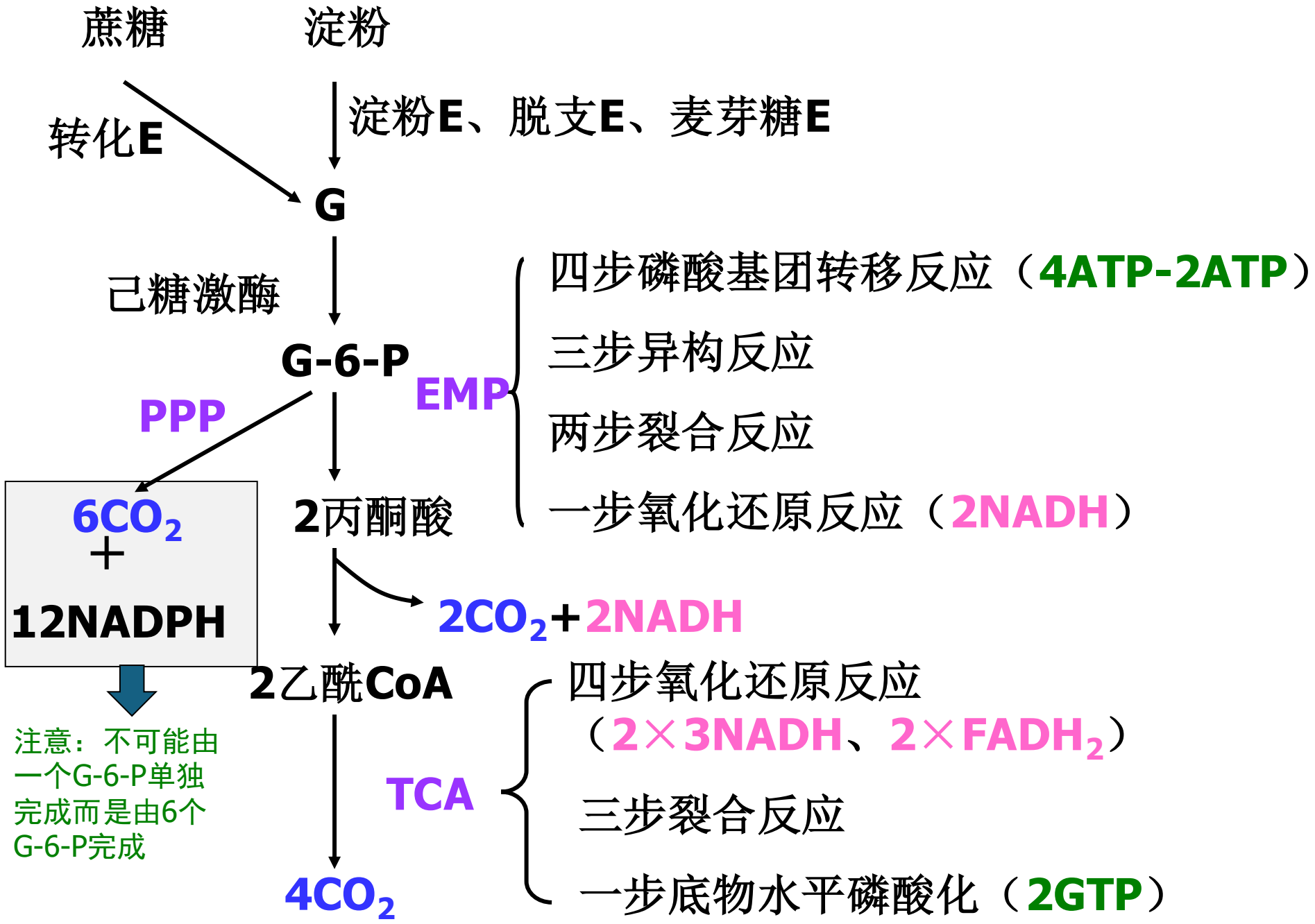
Oxidative phase (irreversible)

Non-oxidative phase (reversible)

Regulation

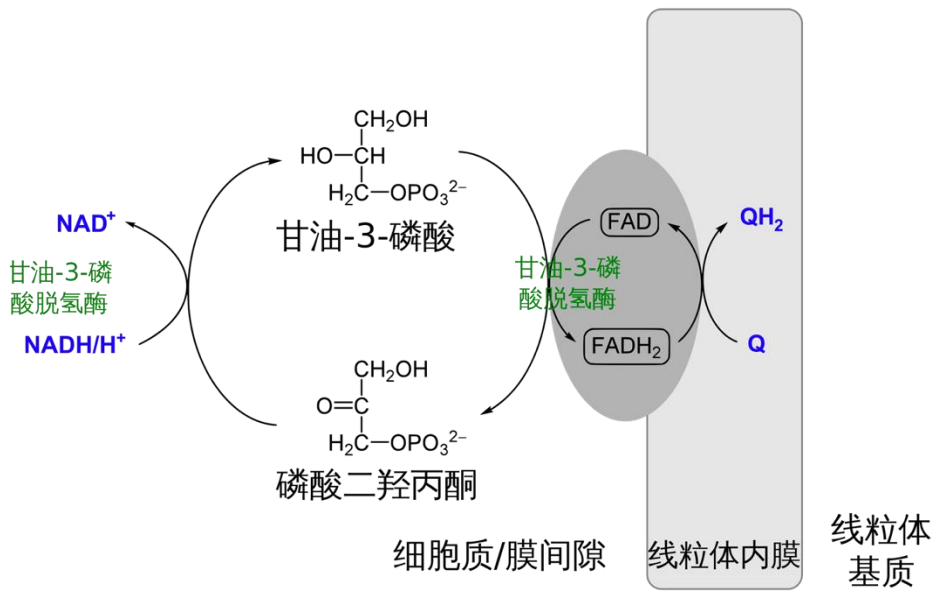
Rate-limiting enzyme: G6PD

NADPH inhibits / $NADP^+$ activates


蔗糖
淀粉
转化E
淀粉E、脱支E、麦芽糖E
G
己糖激酶
G-6-P
EMP
四步磷酸基团转移反应（4ATP-2ATP）
三步异构反应
两步裂合反应
一步氧化还原反应（2NADH）
PPP
6CO2
+
12NADPH
2丙酮酸
2CO2+2NADH
2乙酰CoA
注意：不可能由一个G-6-P单独完成而是由6个G-6-P完成
TCA
四步氧化还原反应
（2×3NADH、2×FADH2）
三步裂合反应
一步底物水平磷酸化（2GTP）
4CO2

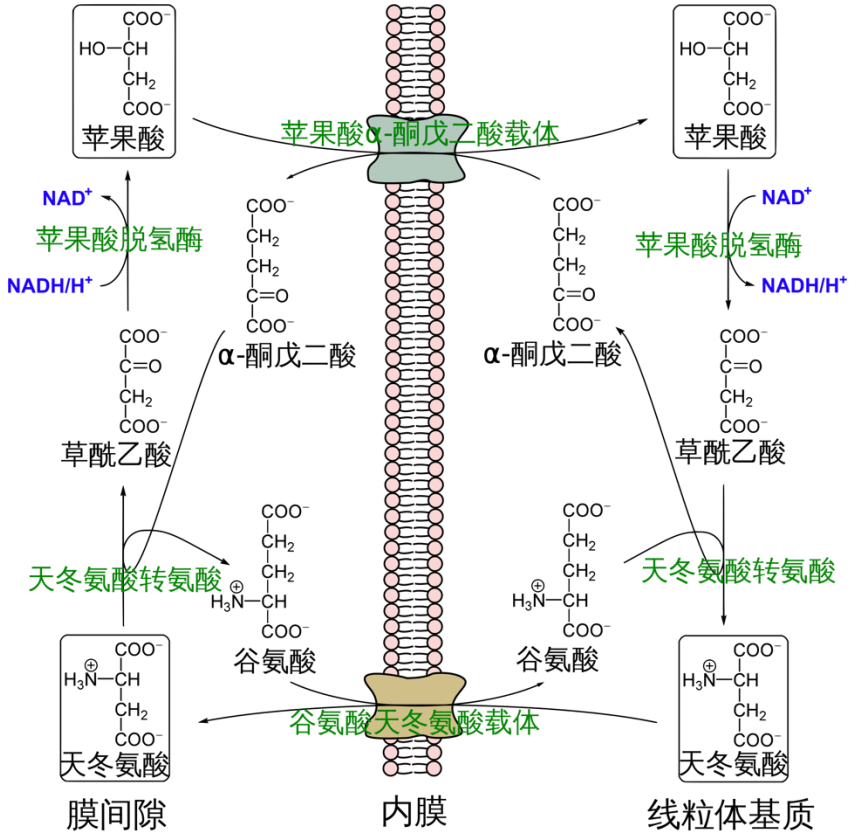
Fate of NADH Produced in Glycolysis

Glycerol-3-Phosphate Shuttle
磷酸甘油穿梭



NADH ⟶ $FADH_2$

Malate-Aspartate Shuttle
苹果酸穿梭

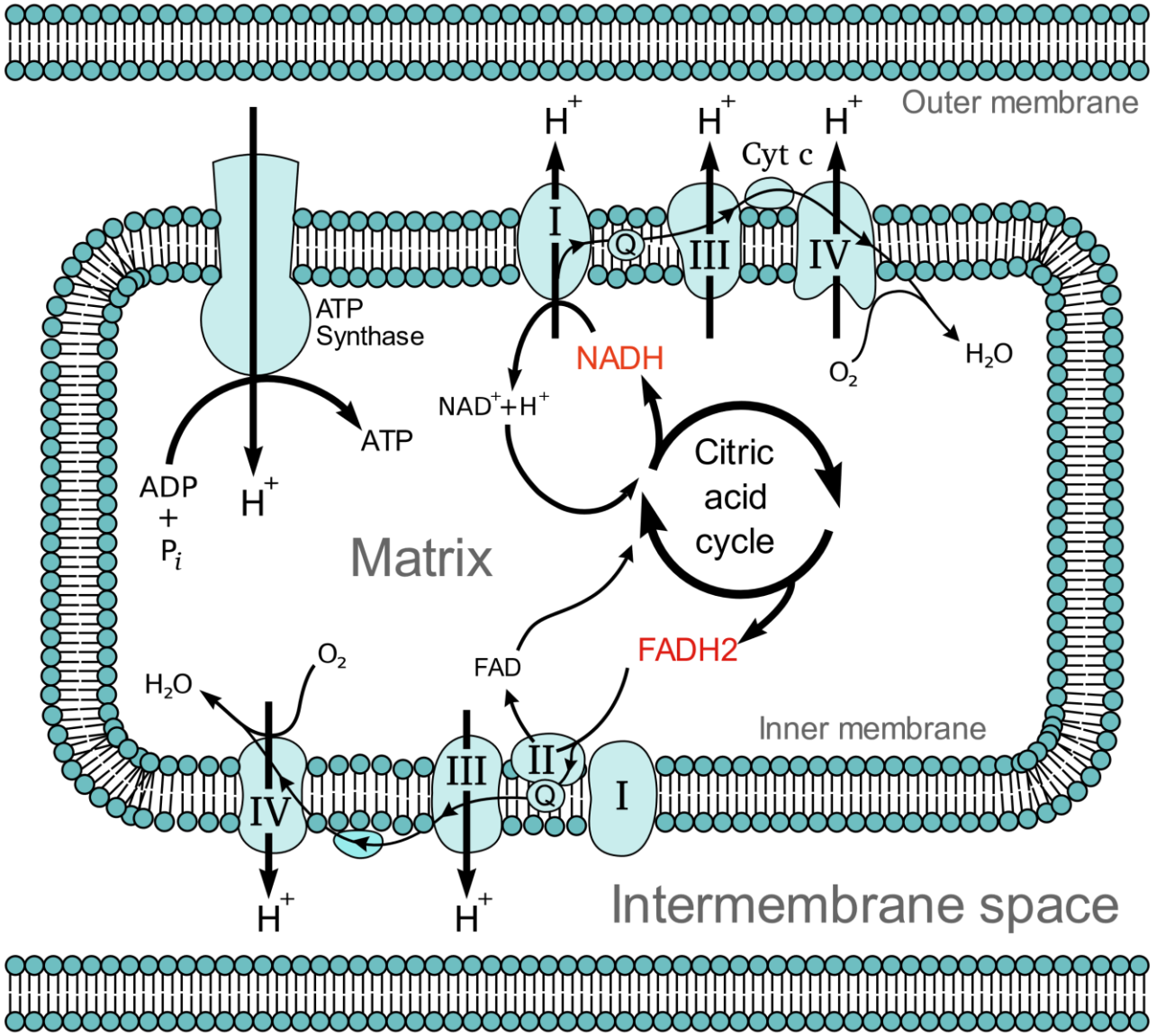


NADH ⟶ NADH

$$G + O_2 \longrightarrow CO_2 + H_2O + ATP$$

Biological Oxidation

生物氧化



Biological Oxidation

Biological oxidation refers to the process in which organic molecules are oxidized within living cells through enzyme-catalyzed reactions, with the released energy conserved in the form of ATP.

Key Features

- Occurs in **living cells**
- Involves **enzyme-catalyzed redox reactions**
- Energy from NADH/$FADH_2$ is used for **ATP synthesis**

Biological Oxidation

Characteristics of Biological Oxidation

Occurs under **mild conditions**

- Physiological temperature
- Near-neutral pH

Proceeds via **stepwise enzyme-catalyzed reactions**

Energy is **released gradually**

Energy is conserved in **high-energy molecules (ATP, NADH)**

Biological Oxidation

Characteristics of Biological Oxidation

Feature	**Biological Oxidation**	**Combustion / 燃烧**
Conditions	Mild (physiological)	High temperature
Process	Stepwise, enzyme-controlled	One-step reaction
Energy release	Gradual, conserved	Rapid, lost as heat
Energy form	ATP, NADH	Heat
CO_2 formation	Decarboxylation reactions	Direct oxidation

Biological Oxidation

Types of Oxidation in Biological Systems

Loss of Electrons / 失电子

$$Fe^{2+} \rightarrow Fe^{3+} + e^-$$

Loss of Hydrogen / 脱氢 (Most Important)

$$\text{Substrate} \rightarrow \text{Oxidized product} + 2H^+ + 2e^-$$

Catalyzed by **dehydrogenases (NAD^+, FAD)**

Gain of Oxygen / 加氧

$$RH + \frac{1}{2}O_2 \rightarrow ROH$$

Biological Oxidation

Formation of Water in Biological Oxidation

Step 1: Oxidation (Loss of Electrons)

$$AH_2 \rightarrow A + 2\,H^+ + 2\,e^-$$

Step 2: Electron Transfer

Electron Transport Chain (ETC), and Energy is released stepwise

Step 3: Reduction (Gain of Electrons)

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2e^- \rightarrow H_2O$$

Biological Oxidation

O_2 is the final electron acceptor

Biological Oxidation	Combustion
Oxidation and reduction are **separated**	Oxidation and reduction occur **simultaneously**
Electrons transferred via **carriers**	Direct electron transfer to O_2
Energy released **gradually** → **conserved as ATP**	Energy released **instantly** → **heat**

Biological Oxidation

High-Energy Compounds

High-energy compounds are molecules that, upon hydrolysis or group transfer, release a large amount of free energy (large negative ΔG°')

Energy is released due to:

- Relief of **electrostatic repulsion**
- Formation of **more stable products**
- **Resonance stabilization**

"High-energy bond" does NOT mean unstable bond!

Example: ATP

Biological Oxidation

Electron Transport Chain (ETC)

The ETC is a series of electron carriers located in the inner mitochondrial membrane that transfer electrons from NADH and $FADH_2$ to O_2

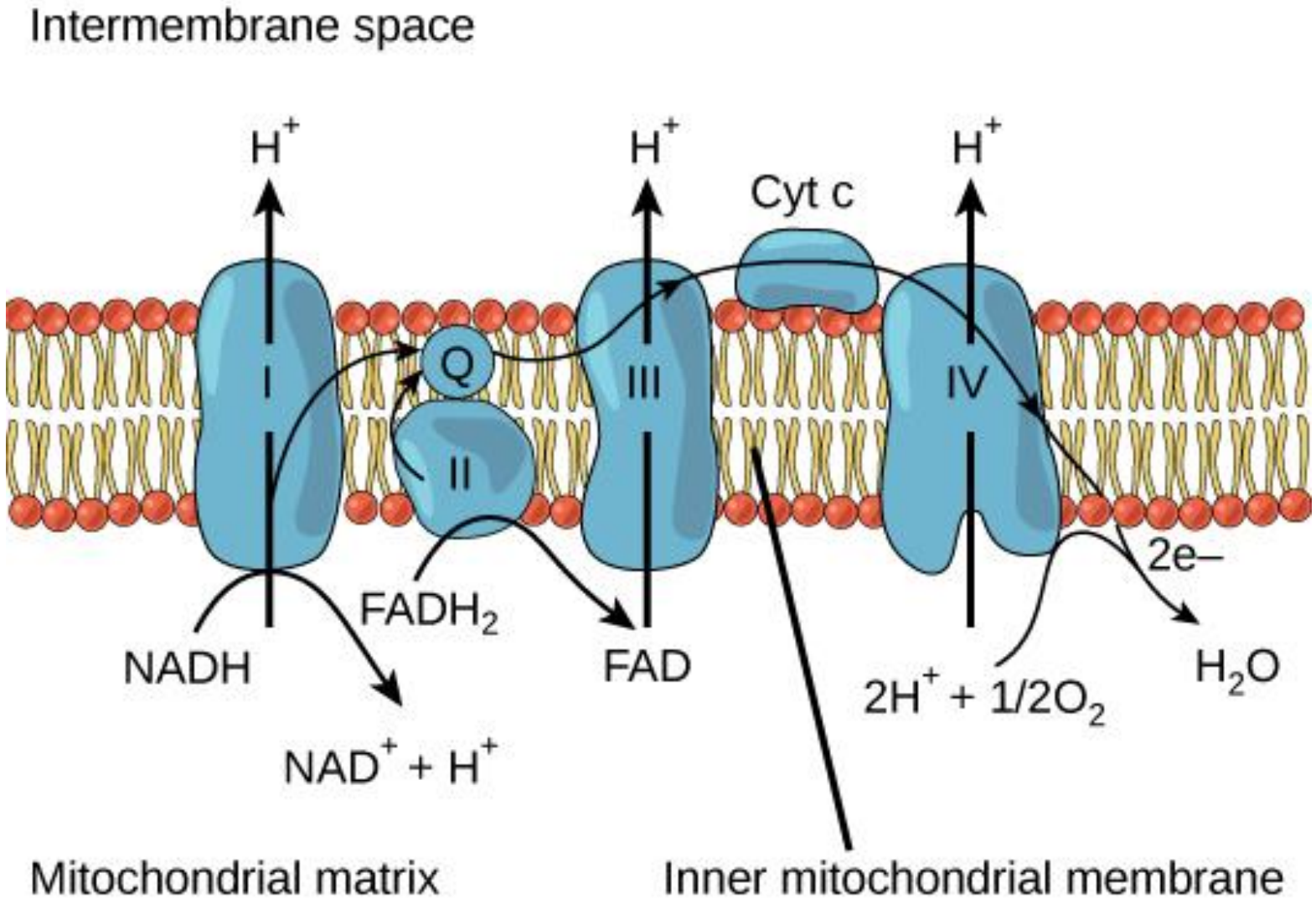
Electrons flow: $NADH/FADH_2 \rightarrow$ ETC $\rightarrow O_2 \rightarrow H_2O$

NADH → Complex I

$FADH_2$ → Complex II

Biological Oxidation

Electron Transport Chain (ETC)



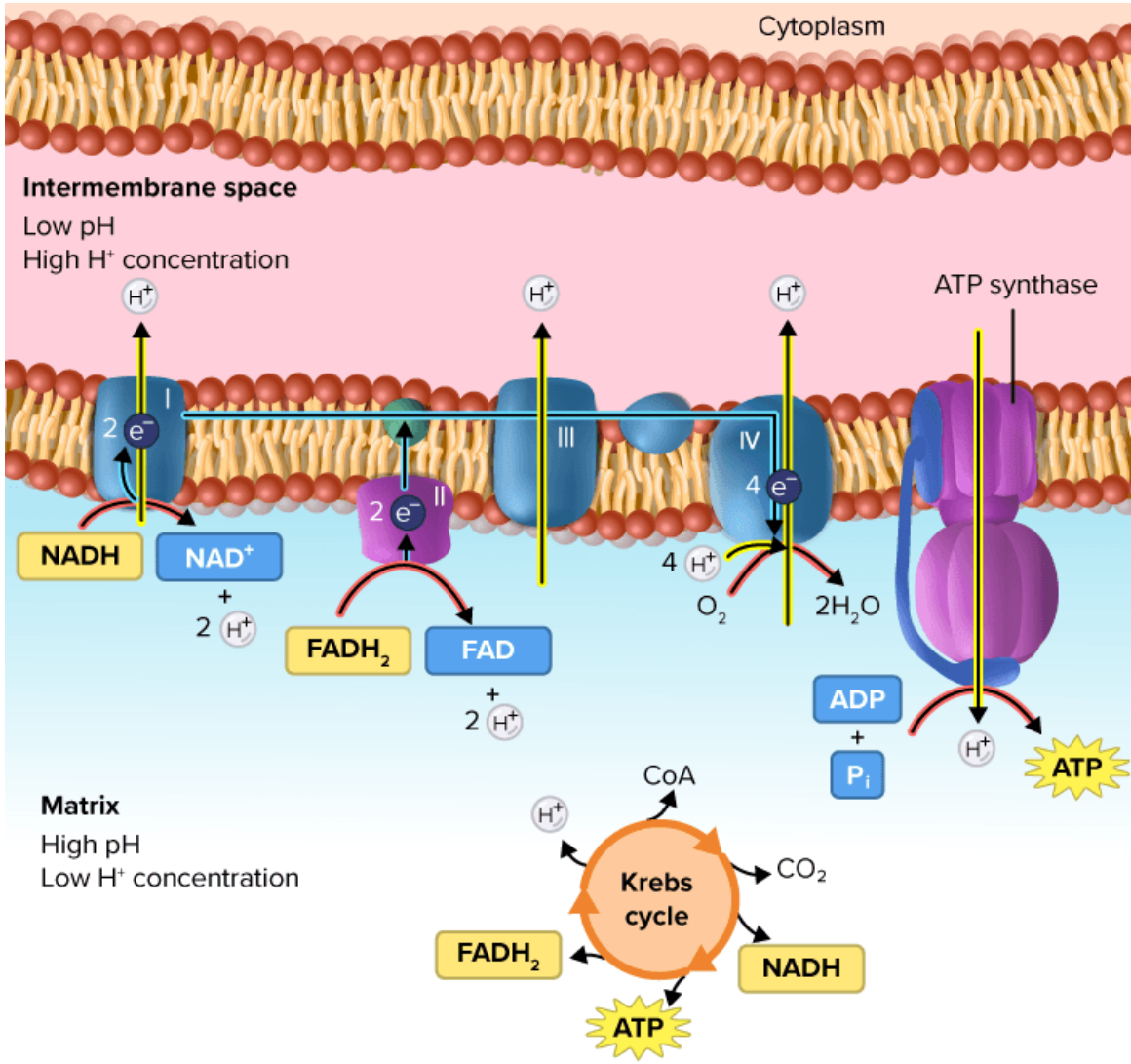
ETC Complexes

Located in the inner mitochondrial membrane

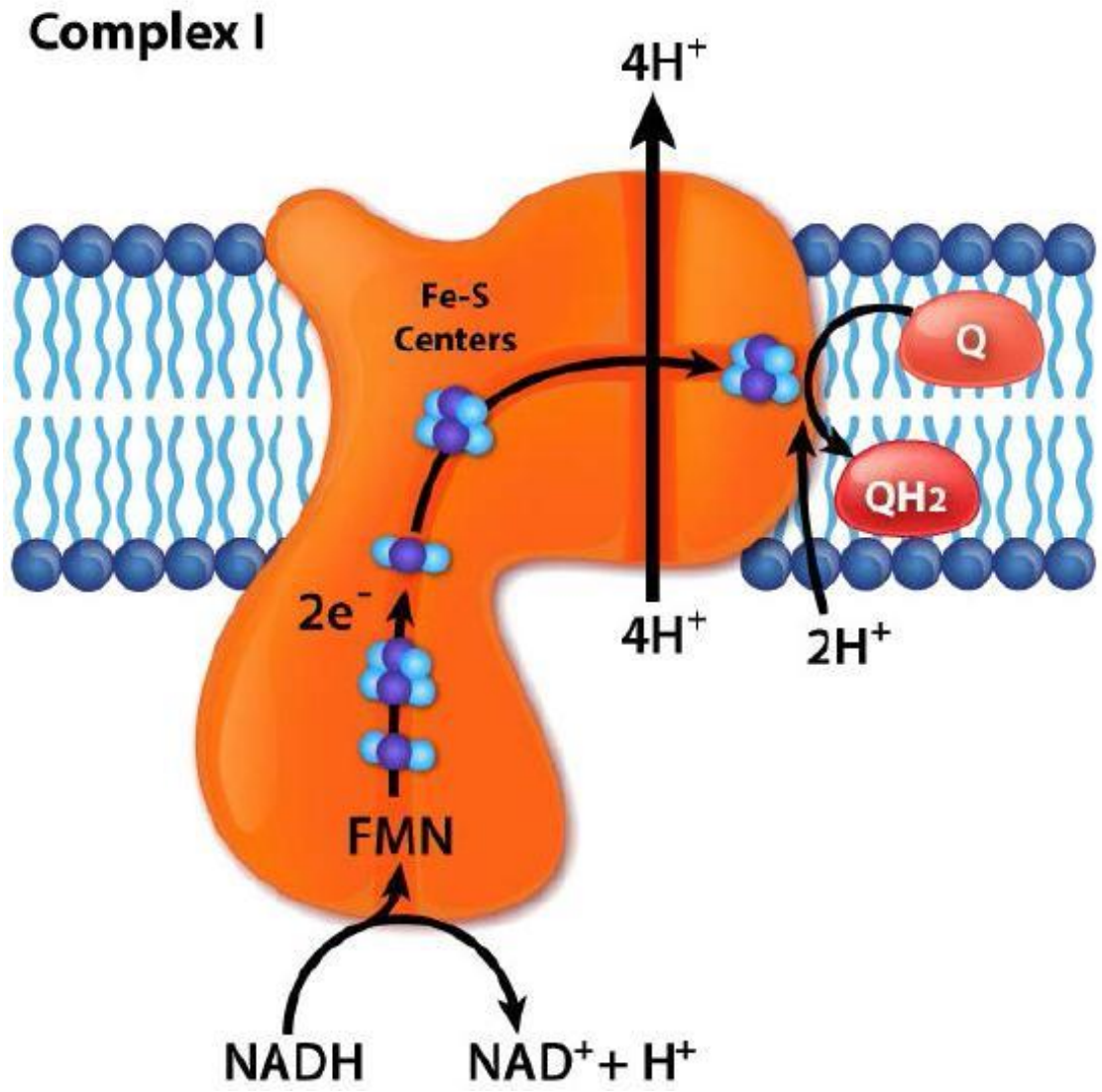
Organized as four functional complexes (I–IV)

Four Complexes

- Complex I – NADH dehydrogenase
- Complex II – Succinate dehydrogenase
- Complex III – Cytochrome bc_1 complex
- Complex IV – Cytochrome c oxidase



Complex I: NADH Dehydrogenase NADH-CoQ还原酶

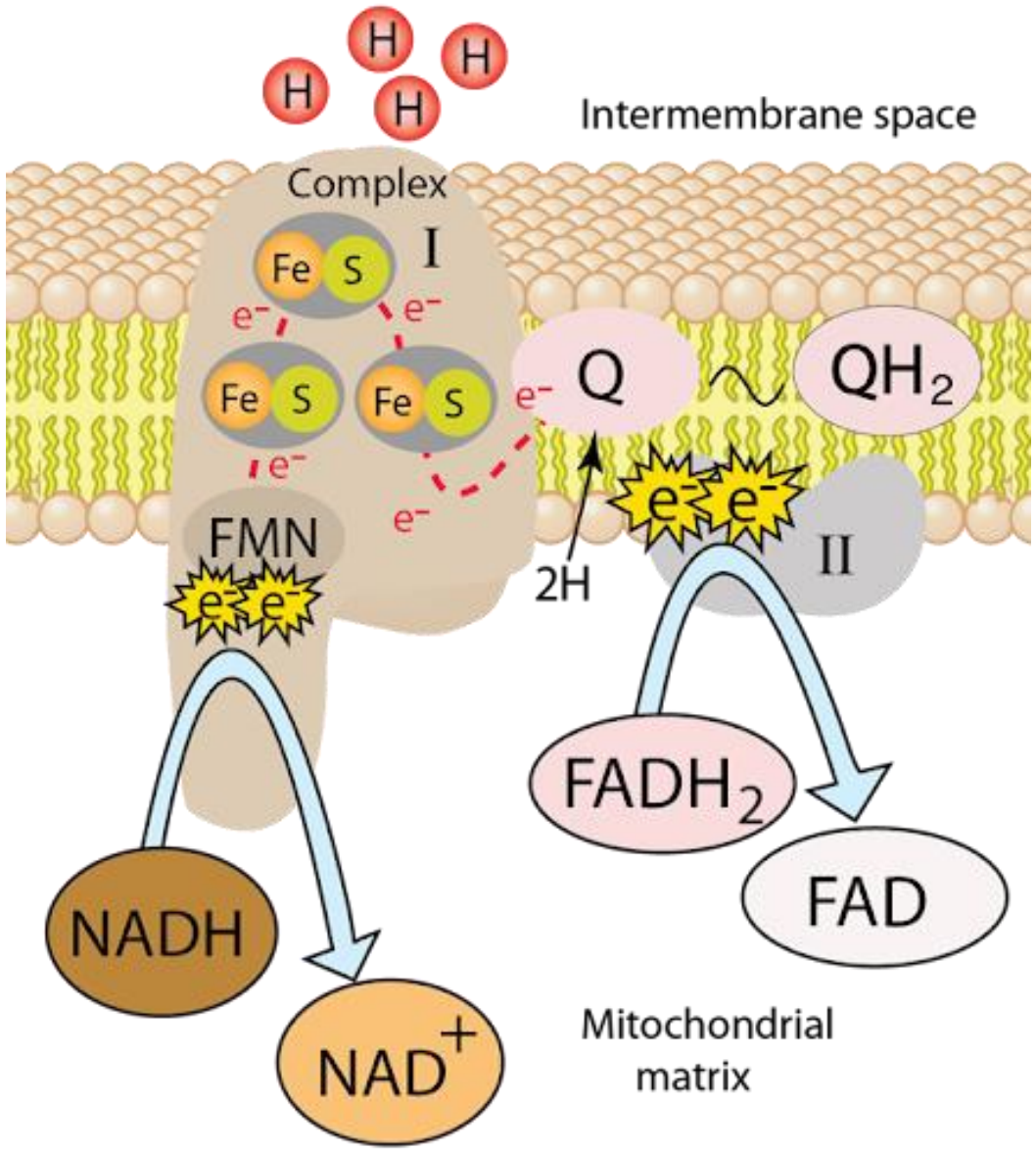


Components

FMN (flavin mononucleotide)

Iron–sulfur (Fe–S) clusters

Complex I: NADH Dehydrogenase NADH-CoQ还原酶



Transfers electrons:

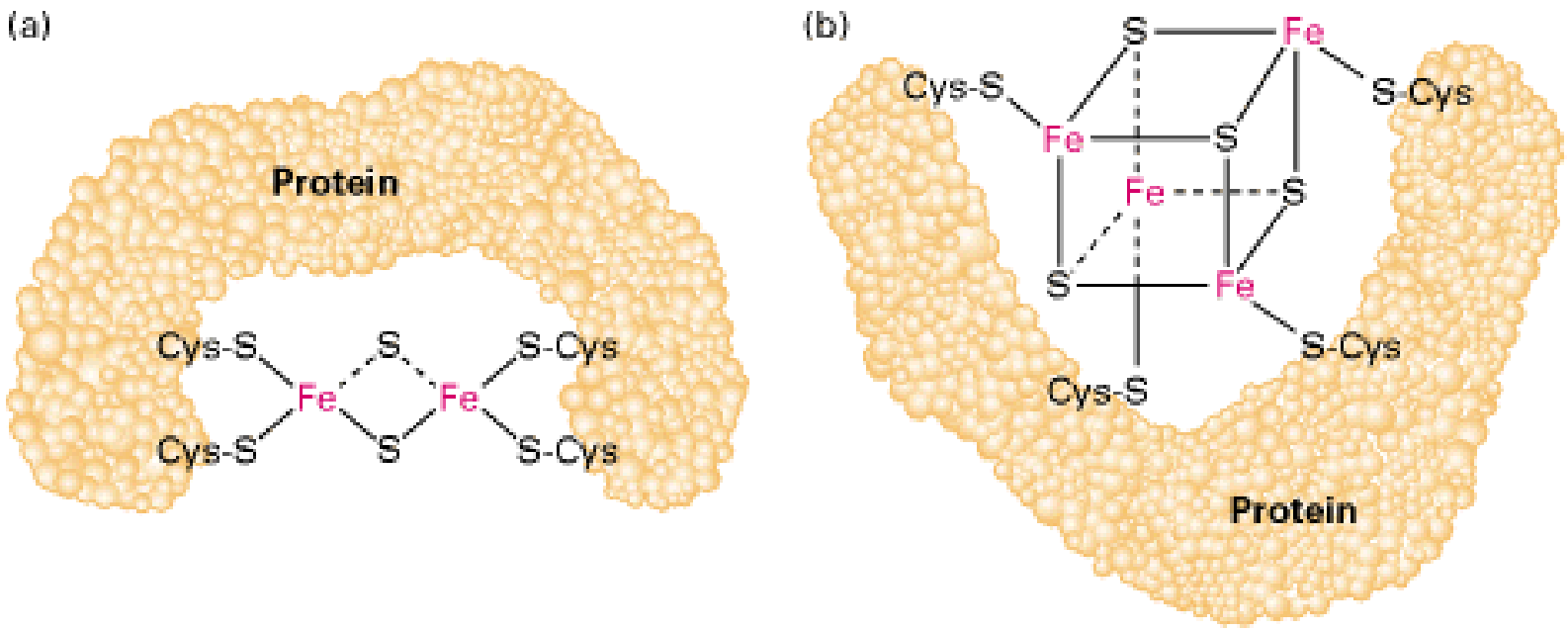
NADH→FMN→Fe–S→CoQ

Pumps protons:

4 H^+ from matrix → intermembrane space

Complex I: NADH Dehydrogenase NADH-CoQ还原酶

Iron–Sulfur Clusters (Fe–S Centers)



2Fe-2S

4Fe-4S

$$Fe^{3+} + e^- \leftrightarrow Fe^{2+}$$

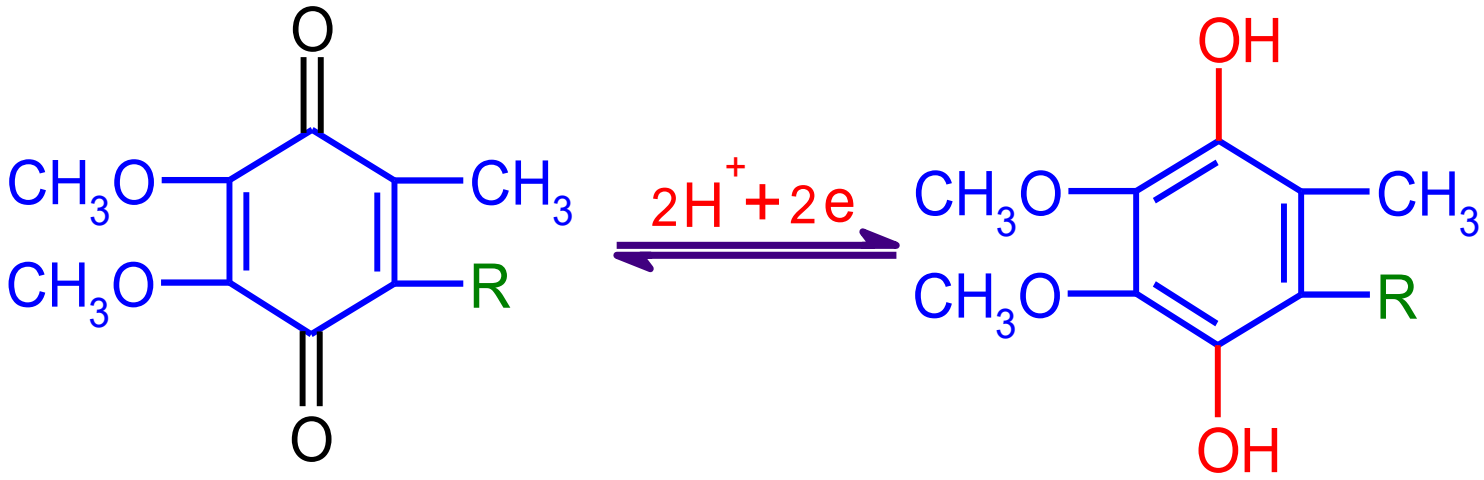
Complex I: NADH Dehydrogenase NADH-CoQ还原酶

Coenzyme Q (Ubiquinone, CoQ) / 辅酶Q（又称泛醌）

Lipid-soluble quinone / 脂溶性小分子

Located in the inner mitochondrial membrane

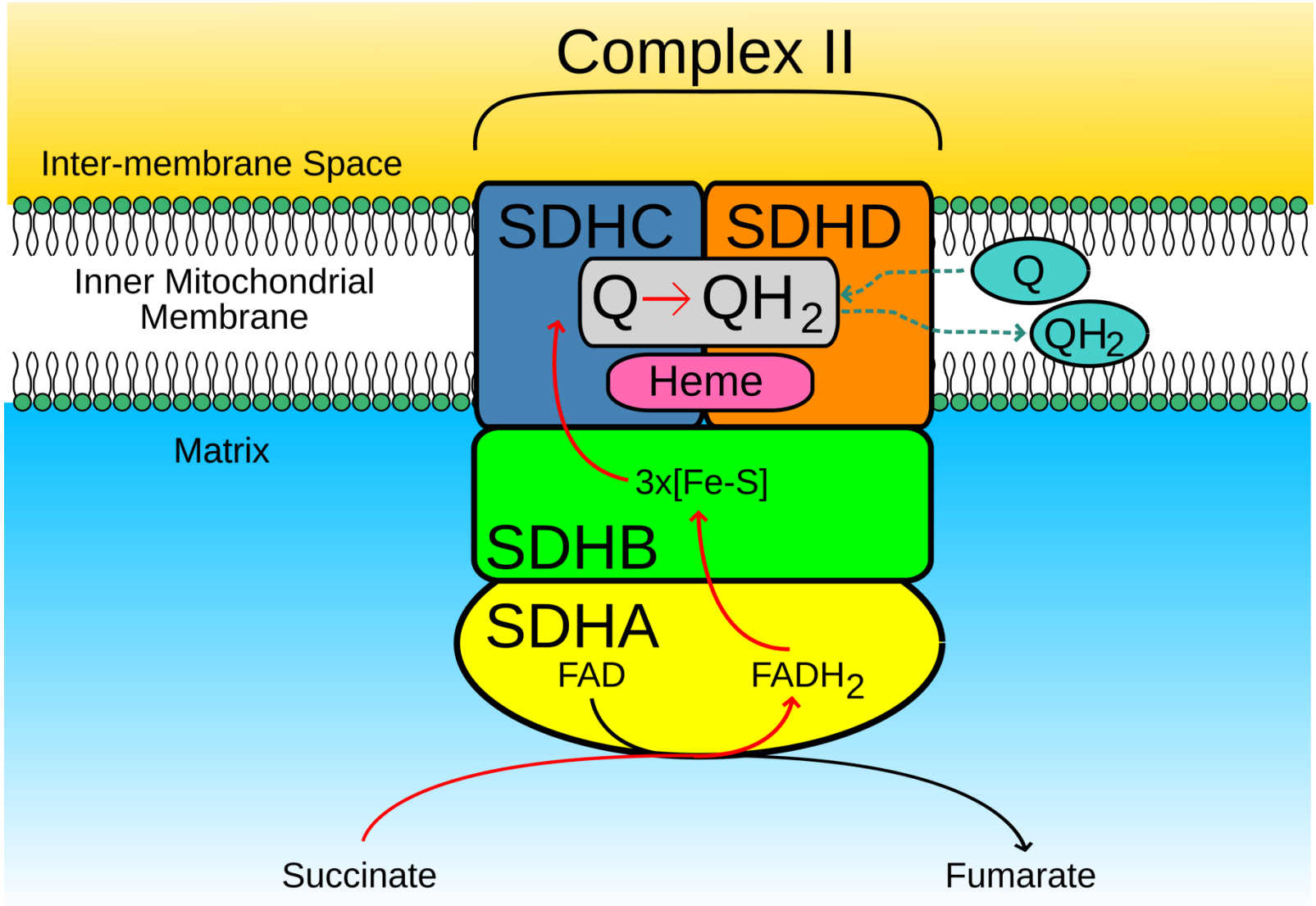
Mobile electron carrier



Coenzyme Q

ubiquinol (QH_2)
还原性醌

Complex II: Succinate-coenzyme Q reductase (SQR) 琥珀酸-CoQ还原酶



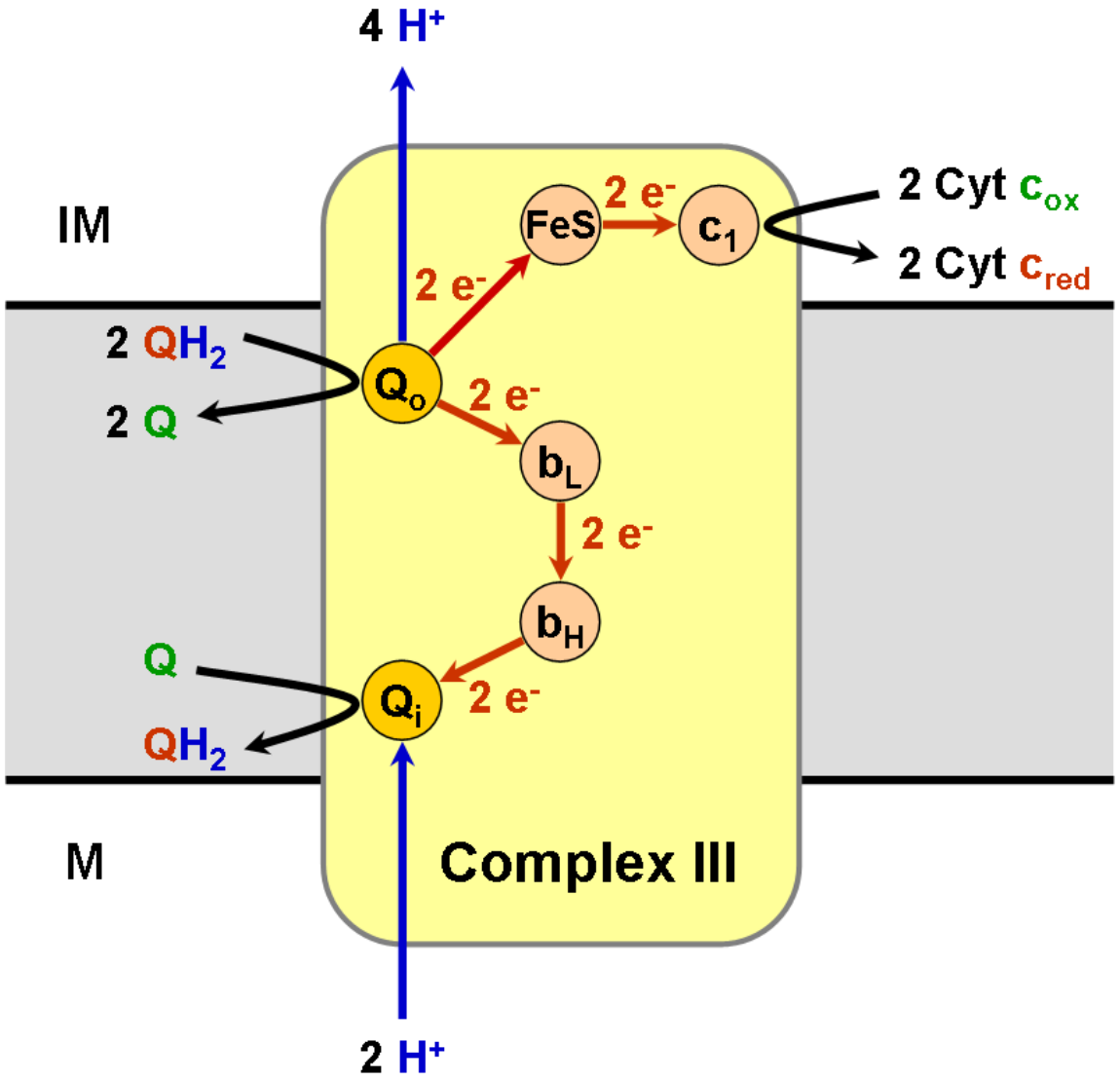
Inner mitochondrial membrane and active site faces the matrix

Contains: FAD, Fe–S

Transfers electrons to CoQ

No H^+ pumping

Complex III: coenzyme Q : cyt c – oxidoreductase 细胞色素C还原酶



Inner mitochondrial membrane

Components

- Cytochrome b
- Cytochrome c_1
- Iron–sulfur (Fe–S) protein

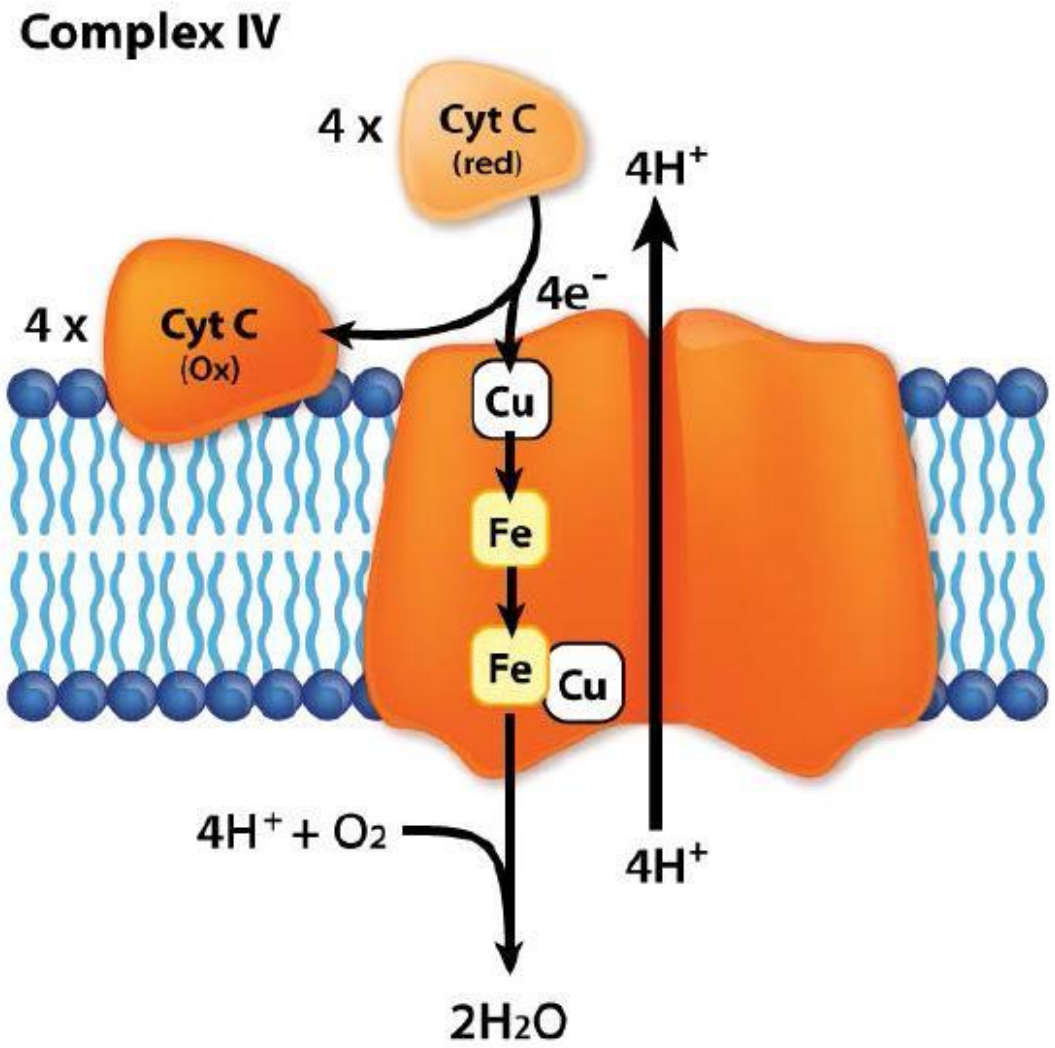
QH_2→Fe–S→c_1→Cytochrome c

Splits **2 electrons** from QH_2:

1 electron → **cytochrome c (one at a time)**

1 electron → recycled via **cytochrome b**

Complex IV: cytochrome c oxidase (COX) 细胞色素C氧化酶



Inner mitochondrial membrane

Components

- **Cytochromes a and a_3**
- **Copper centers (CuA, CuB)**

Pumps 4 H^+ across the membrane (per 4 electrons)

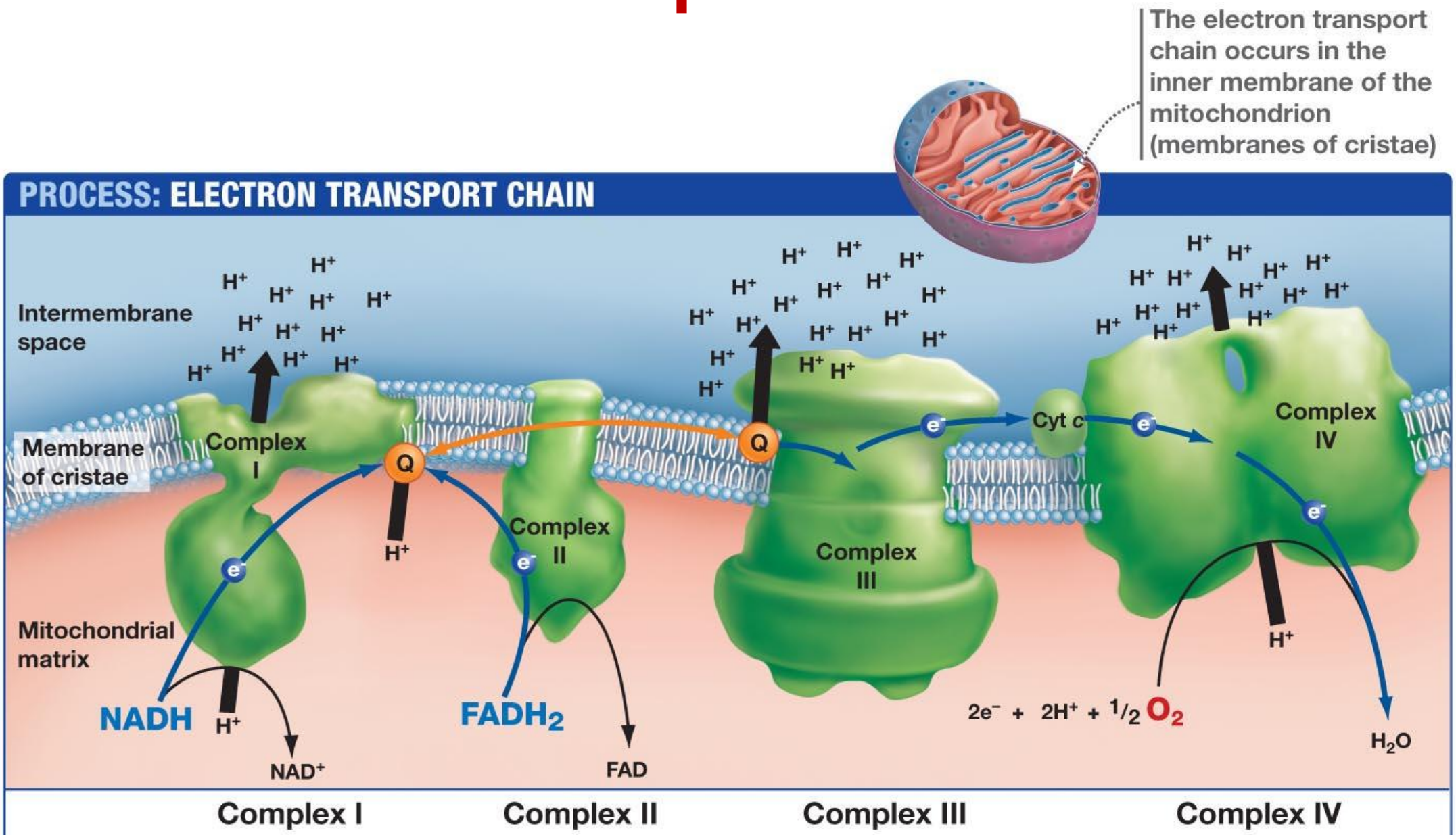
$$O_2 + 4\,H^+ + 4\,e^- \rightarrow 2\,H_2O$$

Features of ETC Complexes

Complex	Name	Electron Source	Electron Transfer	Proton Pumping
I	NADH dehydrogenase	NADH	→ CoQ	Yes
II	Succinate dehydrogenase	$FADH_2$	→ CoQ	**No**
III	Cytochrome bc_1	$CoQH_2$	→ Cytochrome c	Yes
IV	Cytochrome c oxidase	Cytochrome c	→ O_2 → H_2O	Yes

Not all complexes pump protons—this is why NADH and $FADH_2$ yield different ATP.

Electron Transport Chain



Electron Transport Chain

NADH vs $FADH_2$ Entry into ETC

Similarities

Electrons ultimately transferred to $\mathbf{O_2} \rightarrow \mathbf{H_2O}$

Occur in the **same electron transport chain**

Converge at **Coenzyme Q (CoQ)**

Differences

Feature	**NADH**	**$FADH_2$**
Entry point	Complex I	Complex II
Proton pumping	Yes (I, III, IV)	Only III, IV
ATP yield	~2.5 ATP	~1.5 ATP

Electron Transport Chain

How Was ETC Studied?

Redox potential (E°') measurement / 氧化还原电位测定

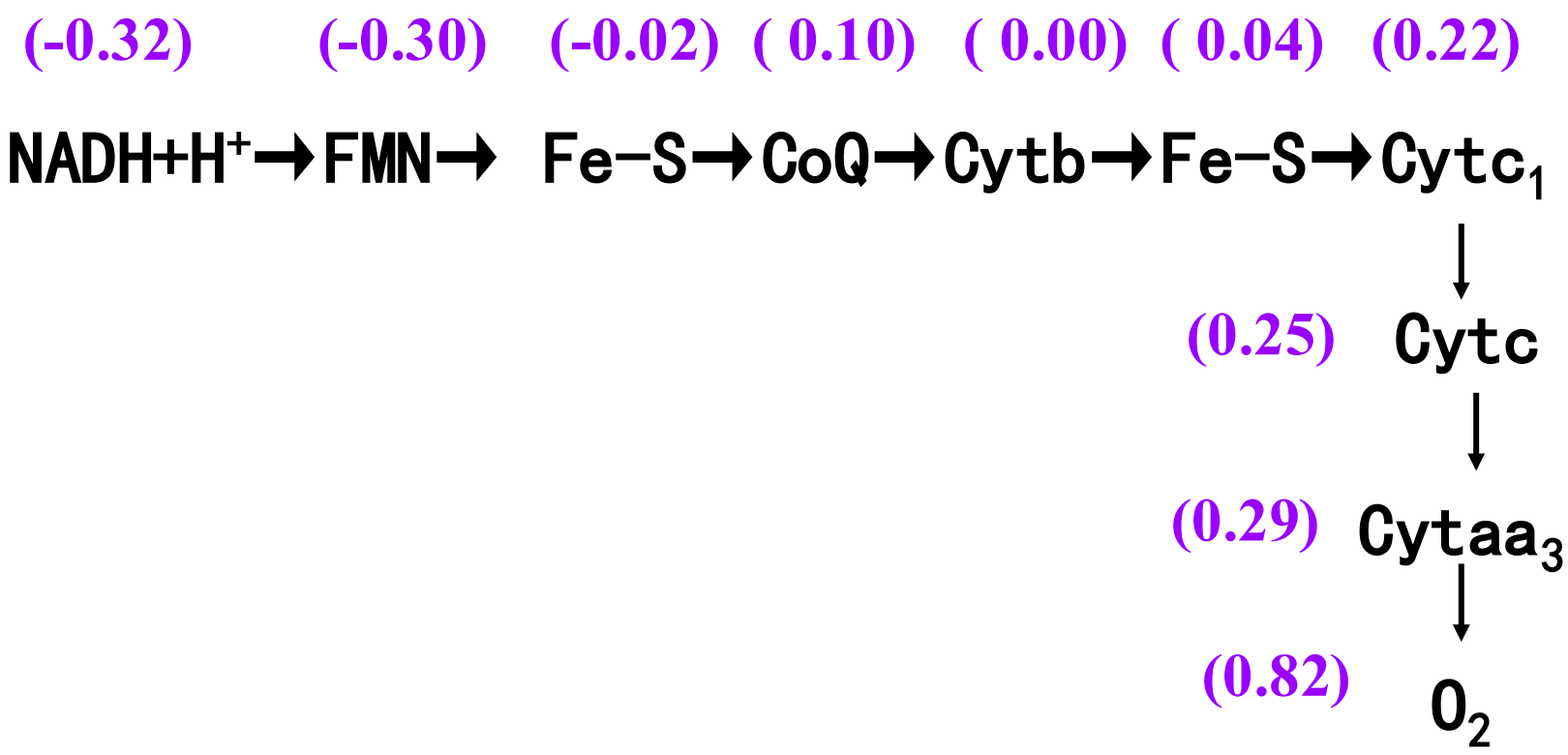
Reconstitution of complexes / 复合物重组

Spectroscopy (oxidation state changes) / 利用光谱测定组分氧化态

Use of inhibitors / 抑制剂

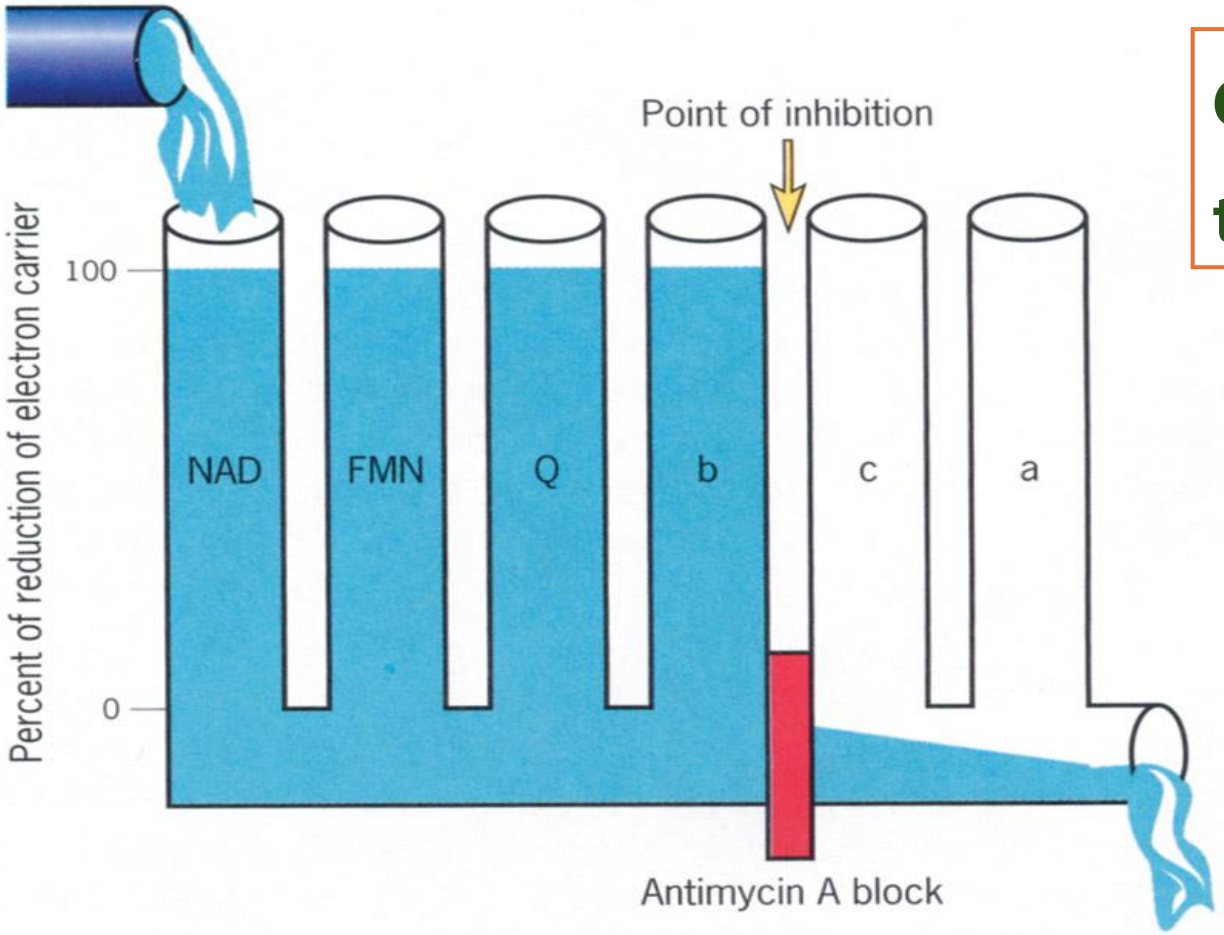
Electron Transport Chain

Redox Potential & Electron Flow



Electron Transport Chain

Electron Transport Chain Inhibitors



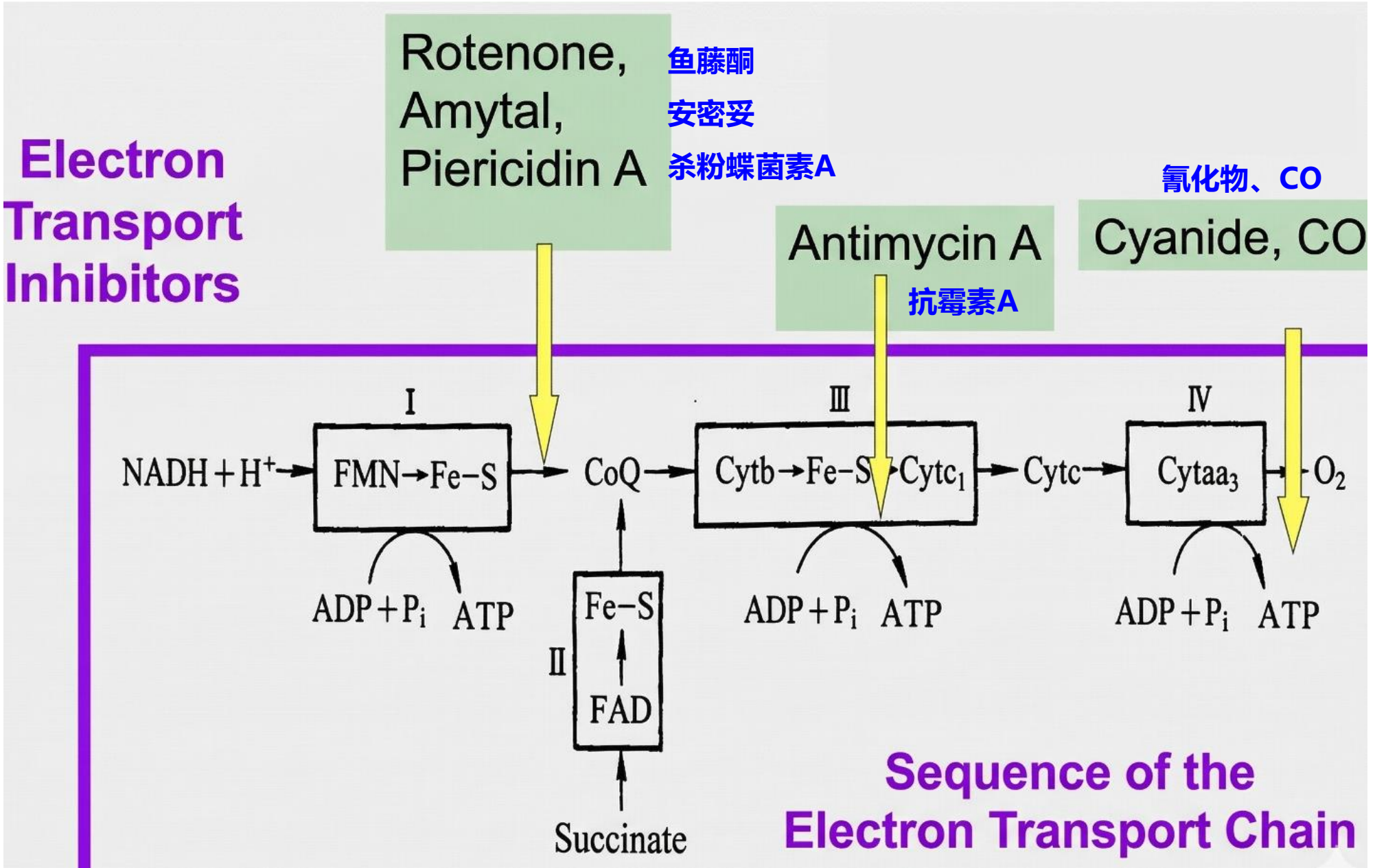
Compounds that block electron transfer at specific sites in the ETC

Block electron flow

Upstream → reduced

Downstream → oxidized

Electron Transport Chain



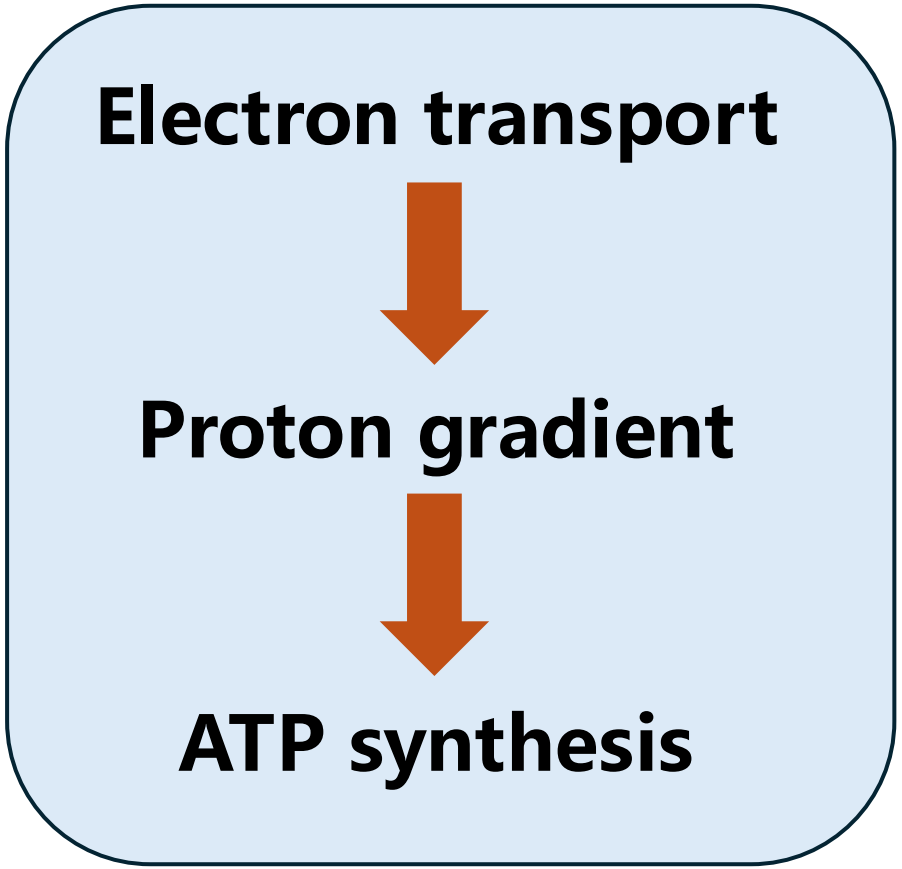
Oxidative Phosphorylation

Oxidative phosphorylation is the process in which ATP is synthesized by coupling electron transport to proton gradient formation (chemiosmosis).

Where Does It Occur?

Inner mitochondrial membrane

Main source of ATP in aerobic cells

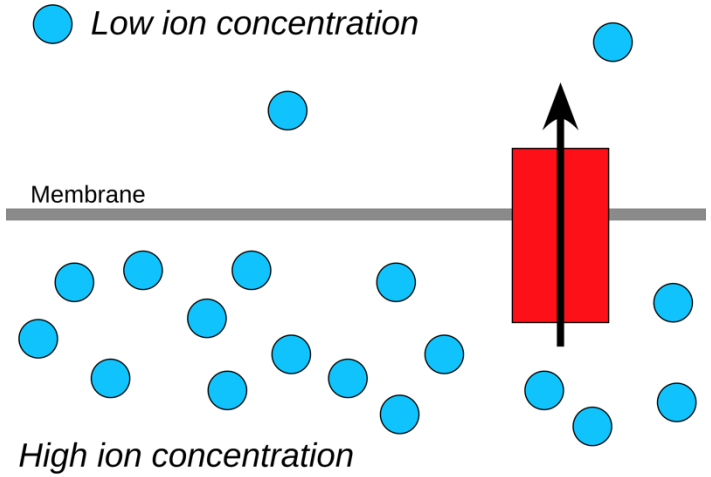


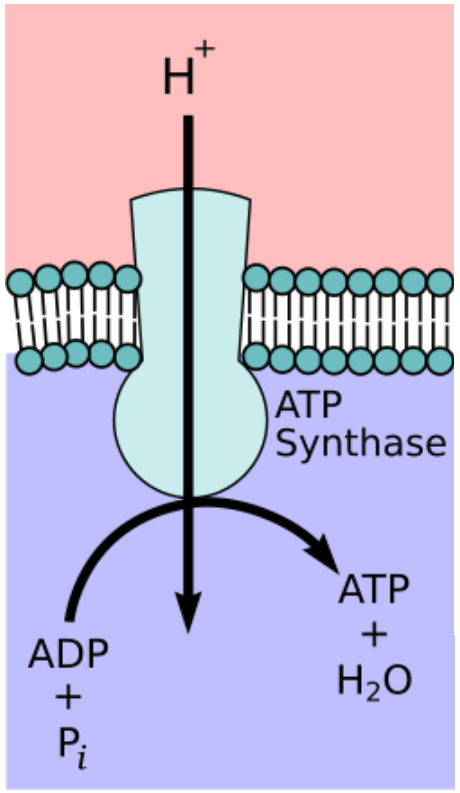
Chemiosmotic

Chemiosmotic mechanism of ATP synthesis



Peter Mitchell 1978 Nobel Prize for Chemistry





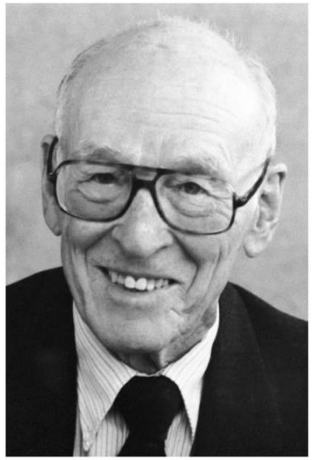


Photo from the Nobel Foundation archive.

Paul D. Boyer

Prize share: 1/4

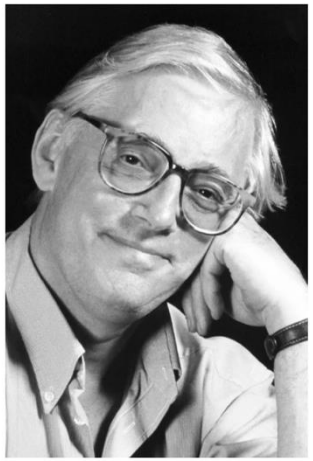


Photo from the Nobel Foundation archive.

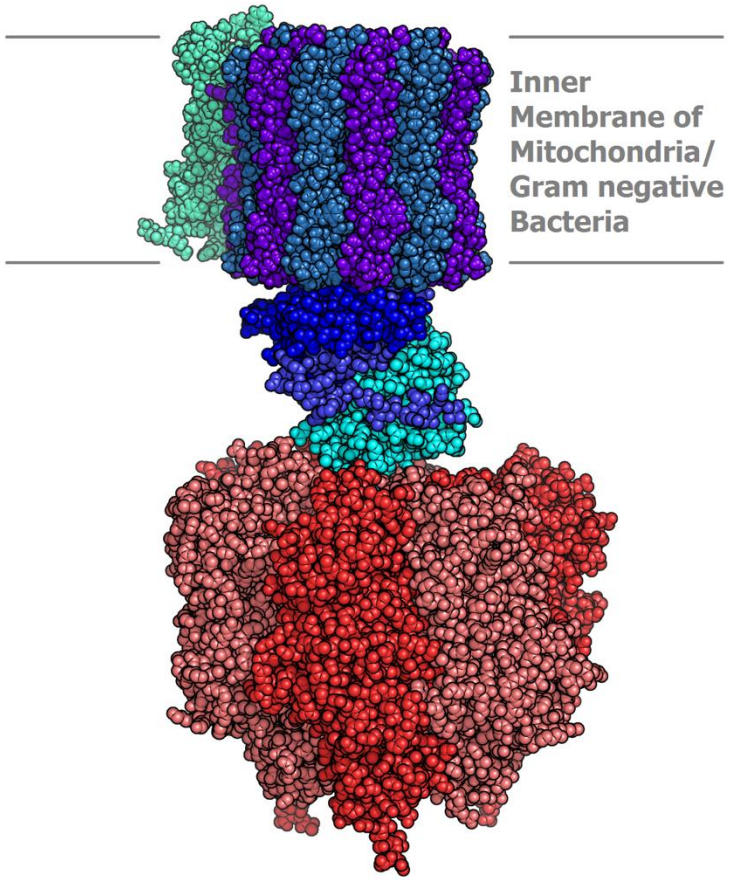
John E. Walker

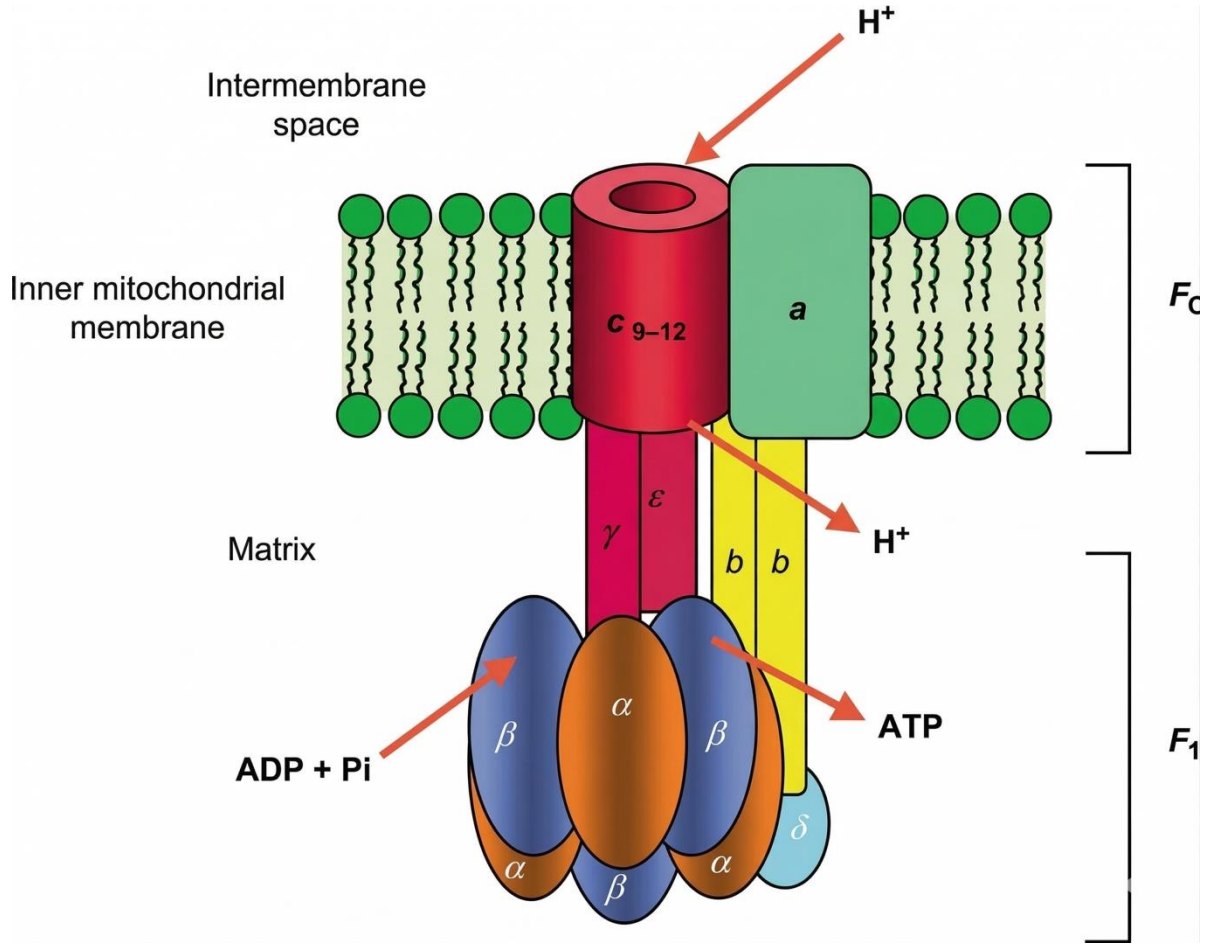
Prize share: 1/4

The Nobel Prize in Chemistry 1997 was divided, one half jointly to Paul D. Boyer and John E. Walker "for their elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP)"

Chemiosmotic

ATP Synthase Structure





Chemiosmotic

ATP Synthase Structure

F_0 (Membrane Portion)

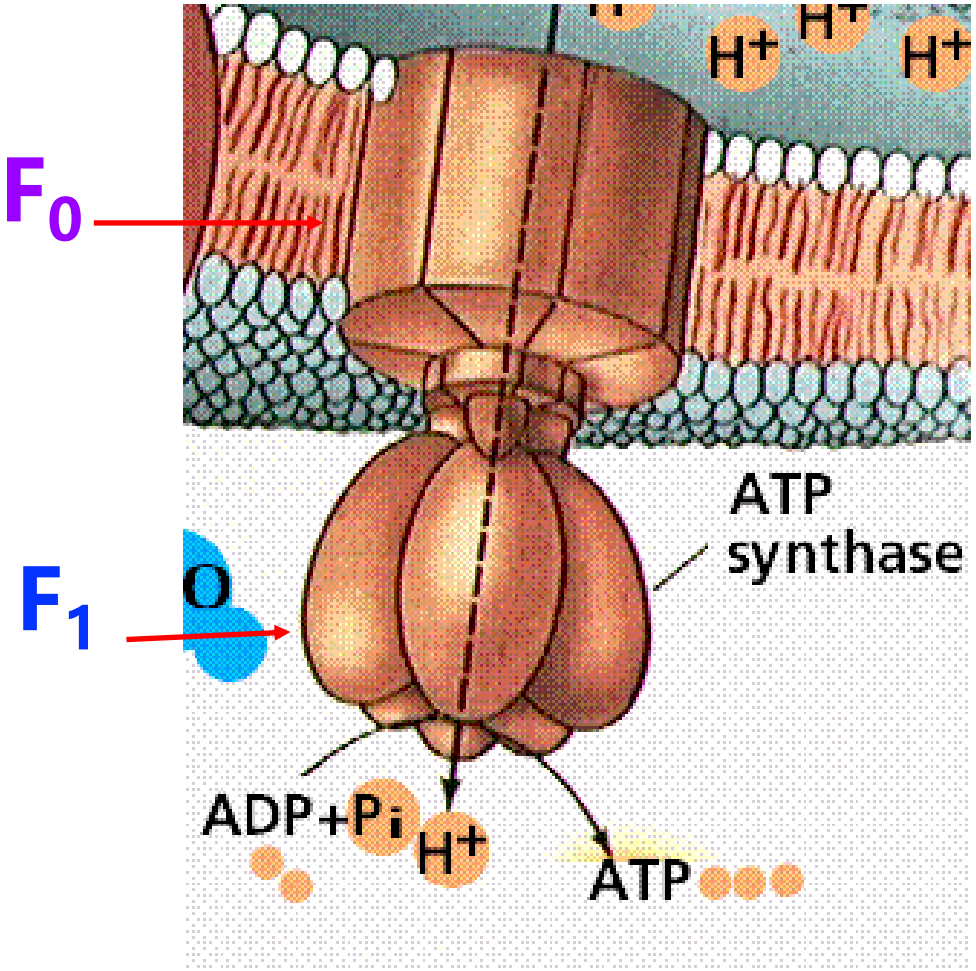
Located in Inner mitochondrial membrane

Function as Proton channel (H^+ flow)

F_1 (Matrix Portion)

Extends into Mitochondrial matrix

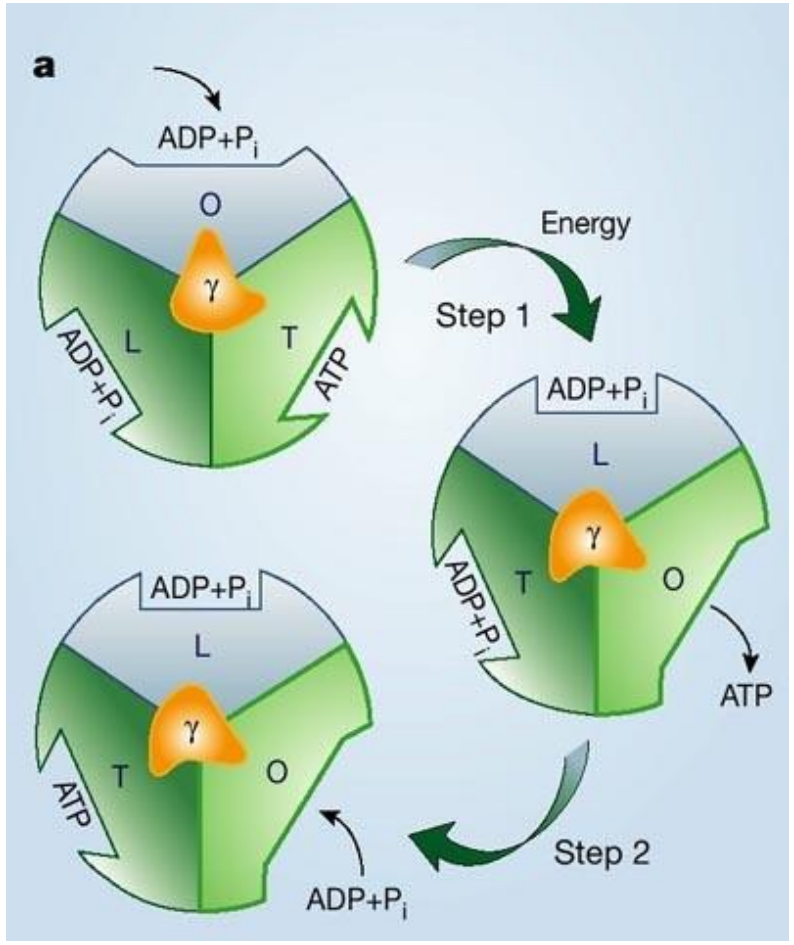
Function as Catalytic site for ATP synthesis



Chemiosmotic

Rotational Catalysis Mechanism

Proposed by **Boyer (1964),** Confirmed by **Walker; shared half of Nobel Prize, 1997**

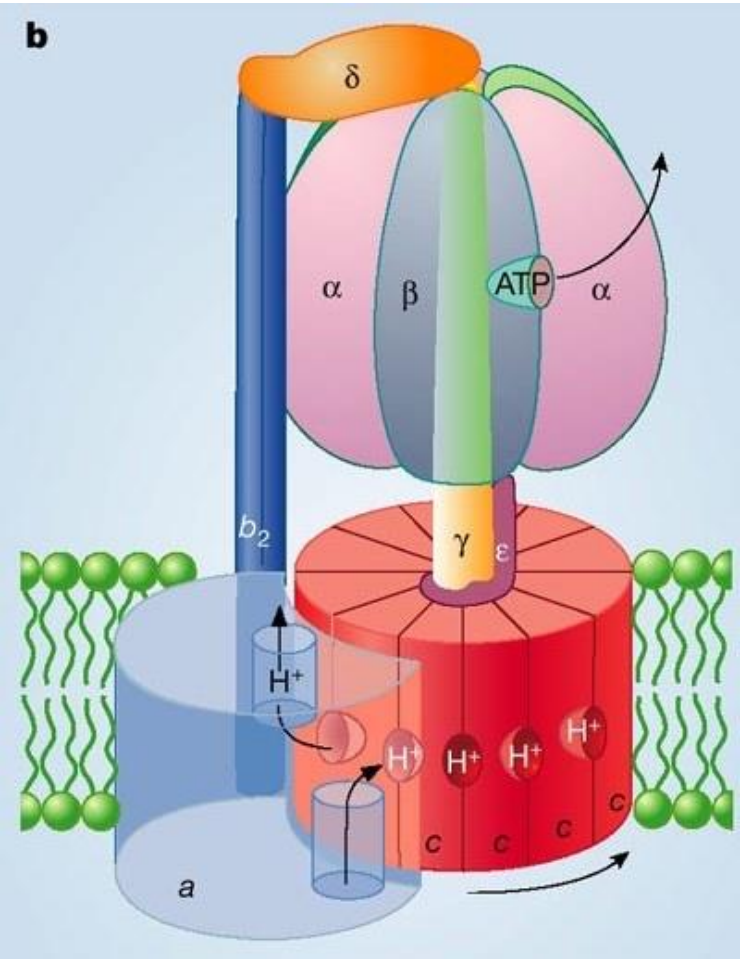


Conformations of β Subunits

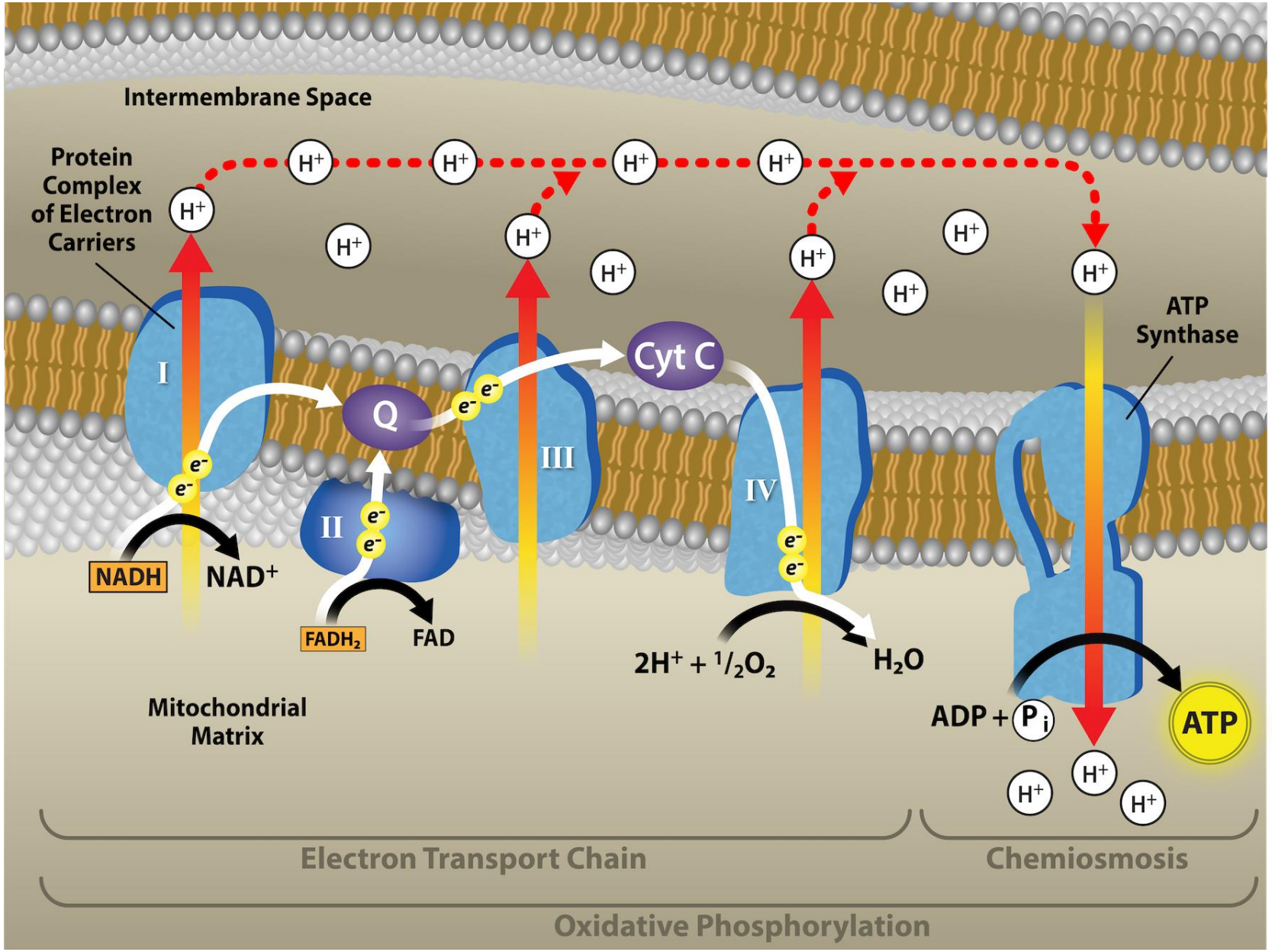
O (Open) → releases ATP

L (Loose) → binds ADP + Pi

T (Tight) → synthesizes ATP



Coupling of Electron Transport and Chemiosmotic



Coupling of Electron Transport and Chemiosmotic

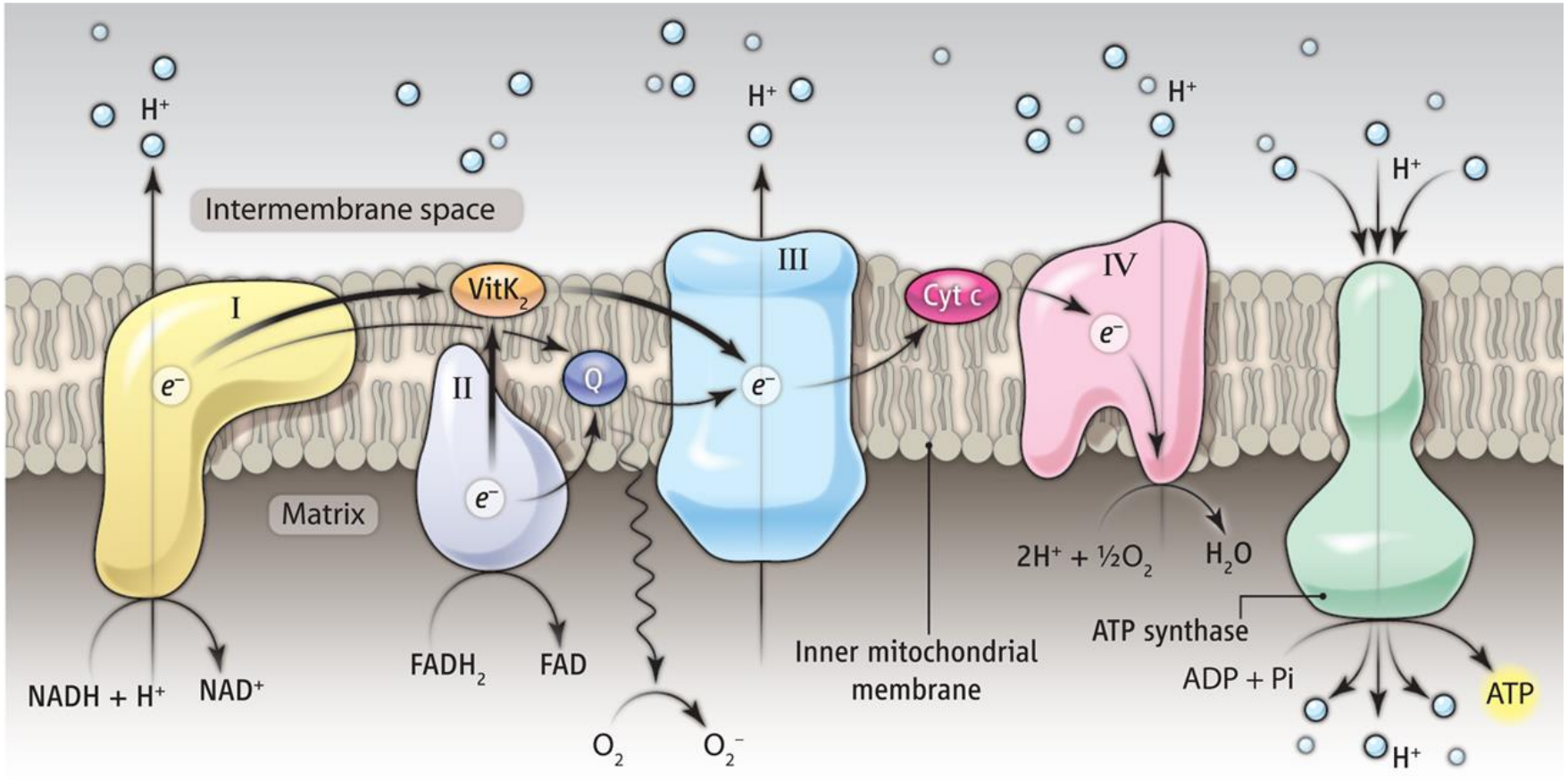
P/O Ratio: Number of ATP molecules produced per pair of electrons transferred to O_2.

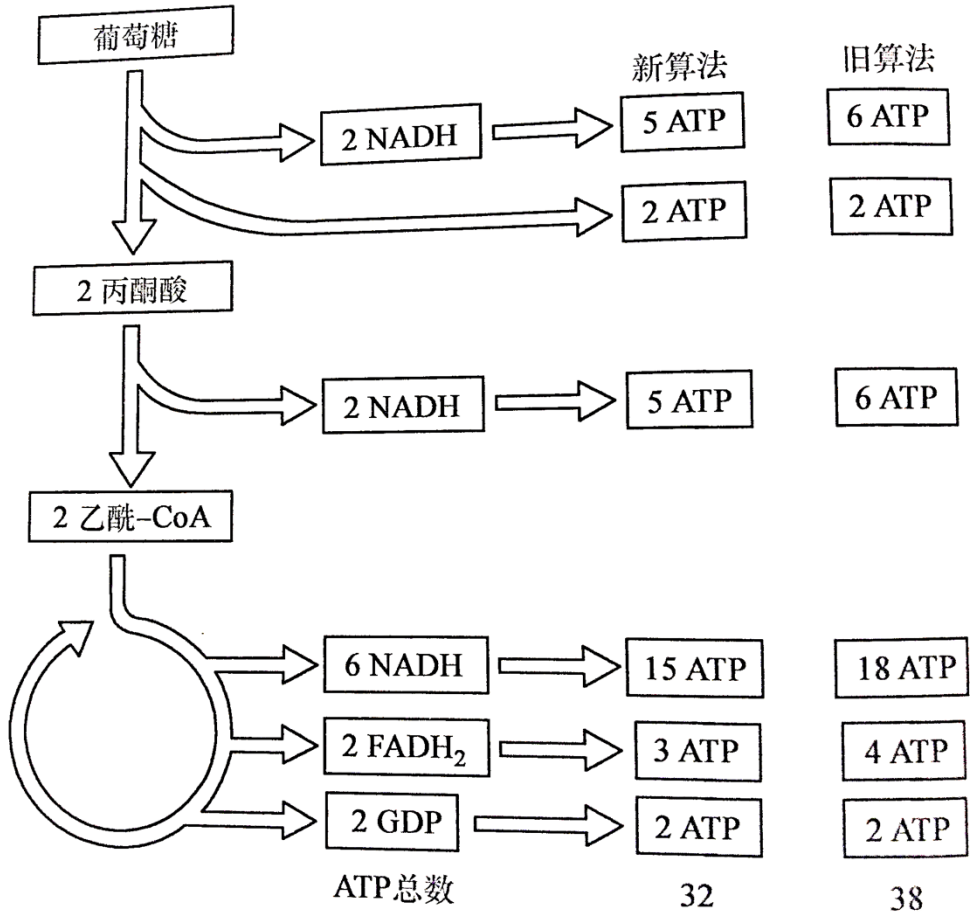
ATP yield depends on where electrons enter the ETC

P/O Ratio

NADH → 2.5 ATP

$FADH_2$ → 1.5 ATP





$$G + 10NAD^+ + 2FAD + 4ADP + 4Pi$$

↓

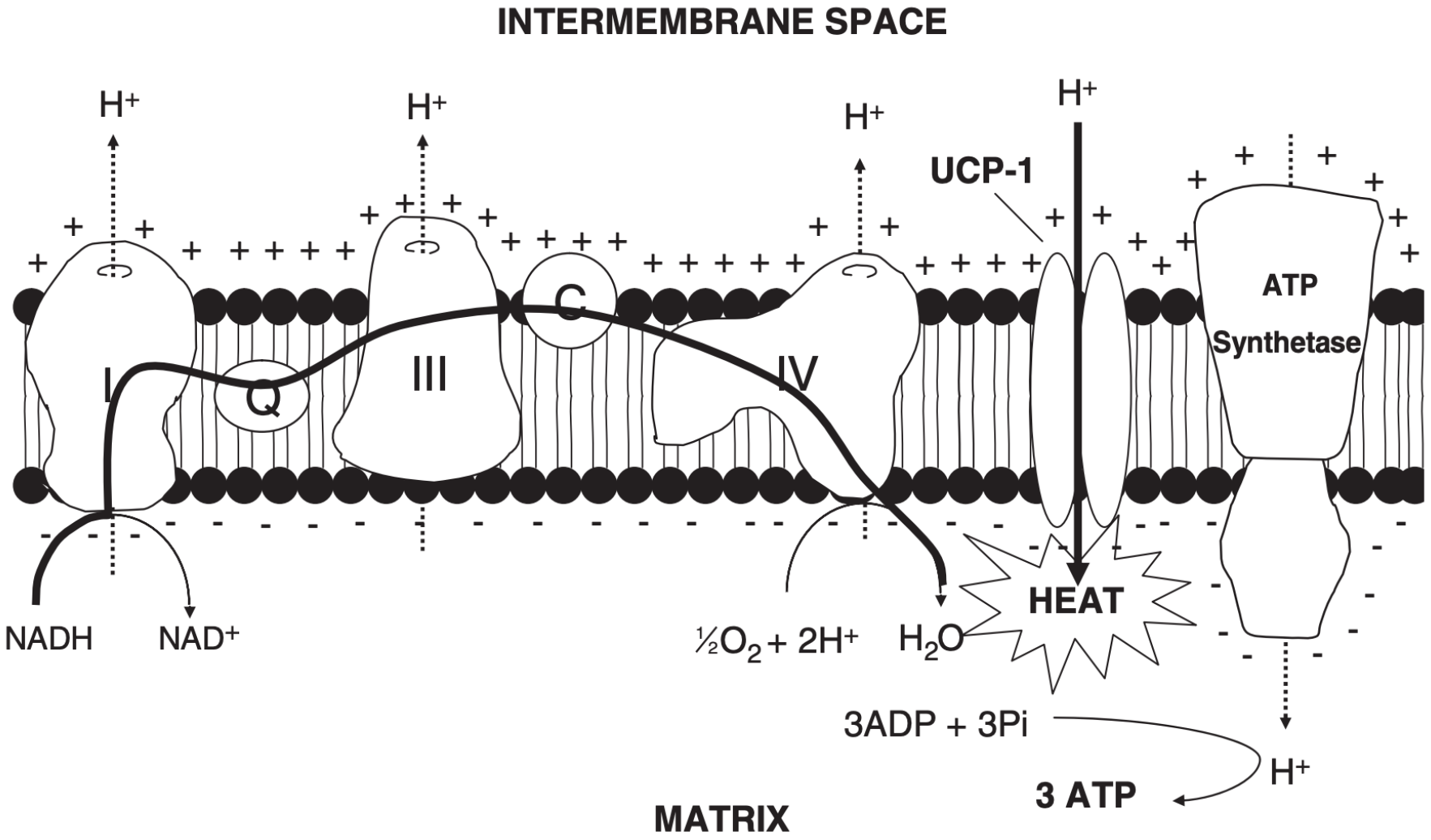
$$6CO_2 + 10NADH + 10H^+ + 2FADH_2 + 4ATP$$

Uncoupling and Inhibition of Oxidative Phosphorylation

Do NOT block electron transport

Disrupt the proton gradient

Energy released as heat



Uncoupling of Oxidative Phosphorylation

Newborn mammals (brown adipose tissue)



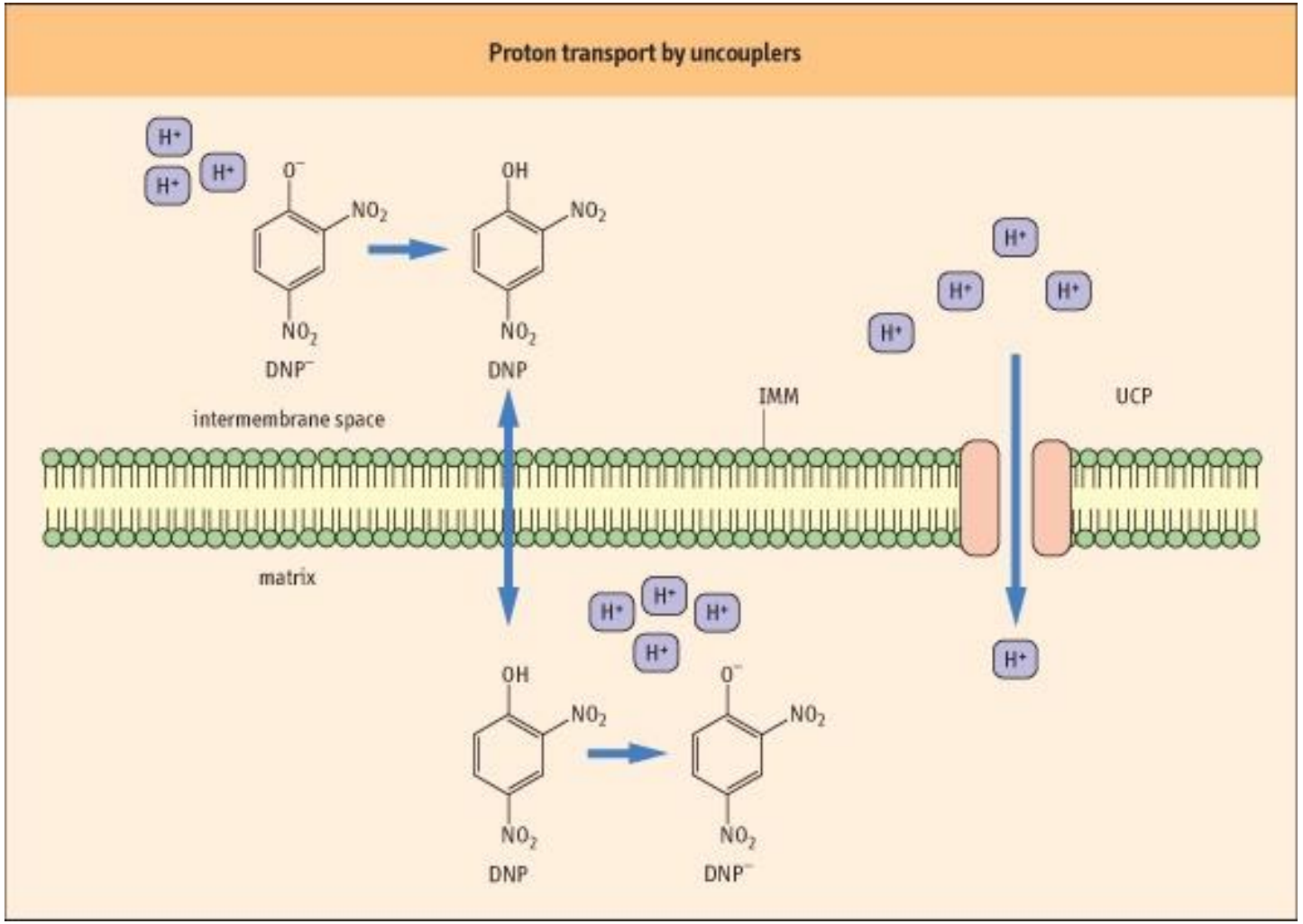


Hibernating animals (e.g., bears)



ETC ON, ATP OFF → Heat produced

Inhibition of Oxidative Phosphorylation



Uncoupler: DNP (2,4-Dinitrophenol)

2,4-二硝基苯酚

Mechanism

DNP acts as a protonophore

Carries H^+ across the inner mitochondrial membrane

Inhibition of Oxidative Phosphorylation

Target: ATP Synthase

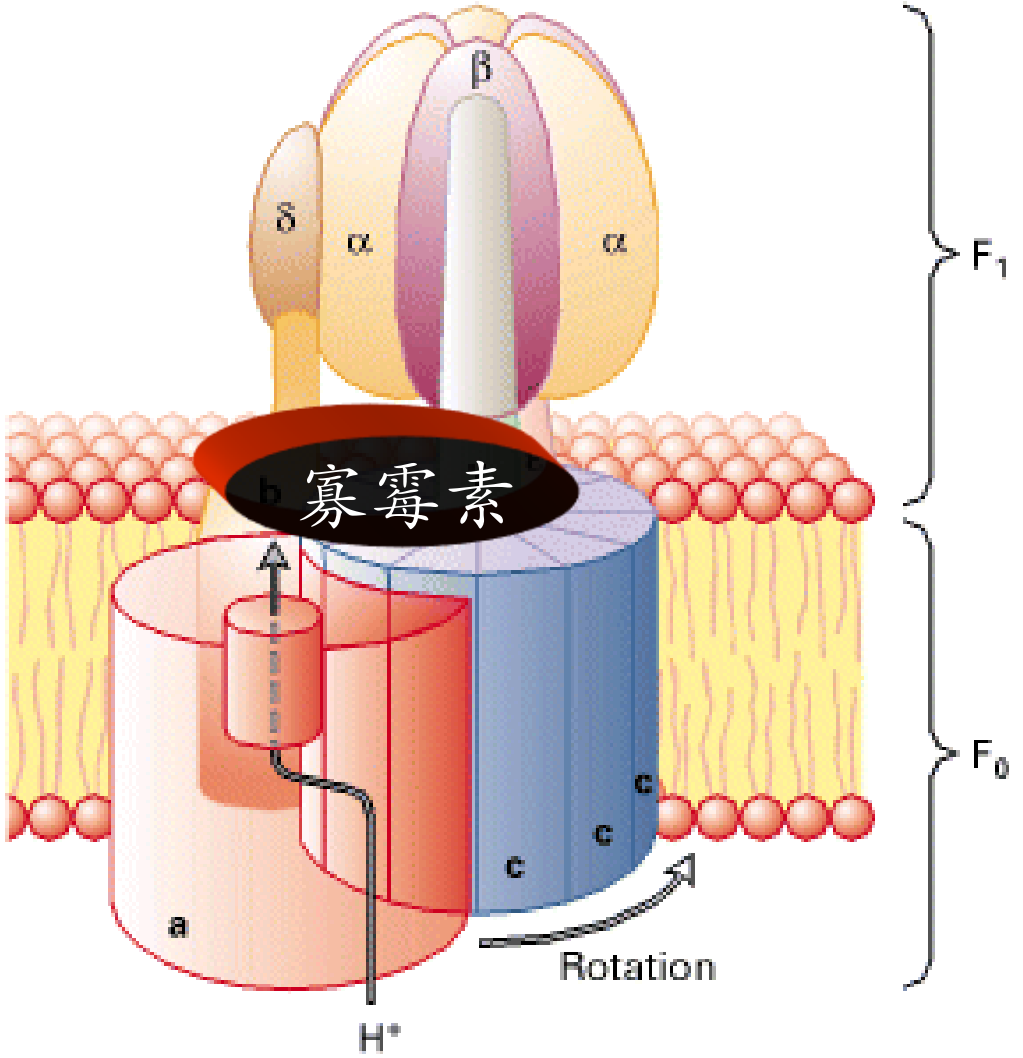
Example: Oligomycin / 寡霉素

Mechanism

Binds to F_0 subunit

Blocks proton channel , and H^+

cannot flow back into matrix



Respiration from Carbohydrate Catabolism perspective

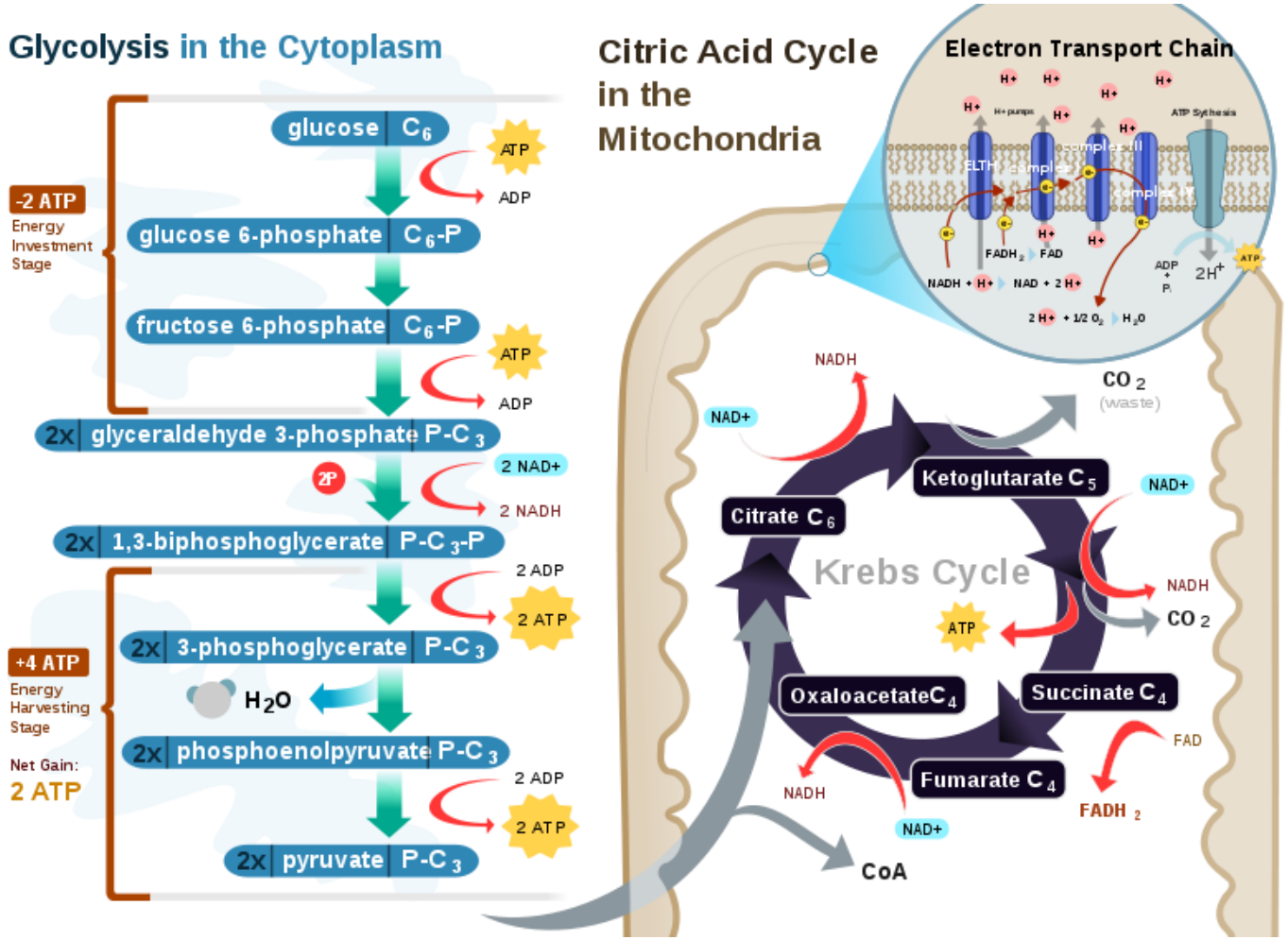
Cellular Respiration

Occurs in:

- Cytosol (glycolysis)
- Mitochondria (TCA + ETC)

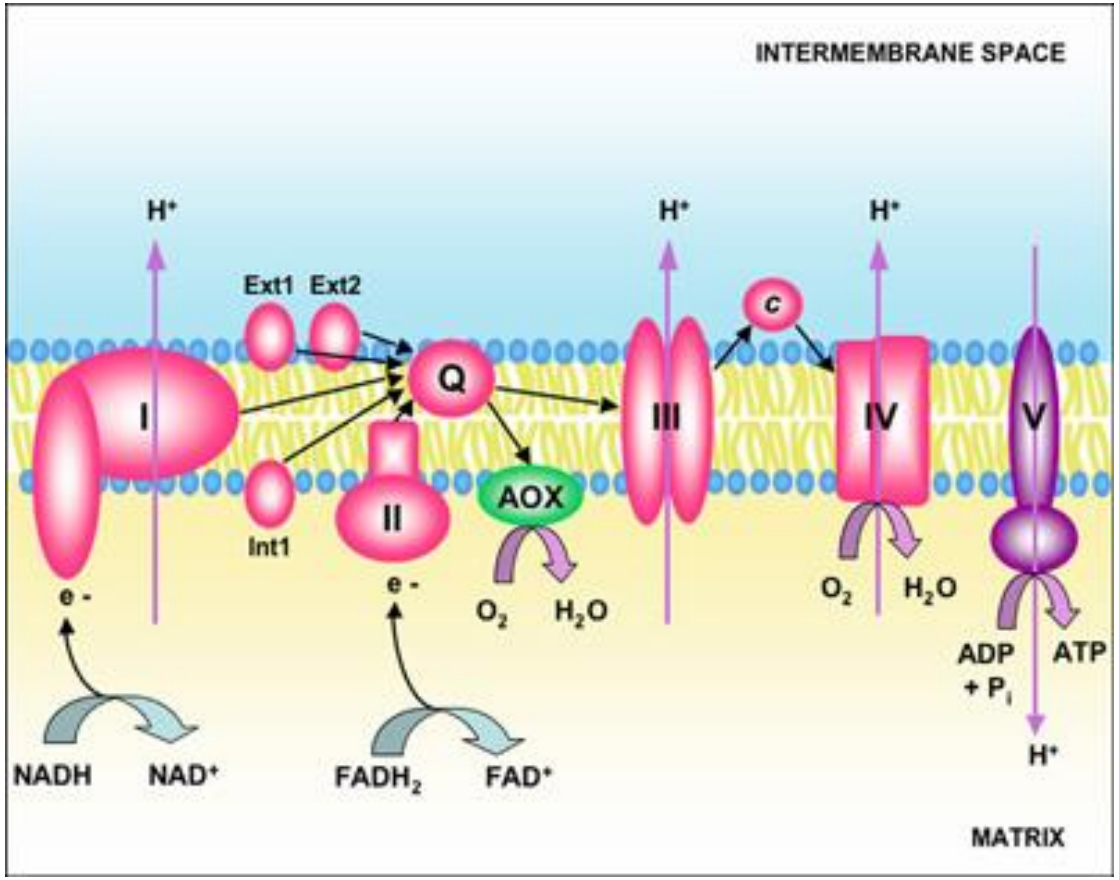
Functions:

- ATP production
- NADH/$FADH_2$ generation
- Metabolic integration



Respiration in Plant Physiology

Respiration is the process by which organic molecules are oxidized to generate ATP, producing CO_2 and H_2O under aerobic conditions.



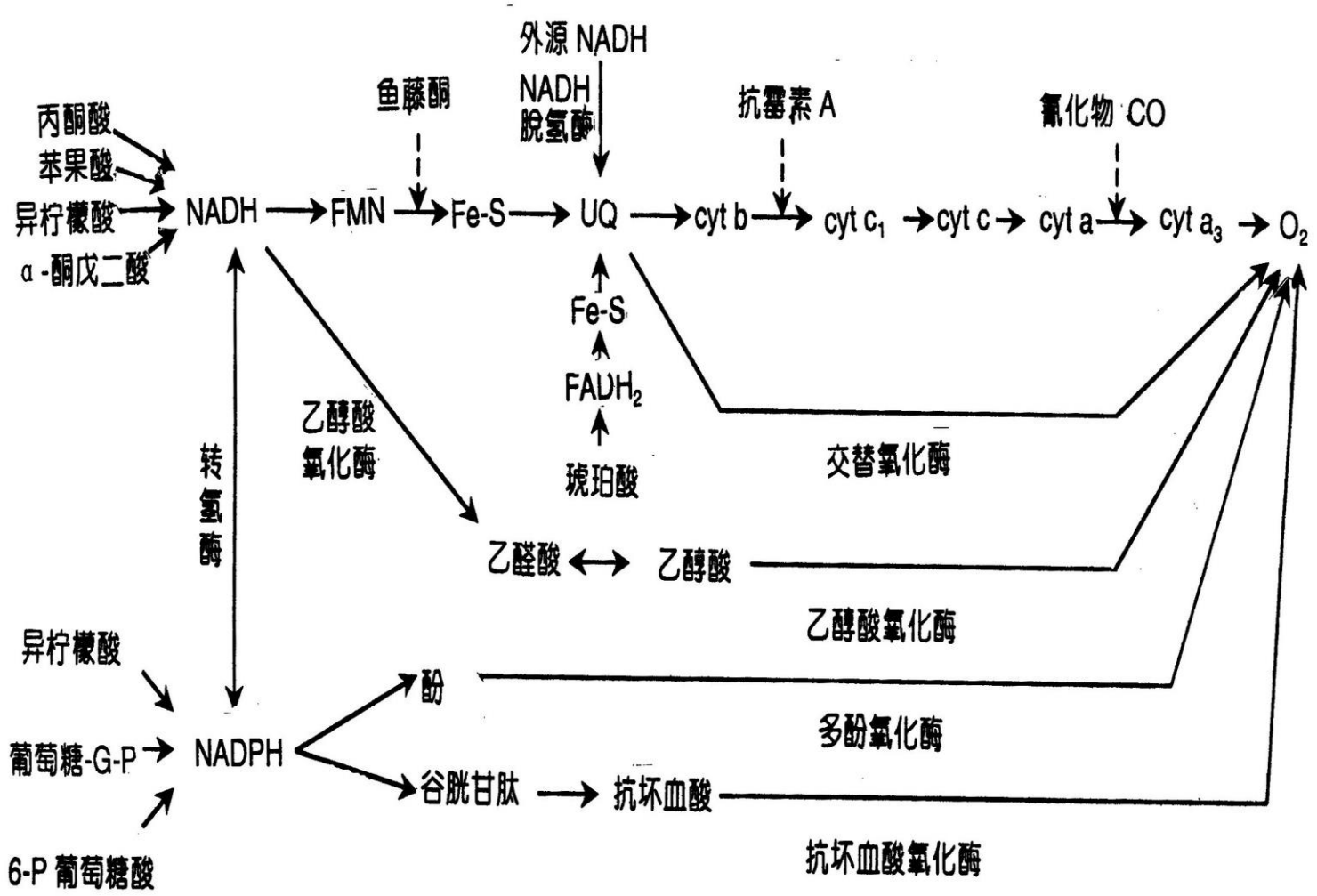
Plant-Specific Feature： **Alternative oxidase (AOX) pathway**

交替途径(抗氰呼吸)

Electrons bypass Complex III & IV and transferres directly to O_2 via AOX

Respiration in Plant Physiology

Plant Respiratory Electron Pathways



Respiration in Plant Physiology

Measurement of Respiration in Plant Physiology

Respiration Rate: Amount of **CO_2 released** or **O_2 consumed** per unit time and mass

Respiratory Quotient (RQ)/ 呼吸商:

$$RQ = \frac{CO_2 \text{ produced}}{O_2 \text{ consumed}}$$

Indicates **Respiratory substrate** and **Oxygen availability**

Respiration in Plant Physiology

Measurement of Respiration in Plant Physiology

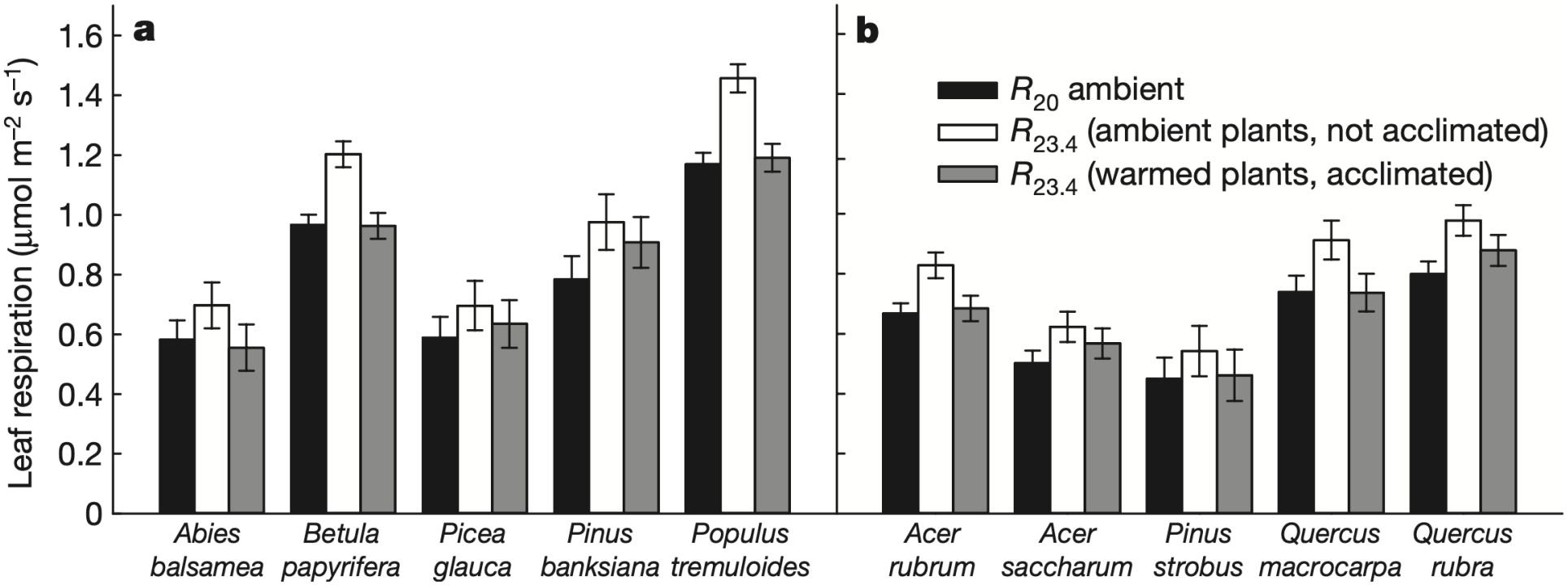
RQ is influenced by both substrate and oxygen availability

Substrate	RQ	Explanation
Carbohydrates	≈ 1.0	Balanced oxidation
Lipids	< 1	More O_2 required
Proteins	< 1	Similar to lipids
Organic acids	> 1	Less O_2 needed

Respiration in Plant Physiology

Internal Factors Affecting Respiration Rate

1. Plant species



Respiration in Plant Physiology

Internal Factors Affecting Respiration Rate

2. Different Among Organs

Young, actively growing tissues → high respiration rate

Reproductive organs > vegetative organs

Highest in: pollen, developing flowers

Example (Apple)

•Young shoots > stems > roots

(Reflects **metabolic activity)**

Respiration in Plant Physiology

Internal Factors Affecting Respiration Rate

3. Effect of Developmental Stage

Young tissues → high respiration

Mature tissues → moderate

Senescent tissues → decline

4. Physical Factors

Water content

Substrate availability

Enzyme activity

Mitochondrial function

Respiration in Plant Physiology

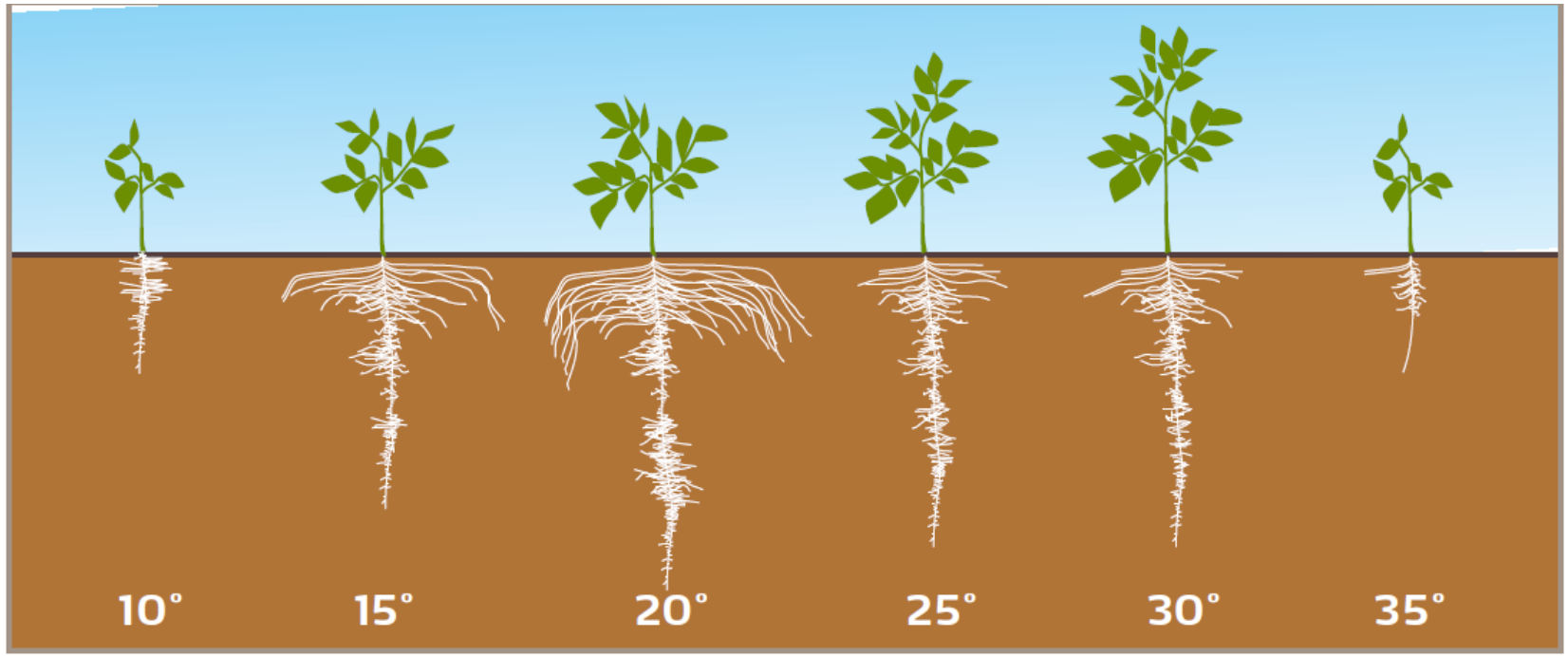
Environment Factors Affecting Respiration Rate

1. Temperature

Both extremes reduce respiration efficiency

Low Temperature Respiration slows; but may continue even below 0°C (cold-adapted plants)

High Temperature increase respiration at short-term; but may cause enzyme denaturation and membrane damage, then declines respiration



Respiration in Plant Physiology

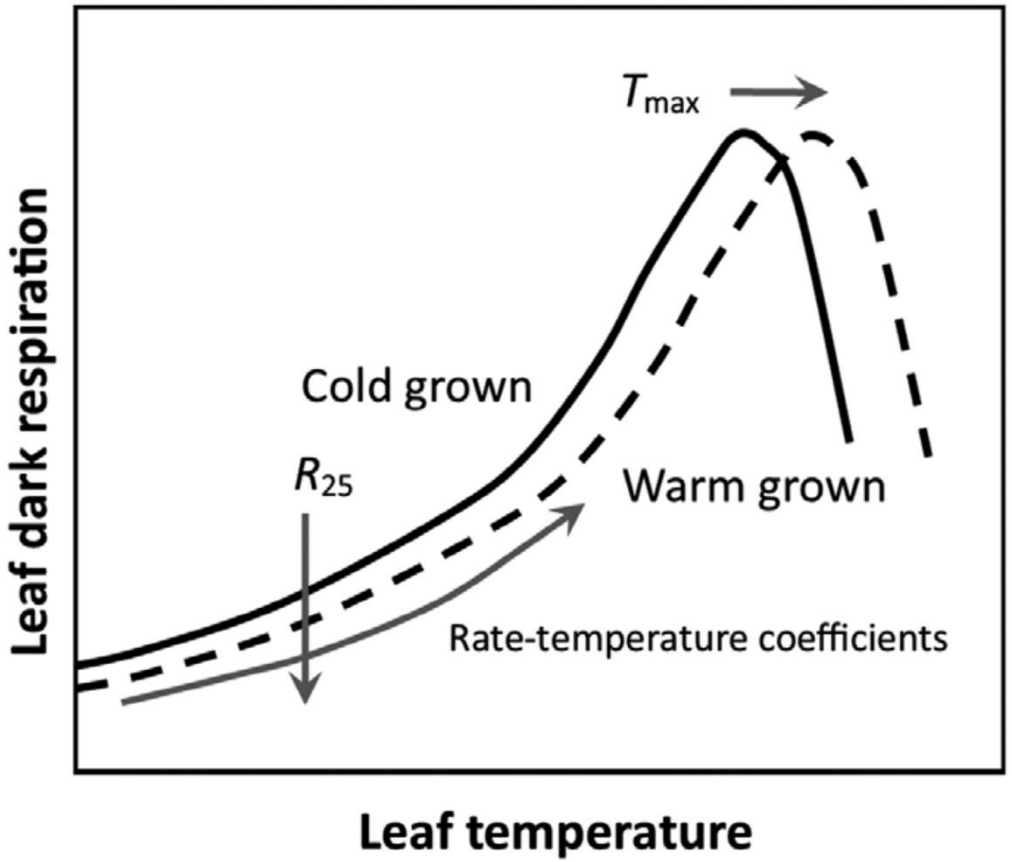
Environment Factors Affecting Respiration Rate

1. Temperature

Optimum Temperature

Temperature at which respiration rate is maximal under steady conditions

Typically 25–35°C (temperate plants)



Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

1. Temperature

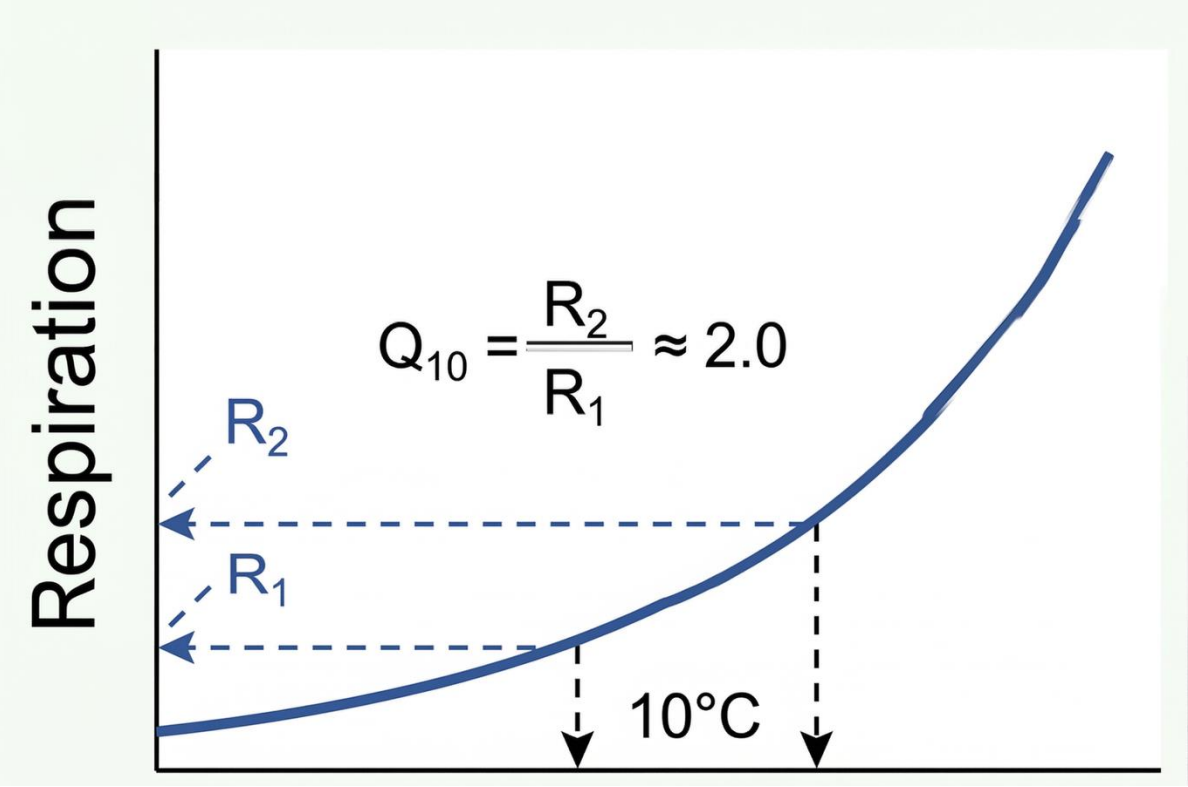
Temperature Coefficient (Q_{10}):

Respiration roughly doubles per 10°C increase (within limits).

$$Q_{10} = \frac{\text{Rate at T+10}}{\text{Rate at T}}$$

Typical Values: 2–2.5 (0–35°C)

Q10: 温度系数



Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

2. Oxygen

Oxygen availability determines both rate and pathway

1. Oxygen and Respiration Rate

O_2 is the final electron acceptor

When O_2 becomes limiting, the respiration rate decreases

2. Oxygen and Respiration Type

At high O_2, Aerobic respiration dominates

At Low O_2, Anaerobic respiration increases

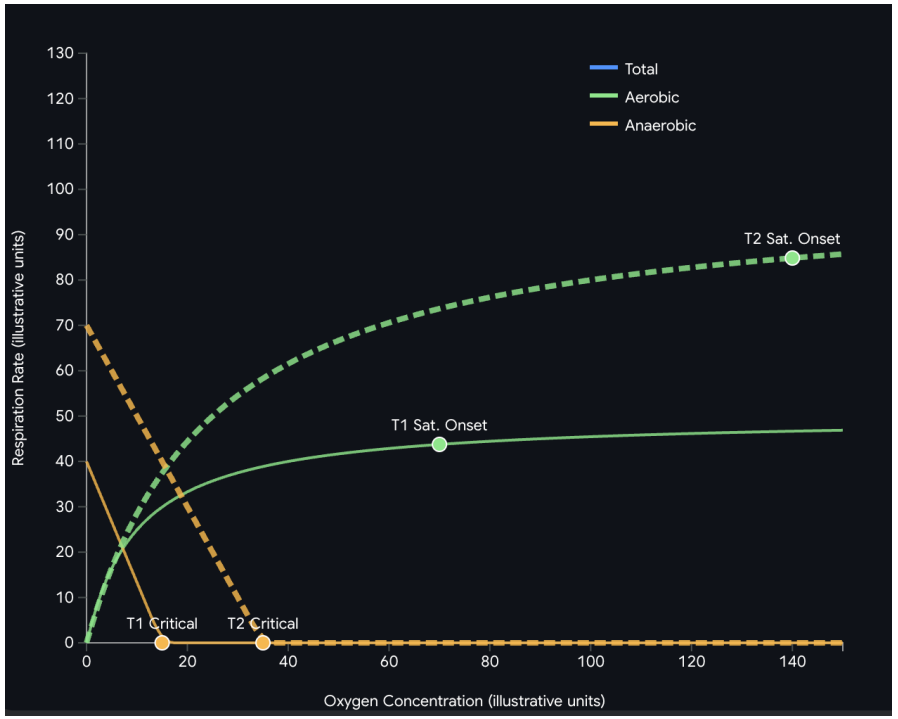
Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

2. Oxygen

Oxygen–Respiration Relationship

Critical Oxygen Concentration / 无氧呼吸的消失点: the minimum O_2 level at which anaerobic respiration disappears



Oxygen Saturation Point/氧饱和点: O_2 level beyond which respiration rate no longer increases

Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

3. CO_2

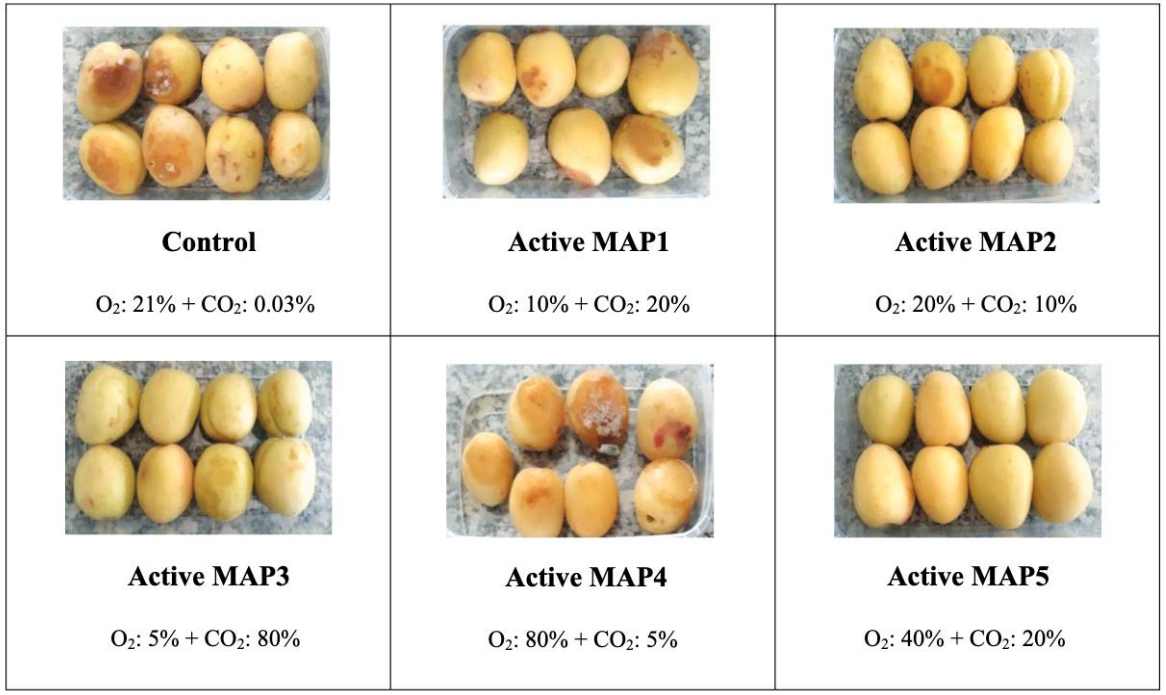
Increasing CO_2 Inhibits respiration

Slows decarboxylation reactions

Alters cellular pH

Limits gas diffusion

Very high → toxic effects



High CO_2 used in fruit storage

Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

3. Water

General Trend：Respiration rate increase with water content

Dry vs Hydrated Tissue

Dry seeds → **very low respiration**

After hydration → **rapid increase**

Drought Response

Early drought increase respiration

Severe/prolonged drought decline respiration

Respiration in Plant Physiology

Environment Factors Affecting Respiration Rate

4. Mechanical Injury

Observation: Mechanical injury increases respiration rate

Loss of cellular compartmentalization, and substrates contact enzymes

Activation of oxidative enzymes

Induction of Wound respiration

Increased demand for repair and biosynthesis

Respiration in Agriculture

Respiration in Seed Maturation and Storage

During Maturation

High respiration:

- supports **biosynthesis**
- supports **dry matter accumulation**

During Storage

Respiration must be minimized to minimalize

- **nutrient loss**
- **viability decline**
- **heat accumulation**

Control Measures

- **Low temperature**
- **Low moisture**
- **Low O_2 / controlled atmosphere**

Respiration in Agriculture

Respiration in Fruit Development and Storage

Development

Respiration supports:

growth

metabolism

Ripening (Climacteric fruits)

Respiration increases sharply/Climacteric rise

Storage

Goal: reduce respiration

Methods:

Low temperature

Controlled atmosphere (↑CO_2, ↓O_2)

Respiration in Agriculture

Respiration and Crop Productivity

Positive Role

Provides ATP

Provides biosynthetic intermediates

Negative Role

Consumes photosynthates (carbon loss)

Agronomic Implication

Optimize conditions to reduce unnecessary respiration and improve carbon use efficiency

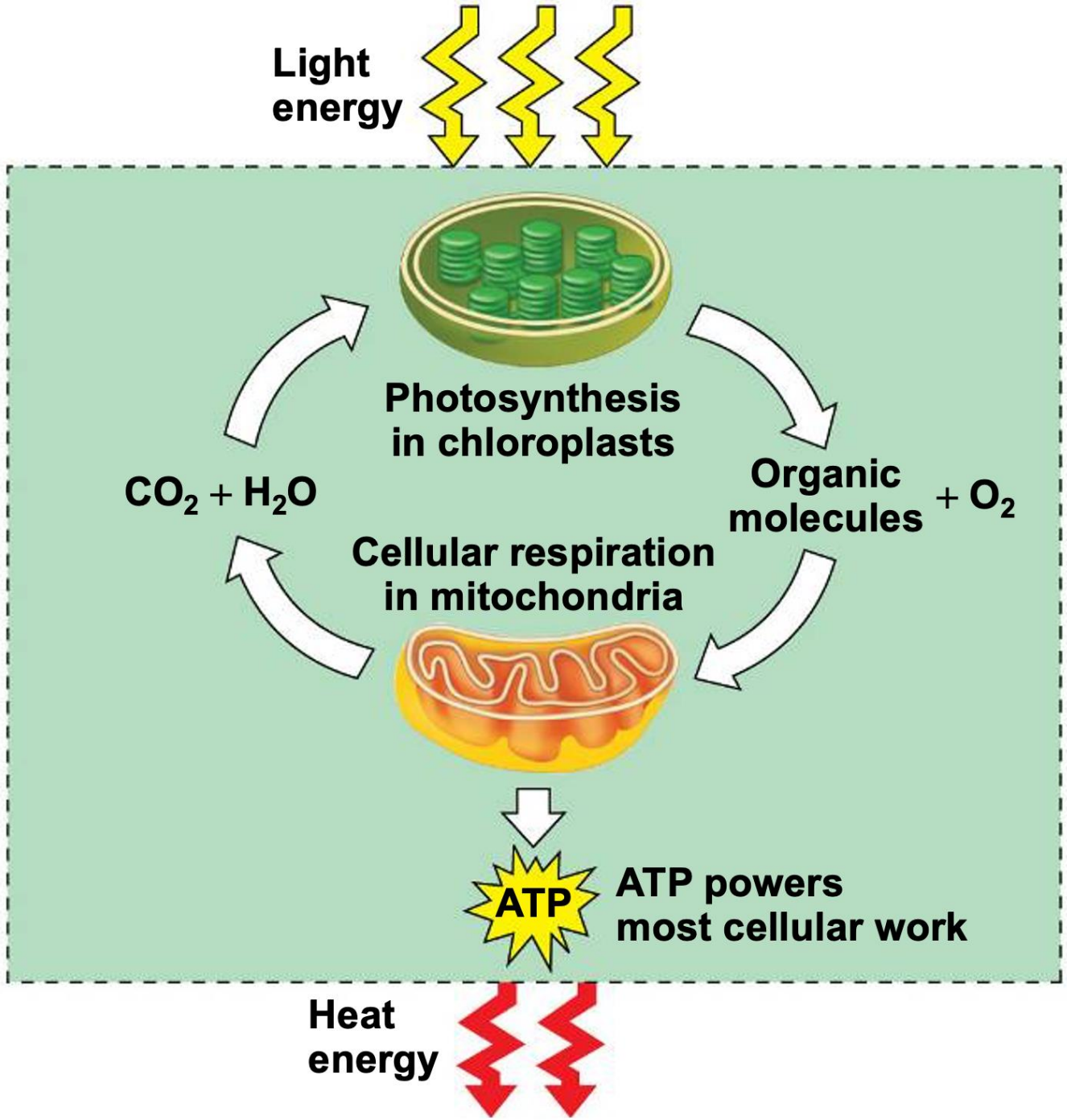
Balance between photosynthesis and respiration

Outline

Introduction

Respiration

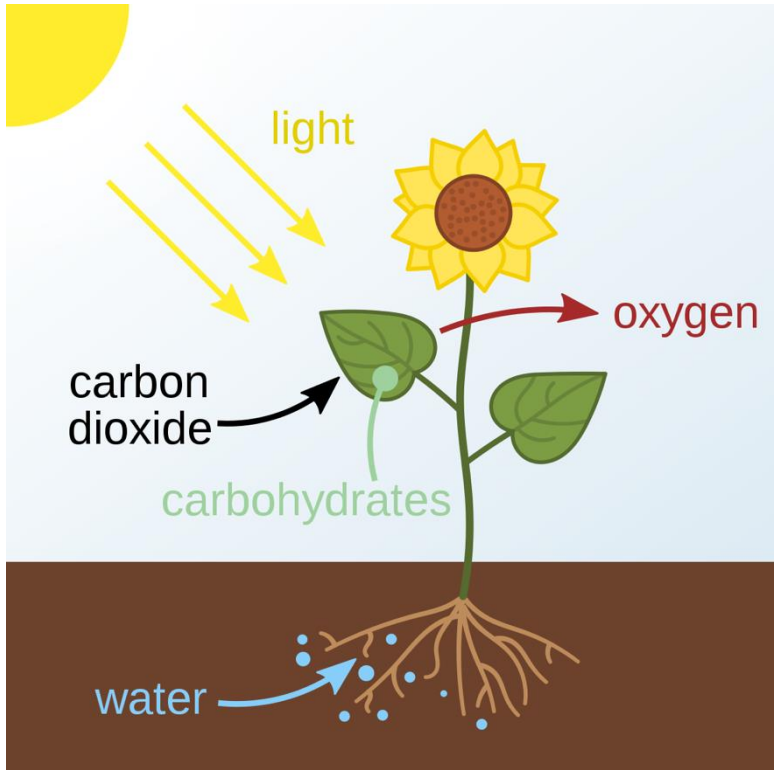
Photosynthesis



What is photosynthesis?

- Photosynthesis, was from the Greek φῶς, *phōs*, "light", and σύνθεσις, *synthesis*, "putting together".

Conversion of light energy into chemical energy stored in organic molecules.



What is photosynthesis?

The most famous and falsest chemical equation

$$6CO_2 + 6H_2O \xrightarrow[Enzymes]{Light} C_6H_{12}O_6 + 6O_2$$

Glucose is NOT the primary photosynthetic product

- The O of O_2 is from water

Discovery of Photosynthesis

1771–1772 — Joseph Priestley (UK)

Demonstrated that plants can restore "injured air" (now understood as replenishing oxygen, O_2) that had been depleted by combustion or respiration.

1779 — Jan Ingenhousz (Netherlands)

Showed that only the green parts of plants produce oxygen, and only in the presence of light. Established the **light dependency** of photosynthesis.

1782 — Jean Senebier (Switzerland)

Demonstrated that carbon dioxide (CO_2) is required for photosynthesis and is consumed during the process. Linked **CO_2 uptake with oxygen production**.

1864 — Julius von Sachs (Germany)

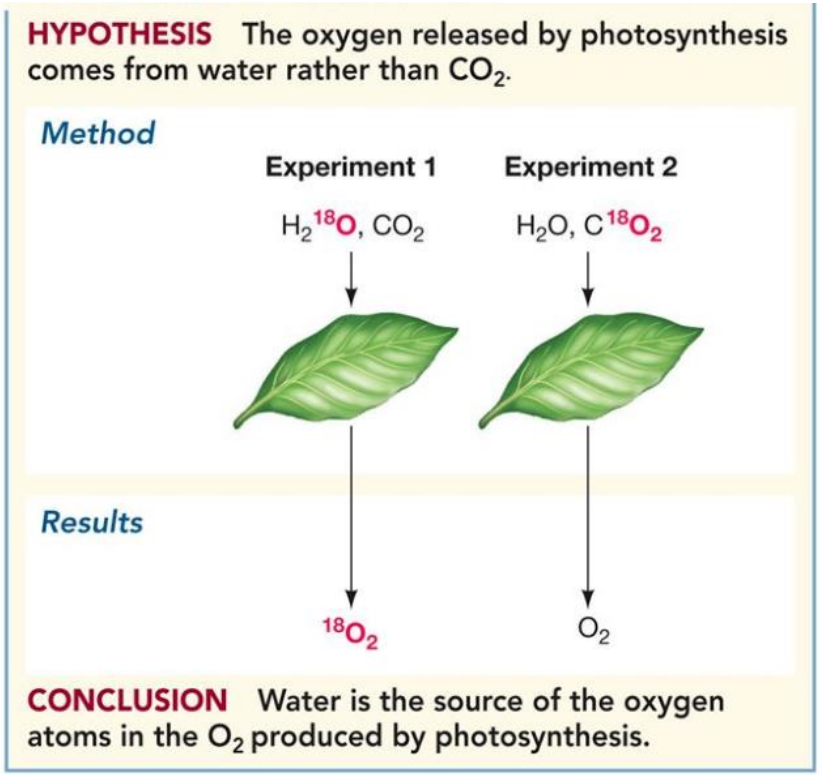
Observed that starch accumulates in chloroplasts under light conditions. Provided evidence that **photosynthesis produces carbohydrates** (stored as starch).

1941 — Samuel Ruben et al. (USA)

Used isotopic labeling ($H_2{}^{18}O$) to show that the oxygen (O_2) released in photosynthesis originates from water, not CO_2. Established **water as the source of evolved oxygen** via photolysis.

Discovery of Photosynthesis

$$6CO_2 + 6H_2O \xrightarrow[Enzymes]{Light} C_6H_{12}O_6 + 6O_2$$



$$12H_2O \rightarrow 24H^+ + 24e^- + 6O_2$$

$$6CO_2 + 24H^+ + 24e^- \rightarrow C_6H_{12}O_6 + 6H_2O$$

$$6CO_2 + 12H_2O \xrightarrow[Enzymes]{Light} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Ruben and Kamen 1941

Concept of Photosynthesis

Carbon Assimilation (碳同化作用)

The process by which autotrophic organisms incorporate inorganic carbon (CO_2) into organic molecules. In plants, this occurs primarily via the **Calvin cycle**.

Photosynthesis (光合作用)

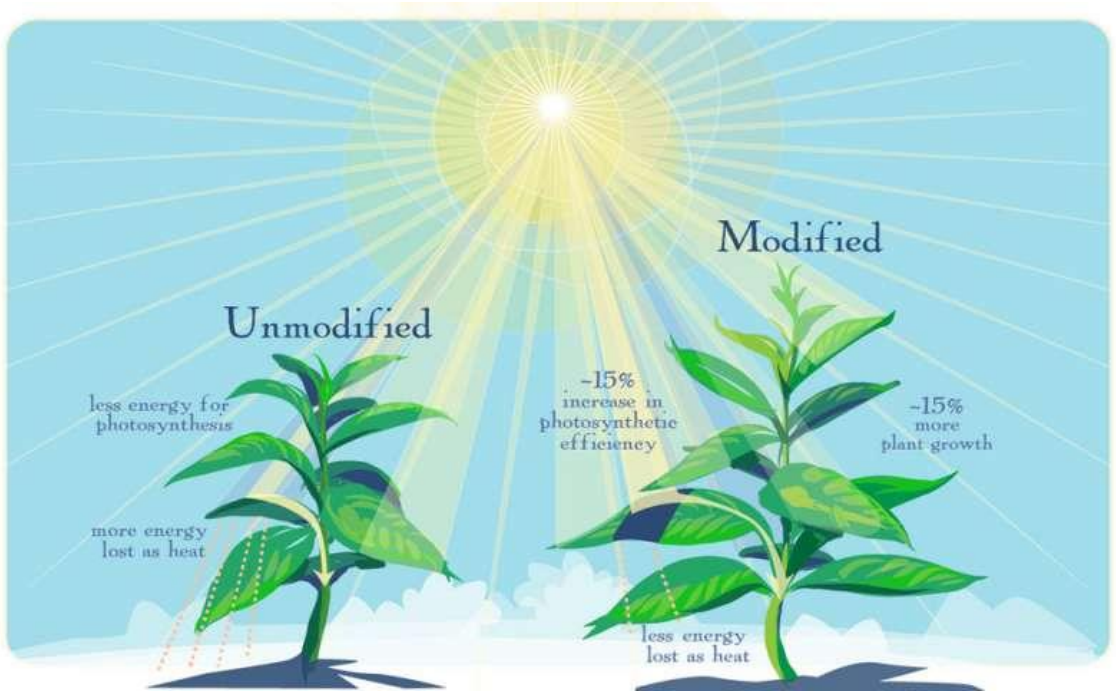
Photosynthesis is the process by which photoautotrophic organisms (plants, algae, and cyanobacteria) use light energy to convert carbon dioxide (CO_2) and water (H_2O) into energy-rich organic compounds, releasing oxygen (O_2) as a byproduct.

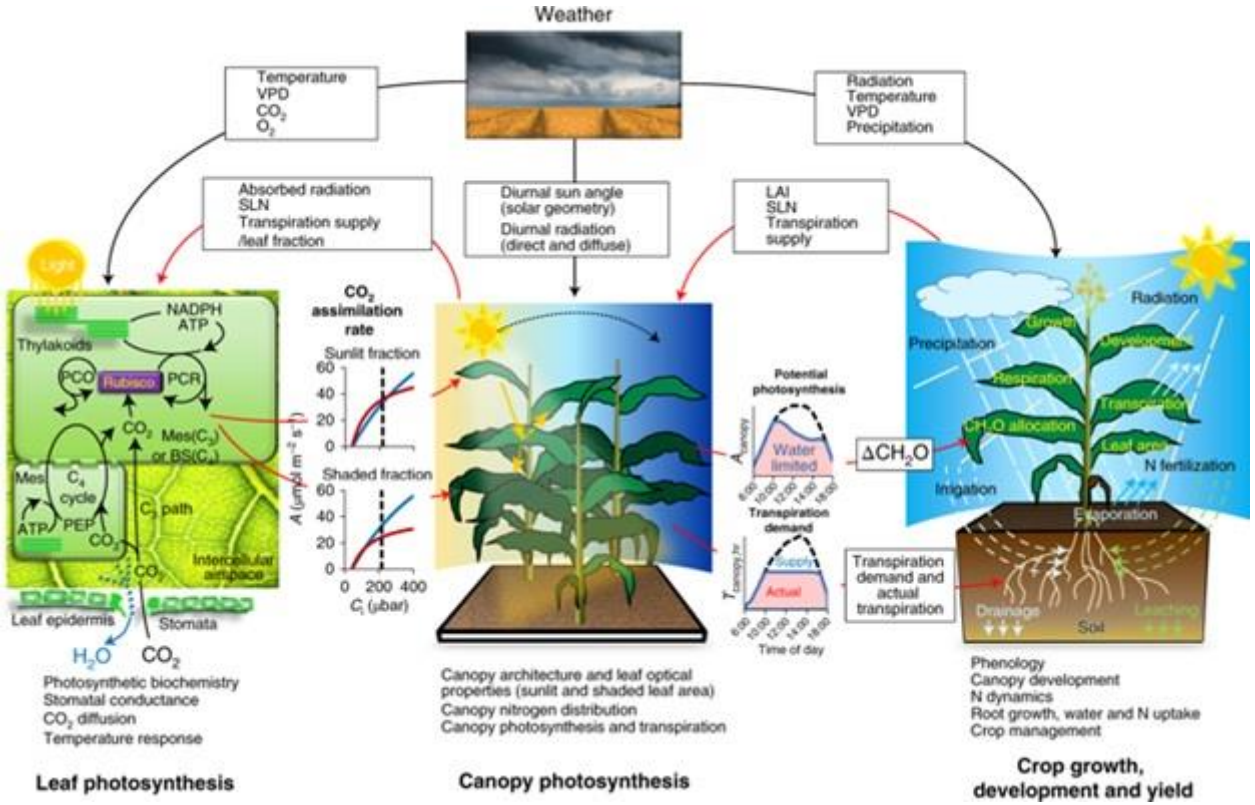
Importance of Photosynthesis

Food

Form the base of nearly all food chains.

Can you think of a food that is NOT somehow tracked back to photosynthetic process?





Importance of Photosynthesis

Fresh air

Removes carbon dioxide from, and adds oxygen to, the atmosphere

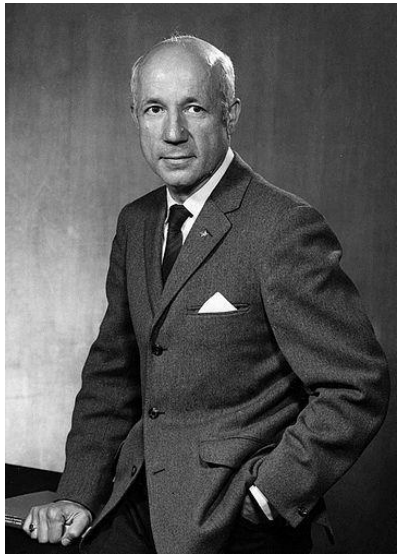




Importance of Photosynthesis



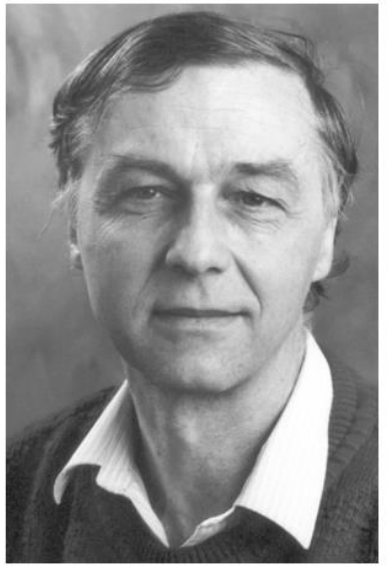
Richard Willstätter
1915



Melvin Calvin
(1961)



Johann Deisenhofer



Robert Huber



Hartmut Michel

1988



Barbara McClintock
1983

历史上授予植物学学家的诺贝尔奖非常少，至今仅有四项诺贝尔“科学奖”是授予植物科学家的。其中三项是光合作用相关研究。

另外，Norman Borlaug因绿色革命获1970和平奖。

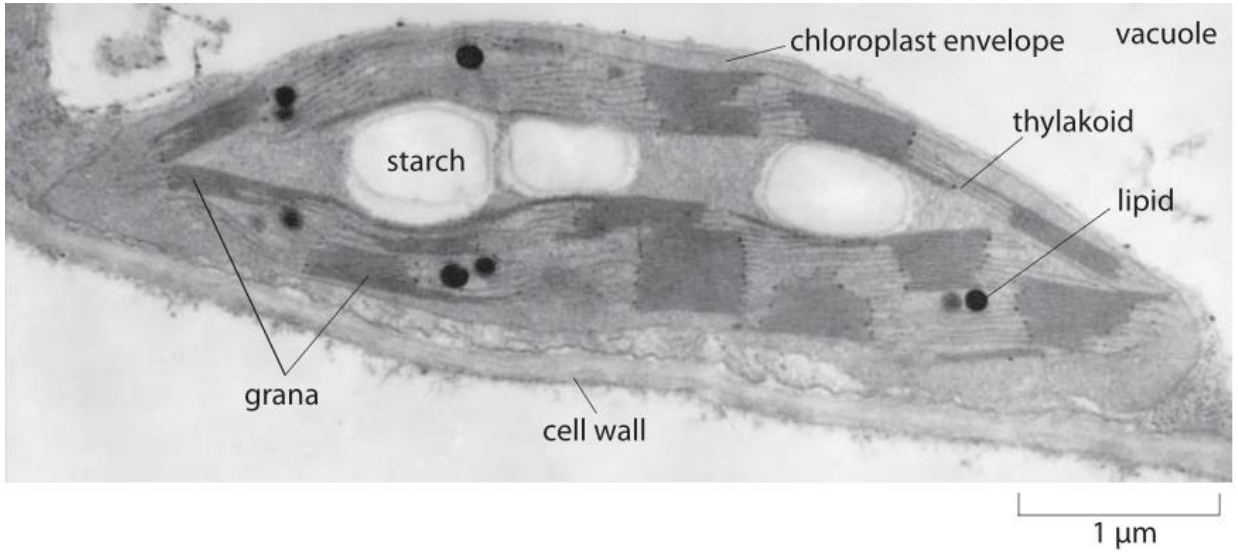
注: 光合作用相关的诺贝尔奖共14项；Govindjee et al., 2004, Photosyn Res

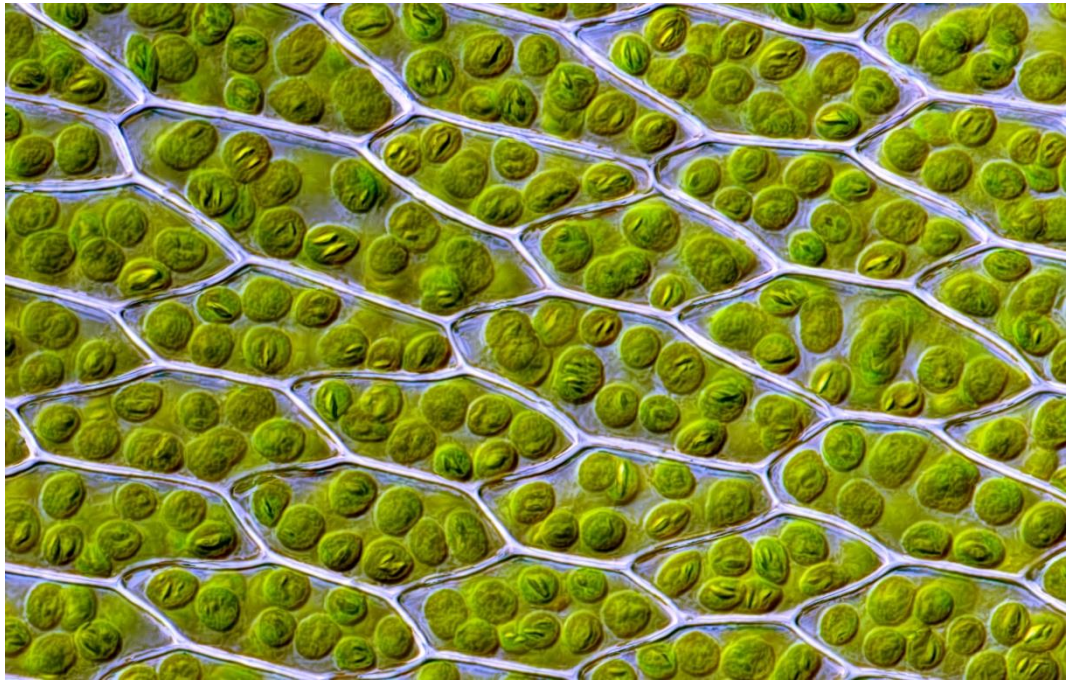
Where Does Photosynthesis Occur?

Photosynthesis occurs in **specialized cellular structures**, with clear spatial organization:

In eukaryotic photoautotrophs (plants and algae), photosynthesis occurs in the **chloroplast** / 叶绿体.

In prokaryotic photoautotrophs (cyanobacteria), photosynthesis occurs on **internal membrane systems** (no chloroplast).





Where Does Photosynthesis Occur?

Structure and Function of the Chloroplast

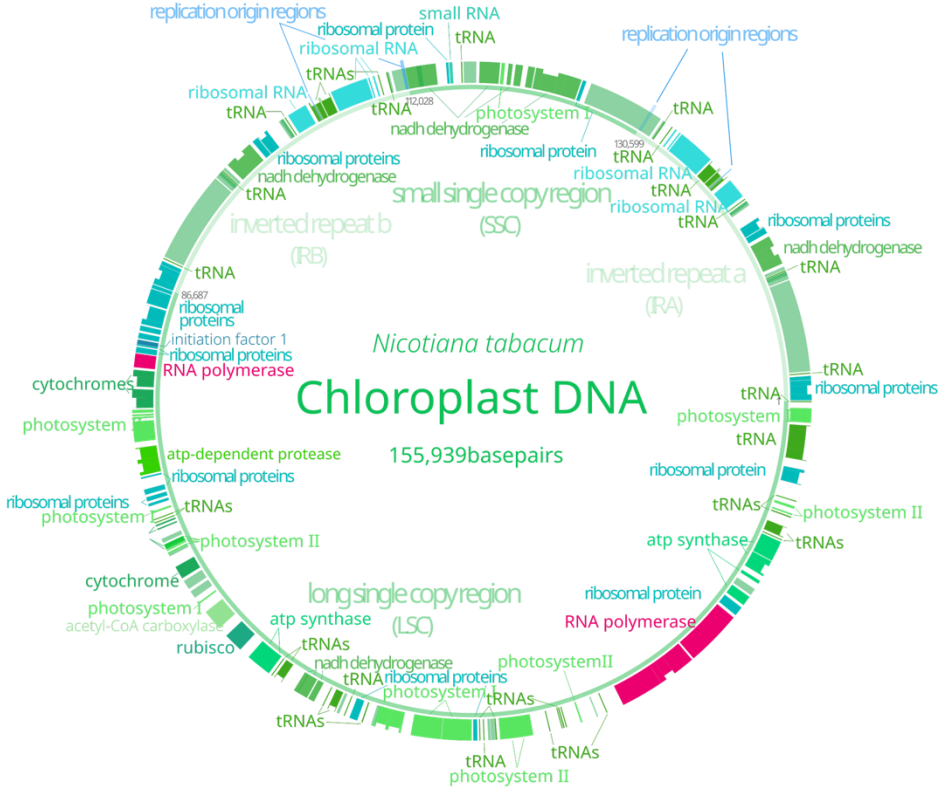
Chloroplasts are typically:

- **5–10 µm in diameter**, **~2–3 µm thick**
- Present in **dozens to hundreds per cell**

Chloroplasts contain:

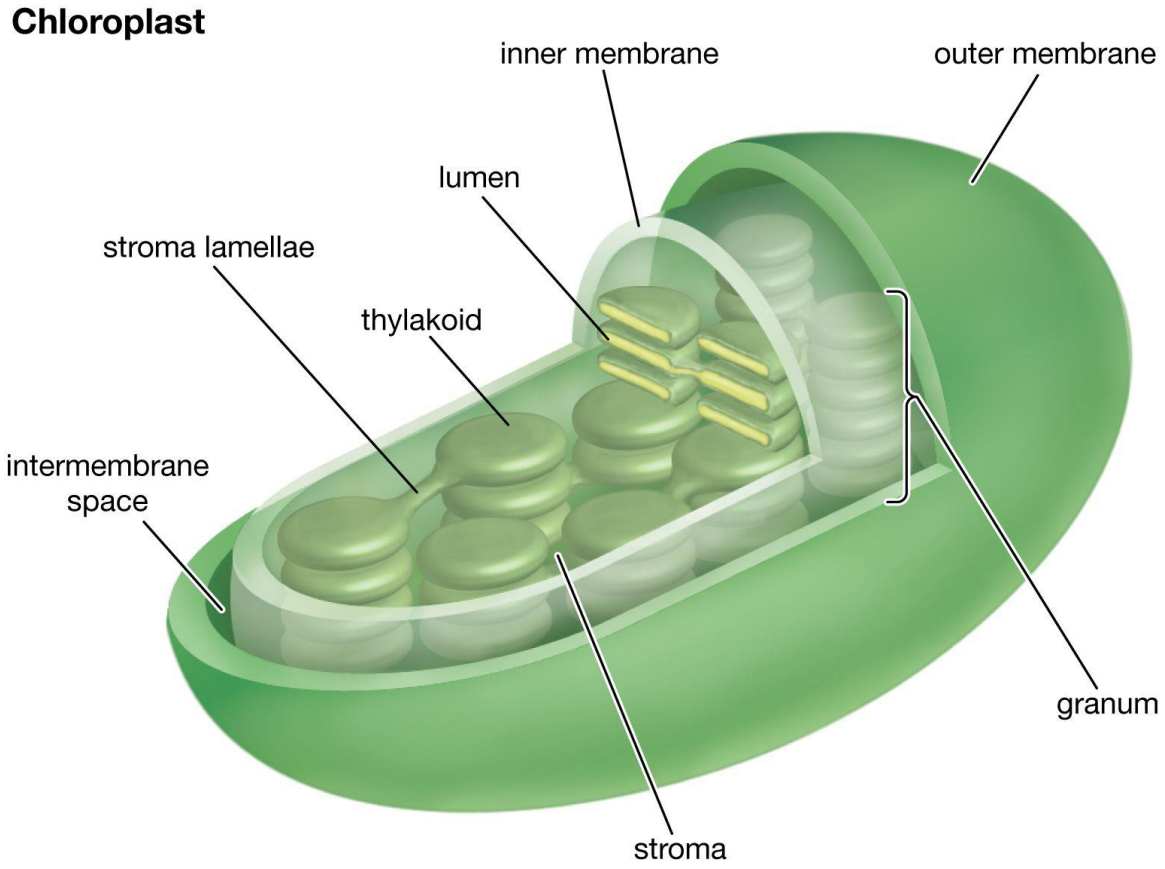
- Their own **DNA and ribosomes**
- Partial capacity for **protein synthesis**

Supports the **endosymbiotic theory**/内共生理论, which claims chloroplasts originated from ancestral cyanobacteria.



Where Does Photosynthesis Occur?

Structure and Function of the Chloroplast



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Envelope Membranes

Outer membrane / 外被膜:

Relatively permeable (non-selective to small molecules and ions)

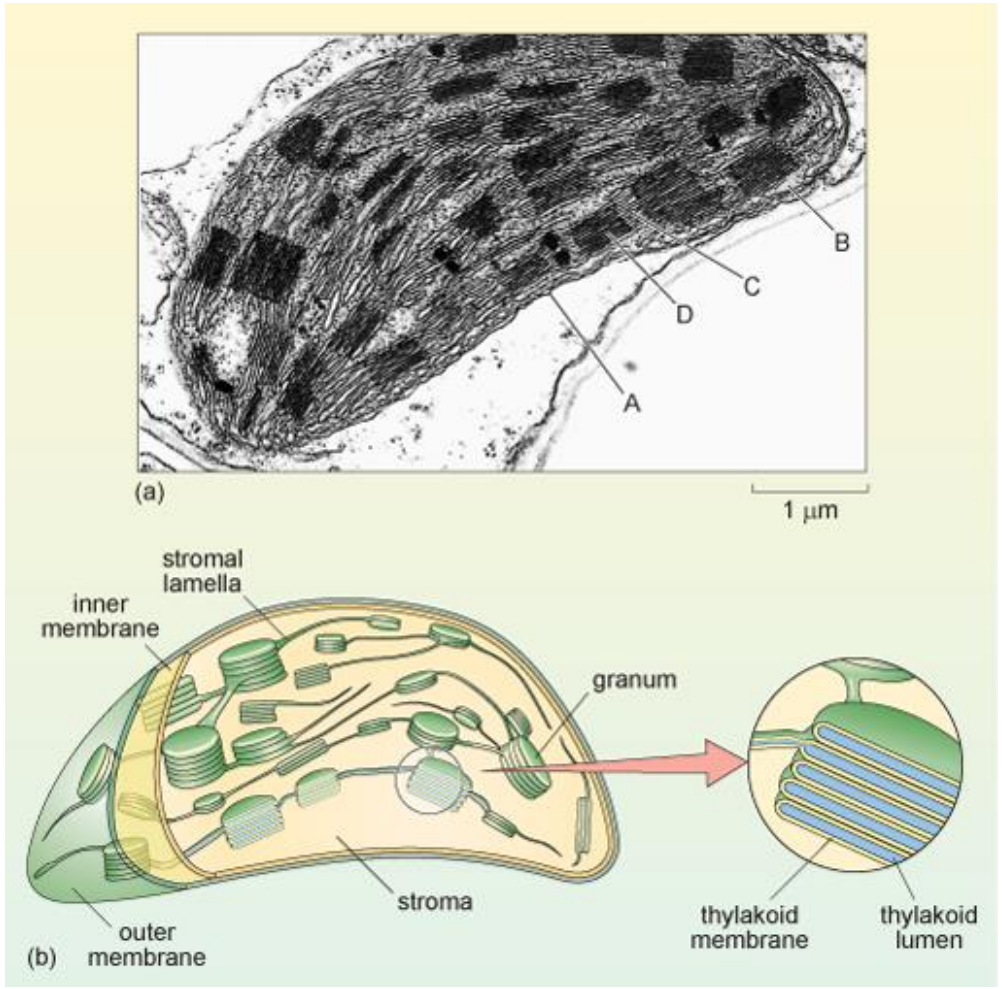
Inner membrane / 内被膜:

Highly **selective**

Regulates transport via specific carriers

Where Does Photosynthesis Occur?

Structure and Function of the Chloroplast



Stroma（基质）

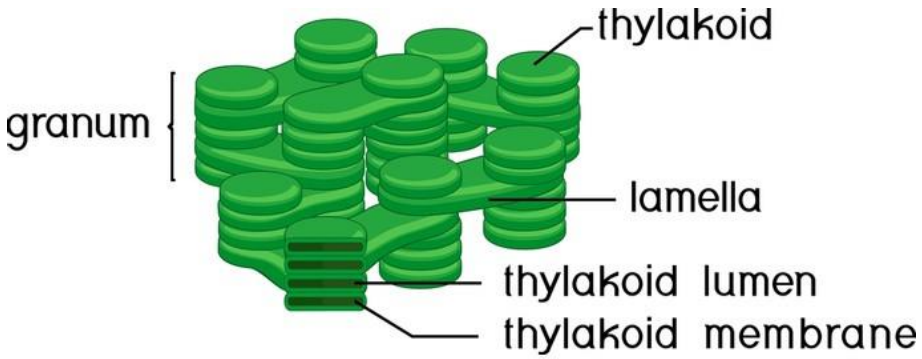
Protein-rich matrix containing:

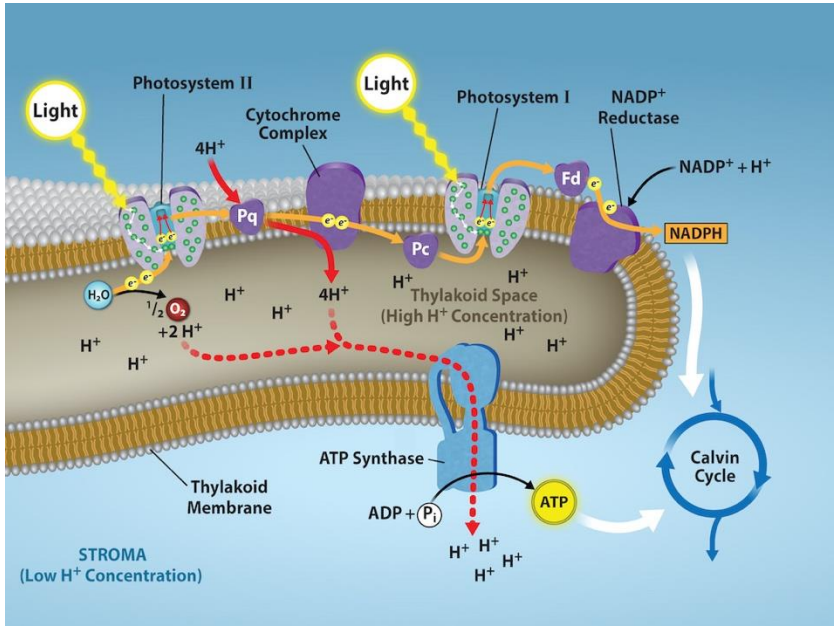
- **Calvin cycle enzymes**
- DNA, RNA, ribosomes
- Starch granules, metabolites

- Site of **carbon fixation and biosynthesis**

Where Does Photosynthesis Occur?

Structure and Function of the Chloroplast





Thylakoid System (类囊体系统)

Flattened membrane sacs and can be organized into

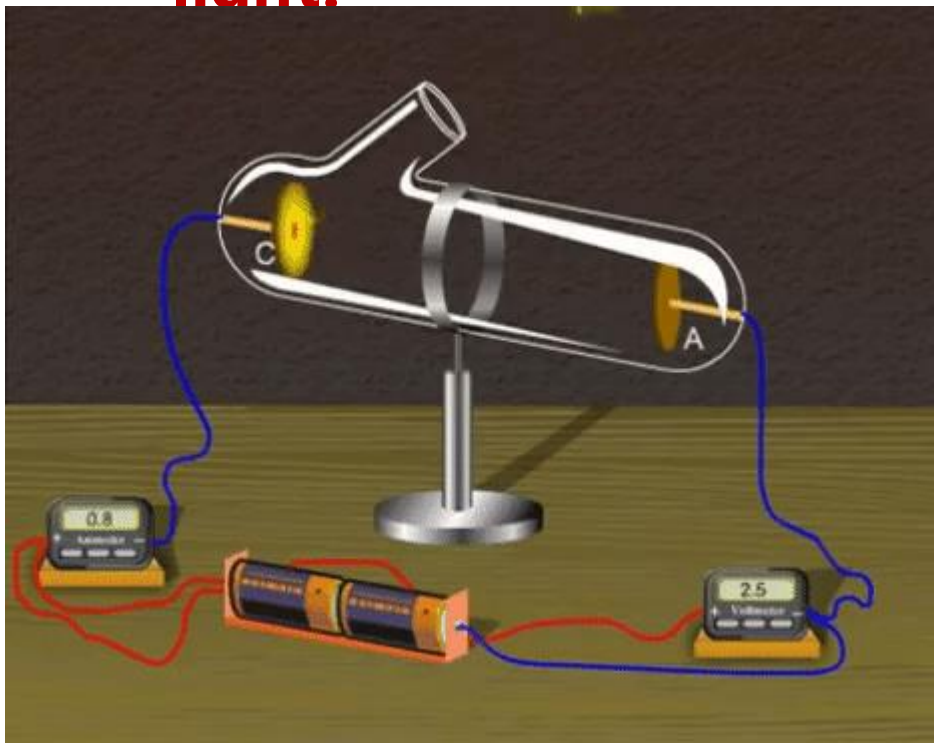
- Grana/基粒(stacked thylakoids)
- Stroma lamellae /间质 (unstacked connections)

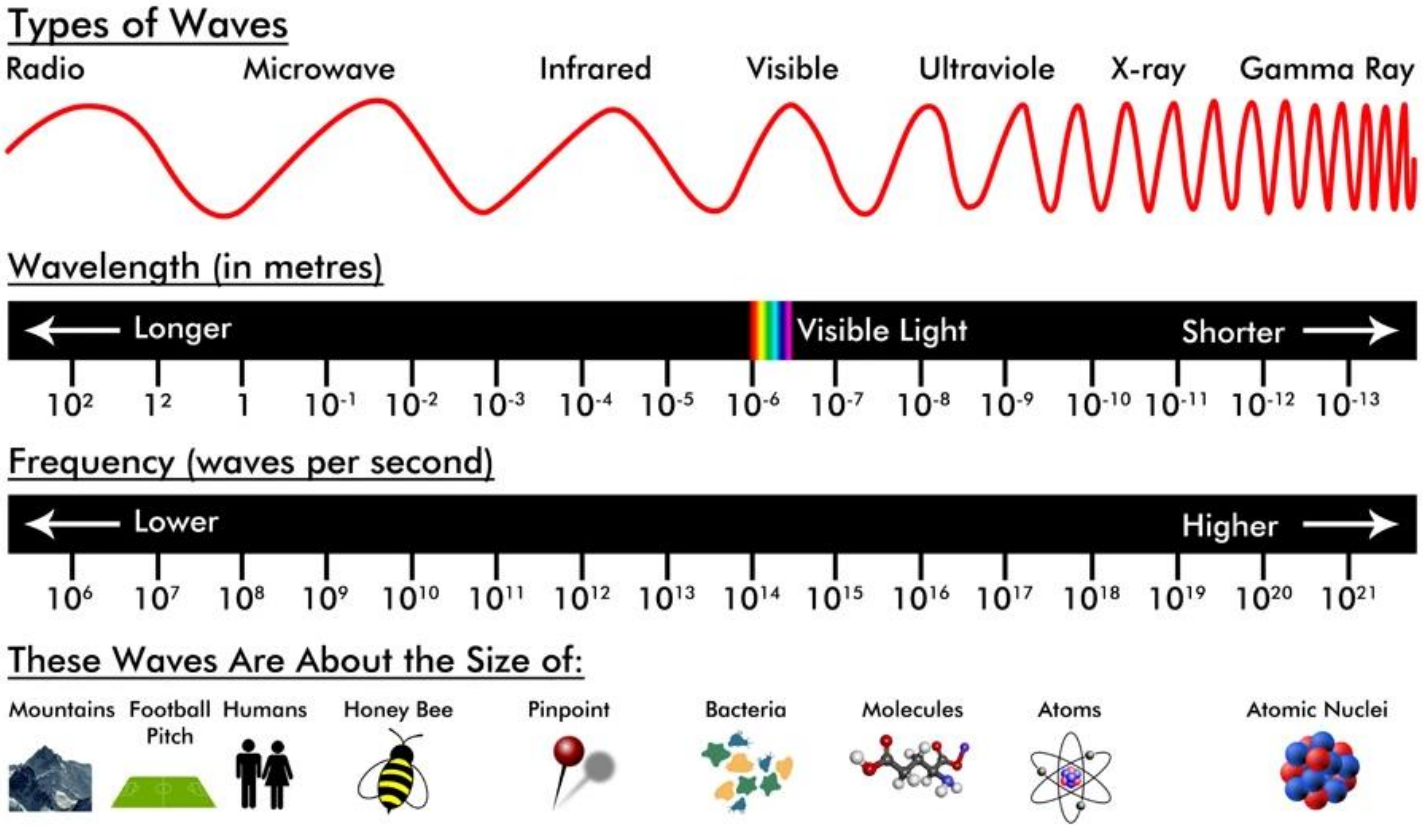
Thylakoid membrane = Photosynthetic membrane

- Photosystems (PSII, PSI)
- Electron transport chain
- ATP synthase

Light absorption

What is light?





Wave–particle duality is the concept in quantum mechanics that every particle or quantum entity may be described as either a particle or a wave.

Light absorption

Plant pigment vs photosynthetic pigment





Light absorption

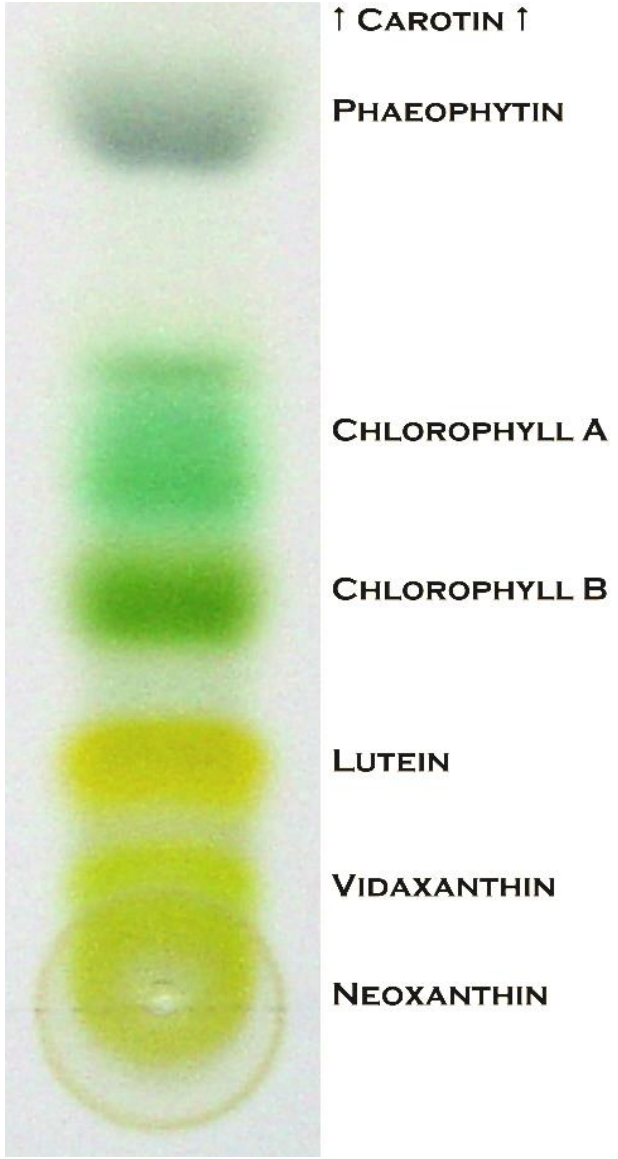
Photosynthetic pigments

Photosynthetic Pigments (光合色素)

Pigments that absorb light energy and participate in photosynthesis

Major classes include:

- Chlorophylls (叶绿素)
- Carotenoids (类胡萝卜素) — including carotenes and xanthophylls (叶黄素类)
- Phycobilins (藻胆素) in cyanobacteria and red algae



Light absorption

Photosynthetic pigments

1. Chlorophylls

Main types: **Chlorophyll a, Chlorophyll b**

Structure:

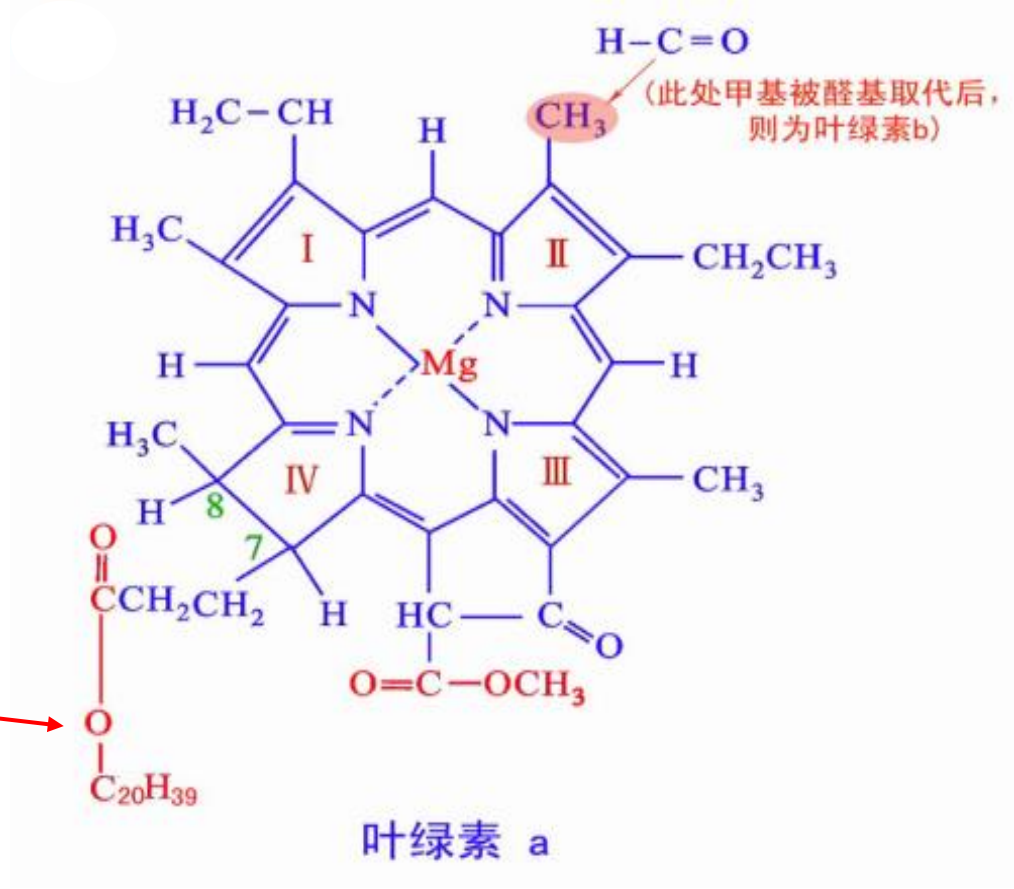
Porphyrin ring(卟啉环) with central **Mg^{2+}**

Hydrophobic **phytol tail** (植醇) (anchors in membrane)

Function:

Primary pigments in **reaction centers**

Absorb mainly **blue and red light**



叶绿素 a

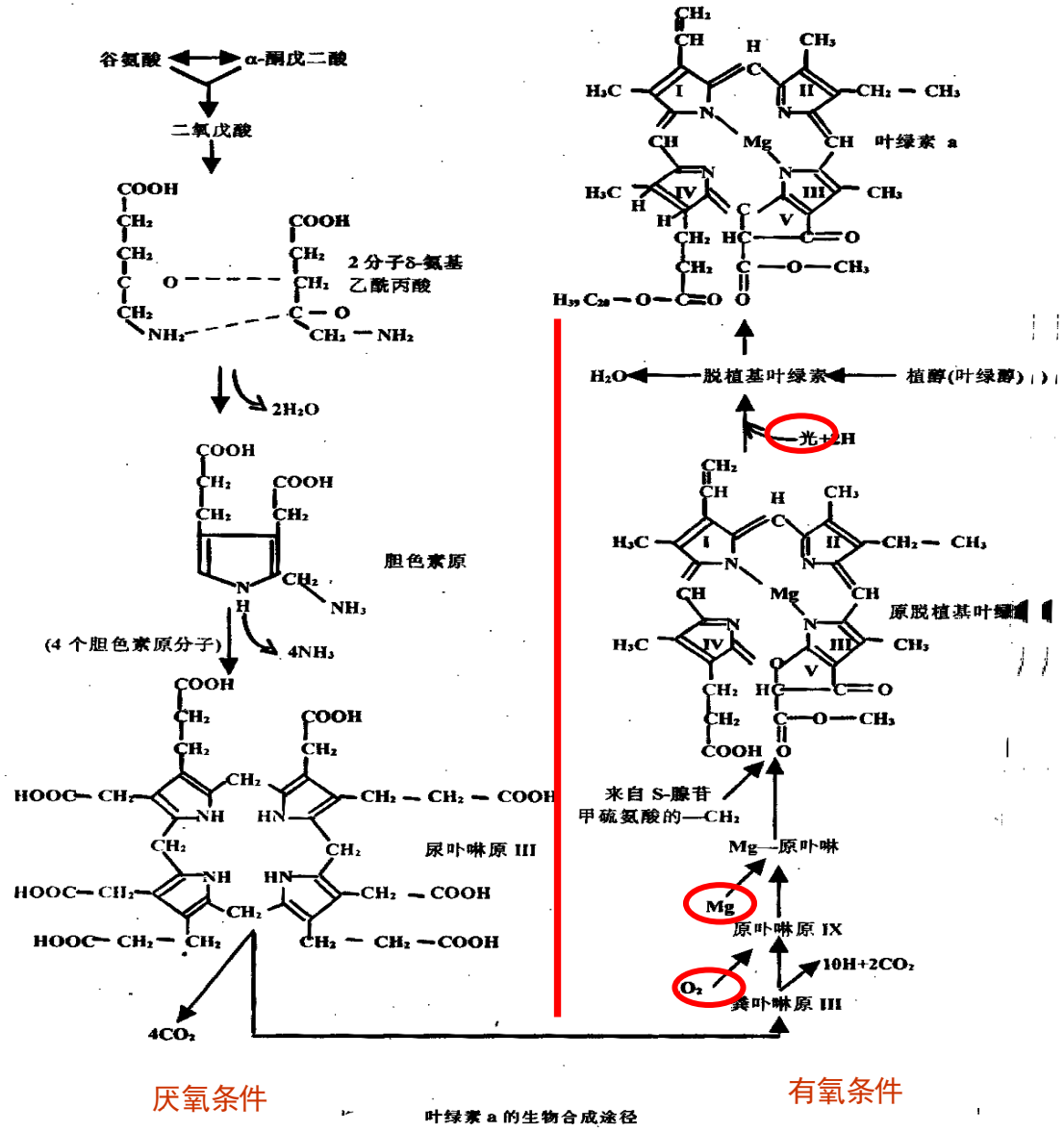
Chl a: $C_{55}H_{72}O_5N_4Mg$

Chl b: $C_{55}H_{70}O_6N_4Mg$

Light absorption

Photosynthetic pigments

Chlorophyll biosynthesis is a tetrapyrrole (四吡咯) pathway, sharing early steps with heme (血红素) synthesis, then diverging toward Mg-containing chlorophyll.



Light absorption

Photosynthetic pigments



Factors Affecting Chlorophyll Biosynthesis

Light is required for conversion of protochlorophyllide/原叶绿酸酯 to chlorophyllide/叶绿素酸酯

In darkness:

- Seedlings become etiolated (黄化; yellow, elongated)
- Chlorophyll synthesis is blocked at protochlorophyllide

Light absorption

Photosynthetic pigments

叶绿素的形成受遗传因素控制，如水稻、玉米的白化苗以及花卉中的斑叶不能合成叶绿素。有些病毒也能引起斑叶。







Factors Affecting Chlorophyll Biosynthesis

Chlorophyll biosynthesis is regulated by nuclear and plastid genes

Examples:

- Albino/白化 mutants cannot synthesize chlorophyll
- Variegated leaves/斑叶 defective chloroplast development

Light absorption

Photosynthetic pigments

Factors Affecting Chlorophyll Biosynthesis

Temperature

Minimum: ~2–4 °C

Maximum: ~40 °C

Optimum: 20–30 °C

Water deficit

Inhibits enzyme activity

Reduces precursor availability

Can accelerate chlorophyll degradation

Mineral Nutrition

N, Mg → structural components

Fe, Cu, Mn, Zn → enzyme cofactors

Oxygen and Redox Conditions

Certain oxidative steps in tetrapyrrole synthesis

Excess light and O_2 cause photooxidation

Leads to chlorophyll damage via ROS

Light absorption

Photosynthetic pigments

2. Carotenoids

Two subgroups:

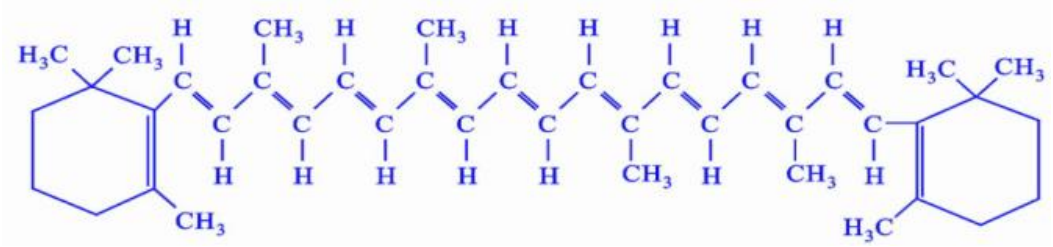
- **Carotenes** / 胡萝卜素 (e.g., β-carotene)
- **Xanthophylls** / 叶黄素类 (e.g., lutein, violaxanthin, neoxanthin)

Chemical feature:

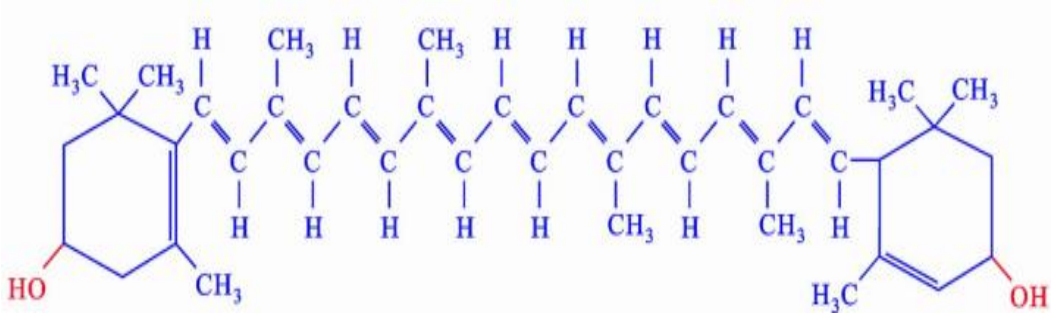
- Long chains of **conjugated double bonds**

Functions:

- Accessory light absorption (blue-green region)
- **Photoprotection** (quenching excess energy, preventing ROS damage)



β- 胡萝卜素 ($C_{40}H_{56}$)



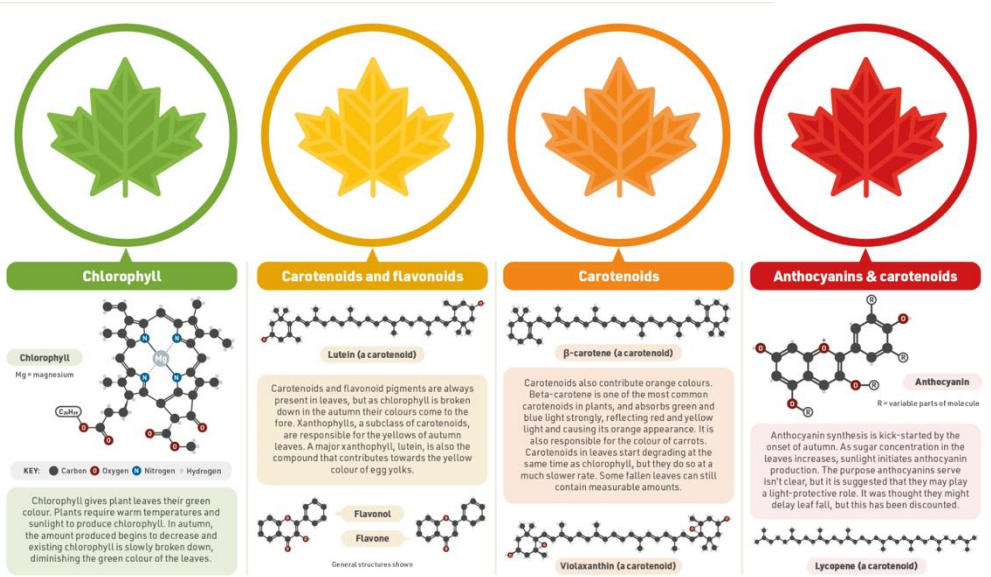
叶 黄 素 ($C_{40}H_{56}O_2$)

Light absorption

2. Carotenoids

Under normal conditions **Chlorophyll : Carotenoids ≈ 3 : 1**







Yellow Leaves (Carotenoid Dominance) occurs during autumn, stress conditions, leaf senescence

Mechanism:

- Chlorophyll degrades rapidly
- Carotenoids remain relatively stable

Red Leaves (anthocyanin accumulation), occurs during autumn (cold nights and light exposure), sometimes in young leaves or stress conditions

Synthesis of anthocyanins/花青素 (NOT photosynthetic pigments)

Light absorption

Photosynthetic pigments

3. Phycobilins / 藻胆素

Found in cyanobacteria, red algae

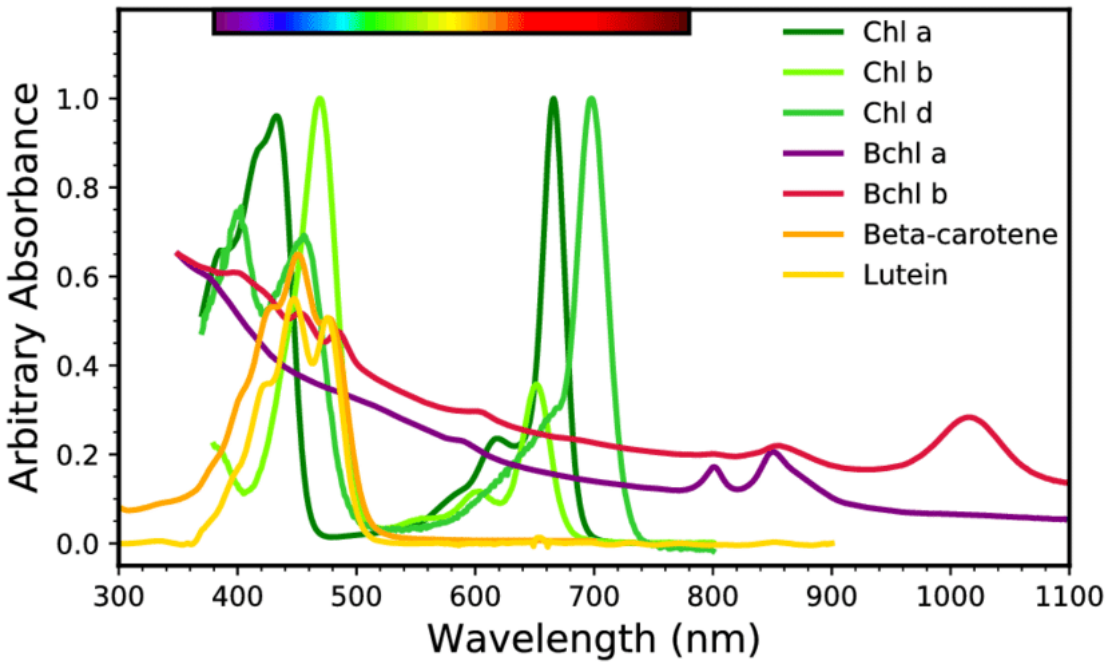
Water-soluble pigments

Organized in phycobilisomes



Light absorption

Absorption spectrum



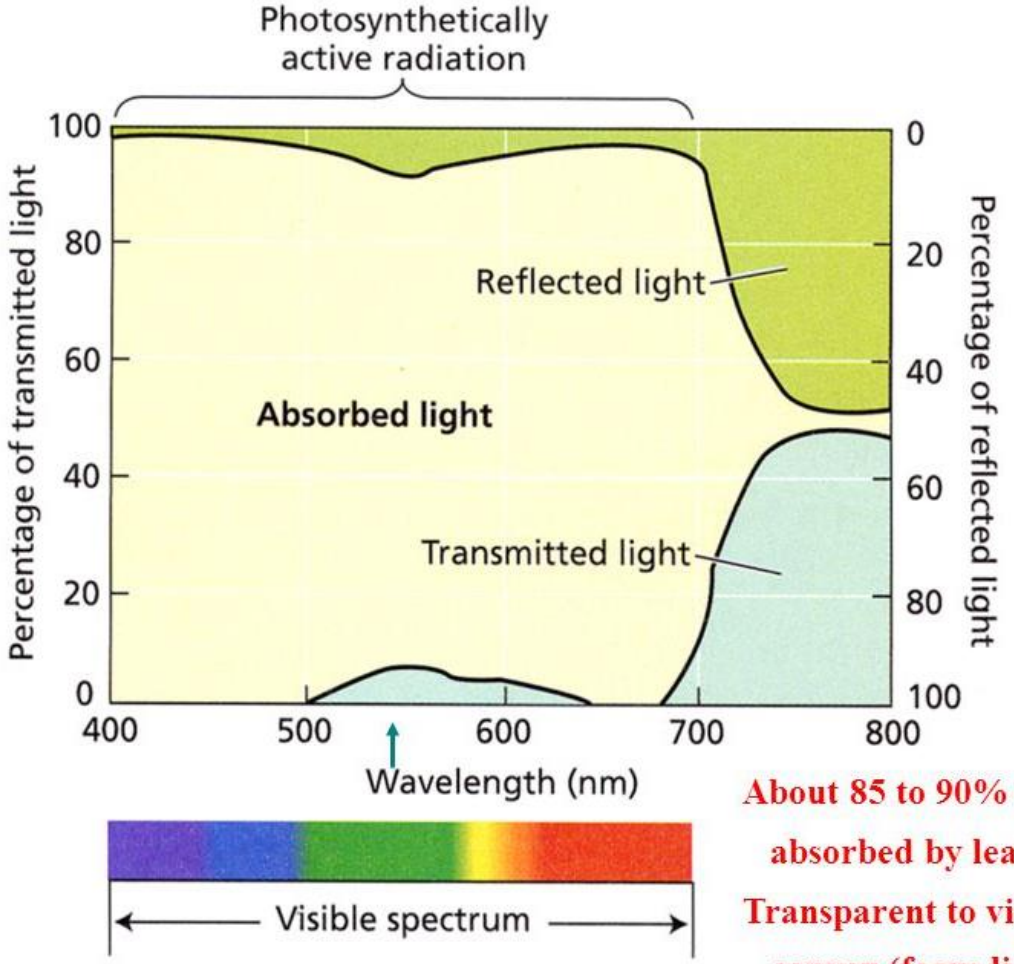


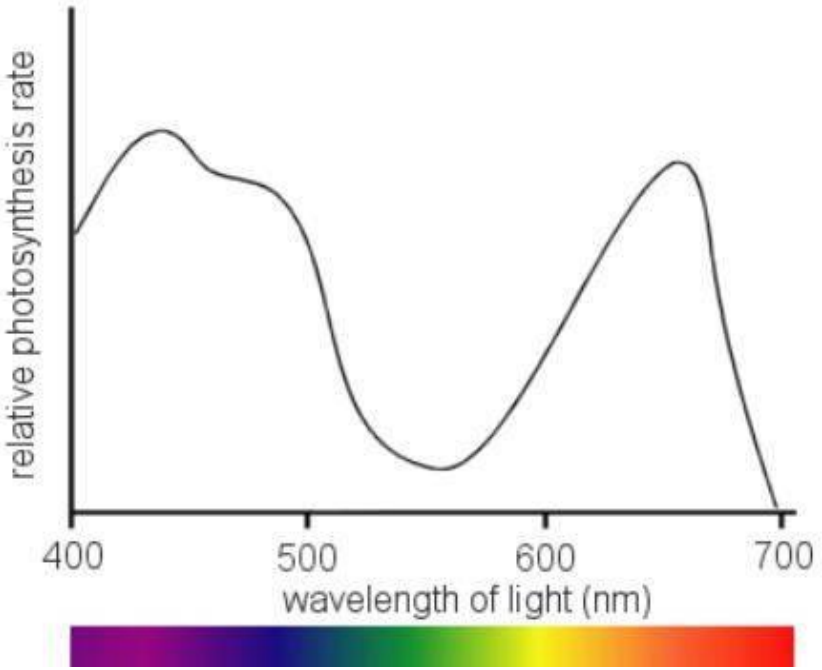
FIGURE 9.3

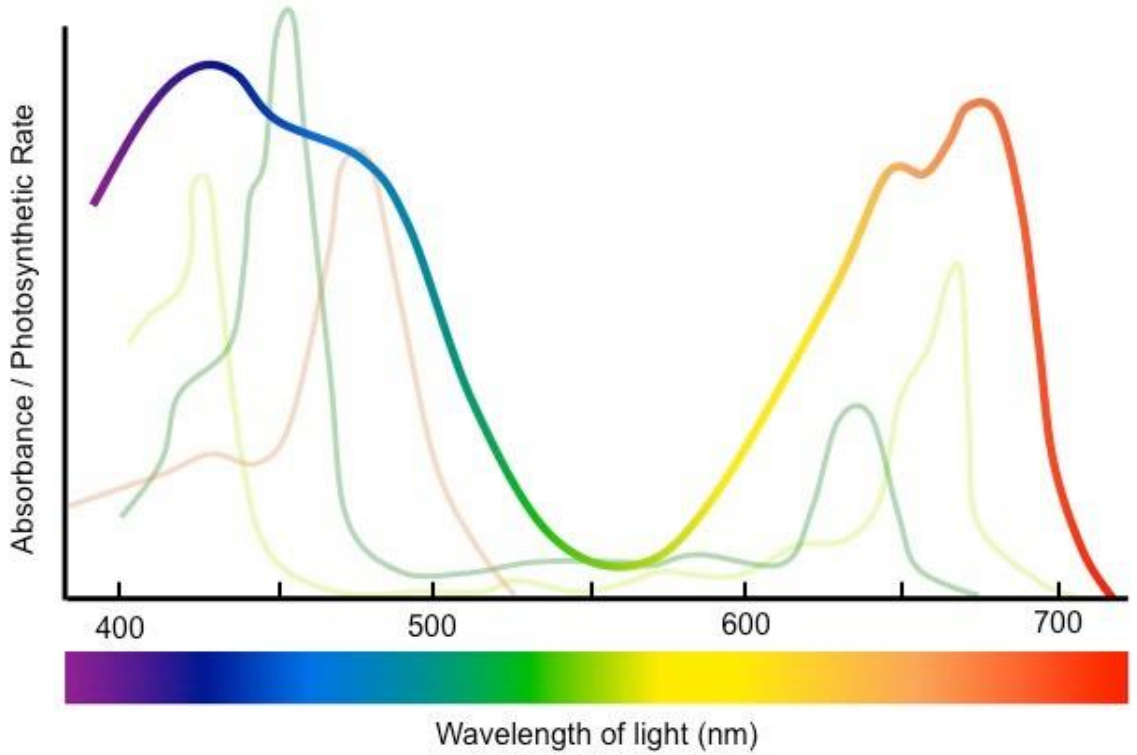
About 85 to 90% of PAR is absorbed by leaf

Transparent to visible light and convex (focus light) at epidermal cells

Light absorption

Action spectrum





- **Absorption spectrum** is the range of wavelengths that can be absorbed by a pigment
- **Action spectrum** means the wavelengths of light trigger photosynthesis

Light absorption

Photochemistry beyond the red limit in chlorophyll f–containing photosystems

Dennis J. Nürnberg[1,*], Jennifer Morton[2], Stefano Santabarbara[3], Alison Telfer[1], Pierre Joliot[4], Laura A. Antonaru[1], Alexand...
+ See all authors and affiliations

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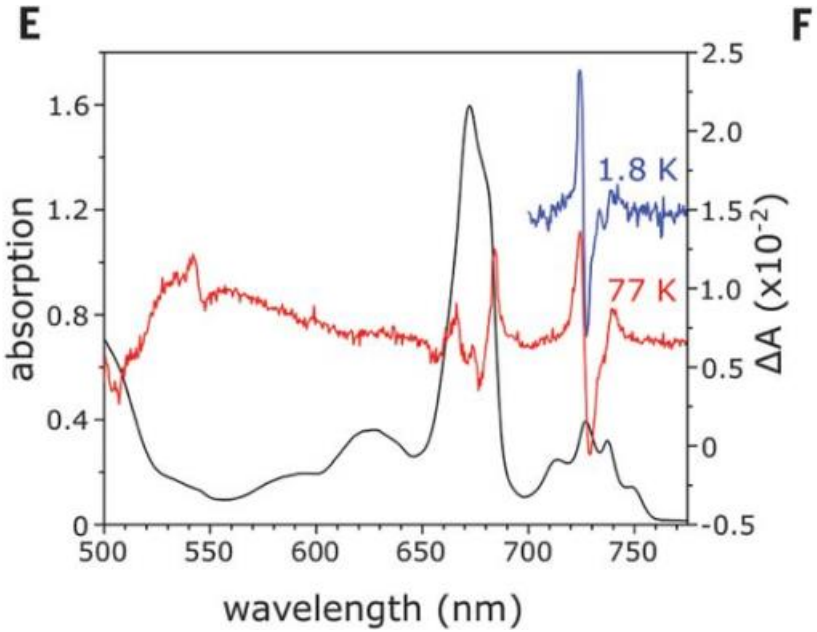
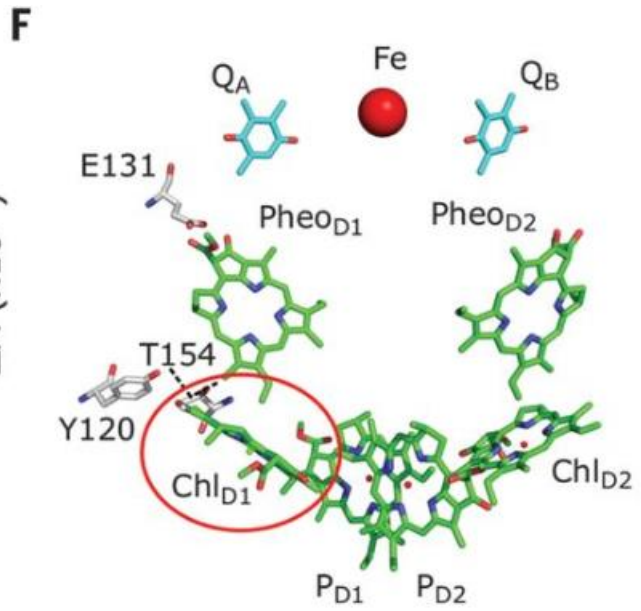
DOI: 10.1126/science.aar8313

Science





搜狐

《Science》：新型光合作用被发现，有望改写教科书！

近日，科研人员发现了新型光合作用。该发现改变了人们对光合作用基本原理的认识，甚至可能改写课本。 这一发现为我们搜寻外星生命量身定制了 ...

Jun 17, 2018



科技日报

新型光合作用可利用近红外光-国际-中国科技网首页

研究负责人、帝国理工学院生命科学学院的比尔·卢瑟福教授认为： “这种新型光合作用改变了我们对标准光合作用'内核'的认识，是一项改写教科书的 ...

Jun 19, 2018

新型光合作用可利用近红外光

2018-06-19 09:54:02 来源: 科技日报 作者: 记者刘霞

或将改写教科书 为农作物改良提供新思路

科技日报北京6月18日电 （记者刘霞）据美国《每日科学》网站报道，根据近日发表于《科学》杂志上的一篇论文，英国帝国理工学院牵头的一个国际科研团队发现，在阴暗环境下生存的蓝藻内，存在一种新型光合作用。与目前地球上占主导地位的利用红光的光合作用不同，新光合作用利用的是近红外光。该发现不仅改变了人们对光合作用基本原理的认识，甚至还可能改写课本。

研究人员解释，目前我们所知的光合作用是通过叶绿素-a来收集光线，并利用光能制造有用的生化物质和氧气。由于叶绿素-a存在于已知的所有植物、藻类及蓝藻中，因此人们普遍认为，红光的能量为光合作用设置了“红光限制”——在产生氧气的化学过程中需要的最少能量。

然而科研团队发现，一些在低能量的近红外光下生长的蓝藻，使用叶绿素-f来进行光合作用，打破了叶绿素-a一统天下的局面——这就是超越“红光限制”的光合作用。

人们此前曾发现，另一种蓝藻（Acaryochloris）也可进行超越“红光限制”的光合作用。但由于其仅发生在单一物种内，且生长地特殊，故被认为是孤例。最新发现的基于叶绿素-f的光合作用则代表了第三种广泛存在的光合作用。

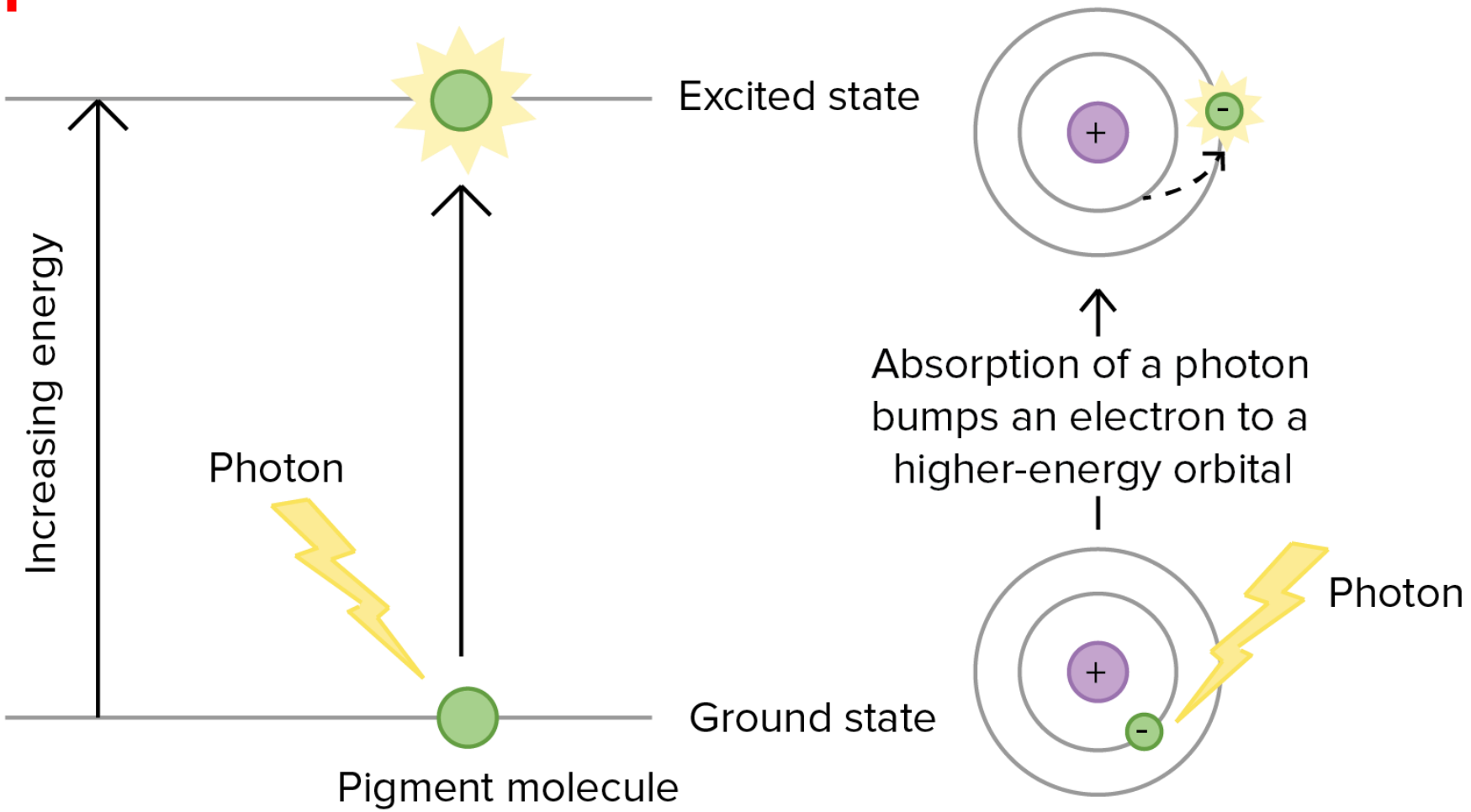
研究人员指出，这种光合作用只存在于特殊的红外光丰富的阴暗环境中，正常光照环境仍是标准红光形式光合作用的“天下”。此外有人认为，超越“红光限制”会导致更严重的光损伤。但新研究表明，在稳定的阴暗环境中，光损伤并非问题。

研究负责人、帝国理工学院生命科学学院的比尔·卢瑟福教授认为：“这种新型光合作用改变了我们对标准光合作用‘内核’的认识，是一项改写教科书的发现。”

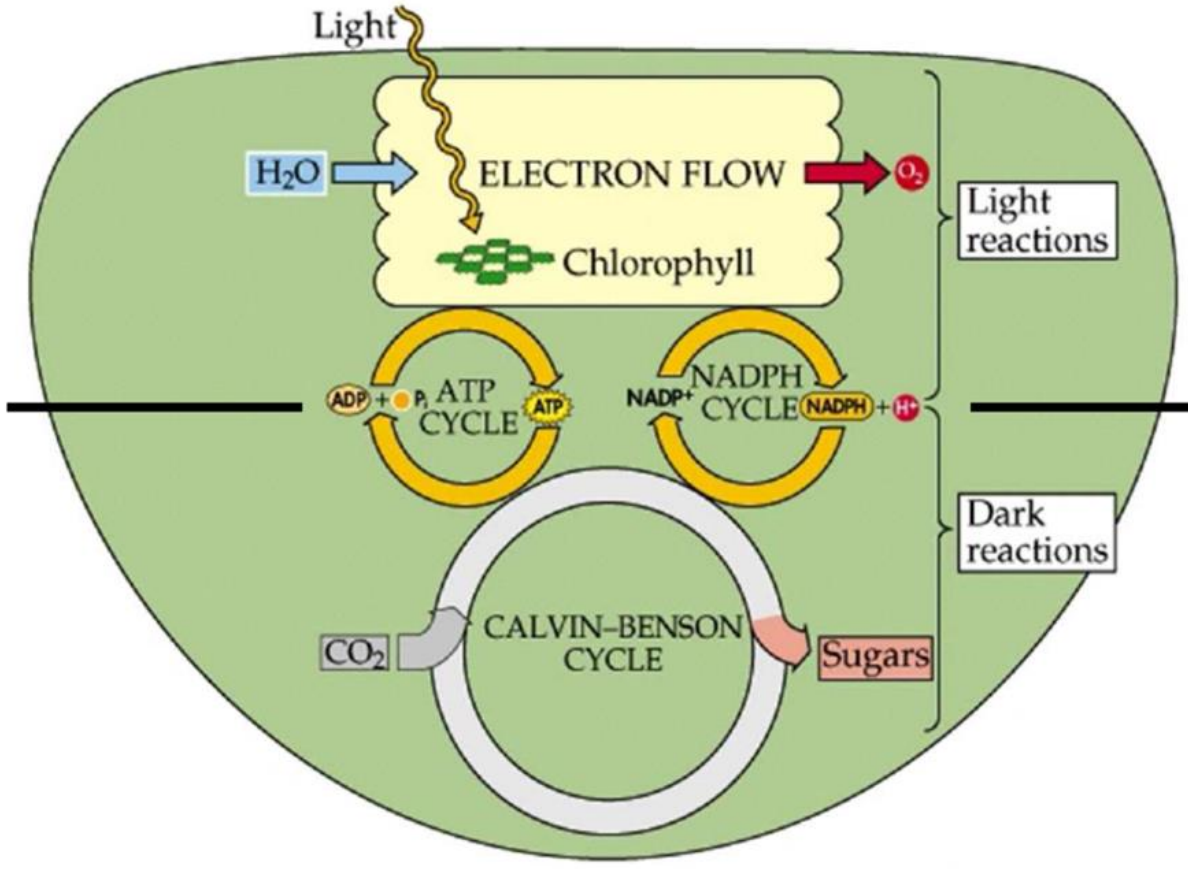
研究人员还表示，新发现也为搜寻外星生命提供了新思路。此外，研究这些蓝藻如何保护自己免受光的亮度变化所导致的损伤，有助于发现更好的作物改良方法。

Light absorption

Light capture



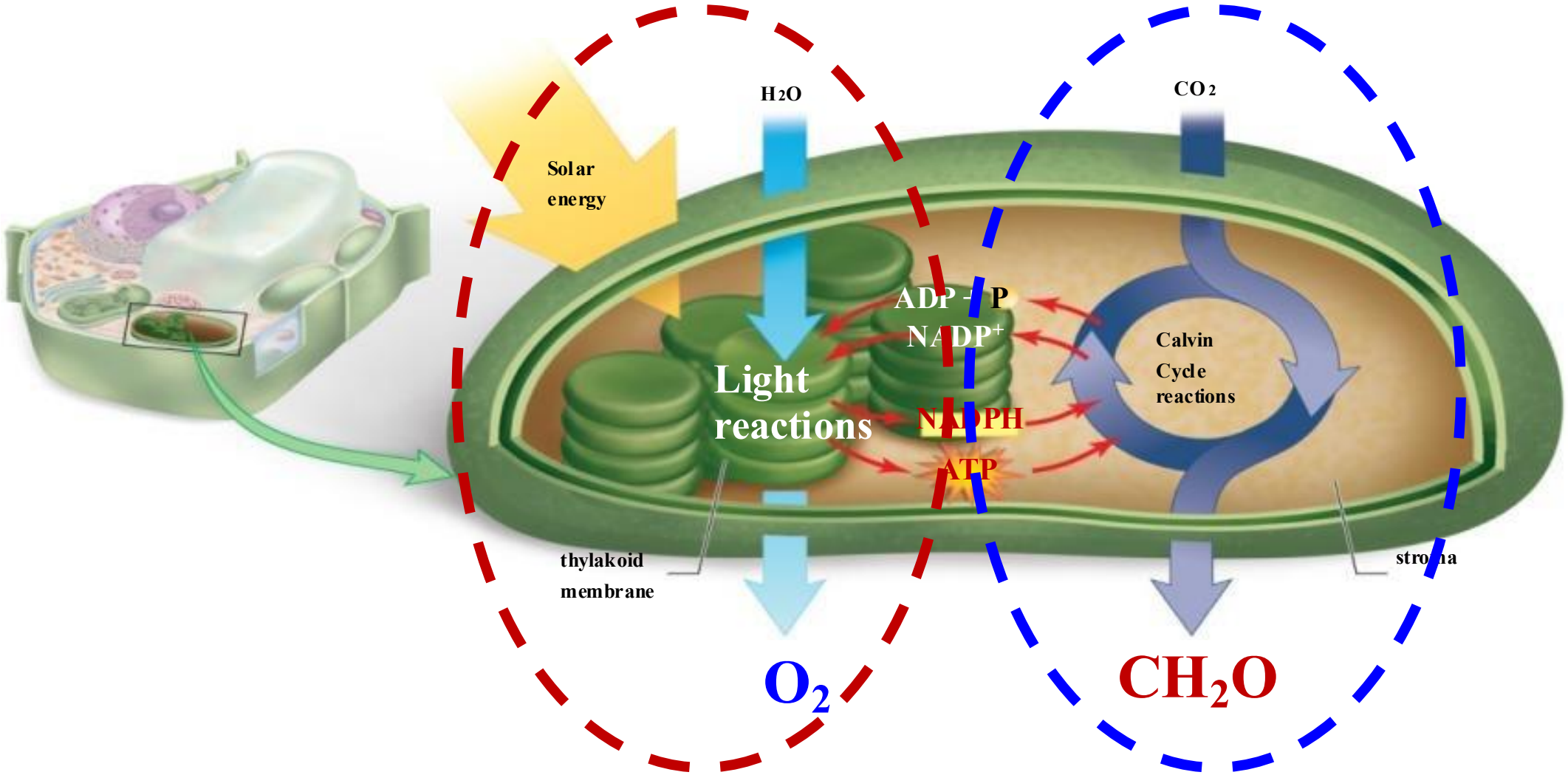
A two(=multi)part photosynthetic process:



1) **Light-dependent reactions**
PHOTOCHEMISTRY.
Light energy captured by chlorophyll is (PARTLY) used for ATP and NADPH synthesis from ADP and $NADP^+$.

2) **Light-independent reactions**
. **BIOCHEMISTRY**.
ATP and NADPH are used to reduce and fix CO_2 generating sugars in the C-B-B cycle.

Photosynthetic Reactions



Where Is Light Absorbed in Photosynthesis?

Chlorophyll does not function freely, but non-covalently bound to proteins forming pigment–protein complexes (叶绿素蛋白复合体)

These complexes are embedded in the thylakoid membrane

Two major categories:

- Chlorophyll a protein complexes (CP) / 叶绿素a蛋白复合体
- Chlorophyll a/b protein complexes (light-harvesting complexes, LHC) / 叶绿素a/b蛋白复合体

Where Is Light Absorbed in Photosynthesis?

Pigment–Protein Complexes

Chlorophyll a protein complexes (CP)

Associated with **reaction centers**

CPI → Photosystem I (PSI) core

CPa → Photosystem II (PSII) core

Contain mainly **chlorophyll a**

Directly involved in **photochemistry**

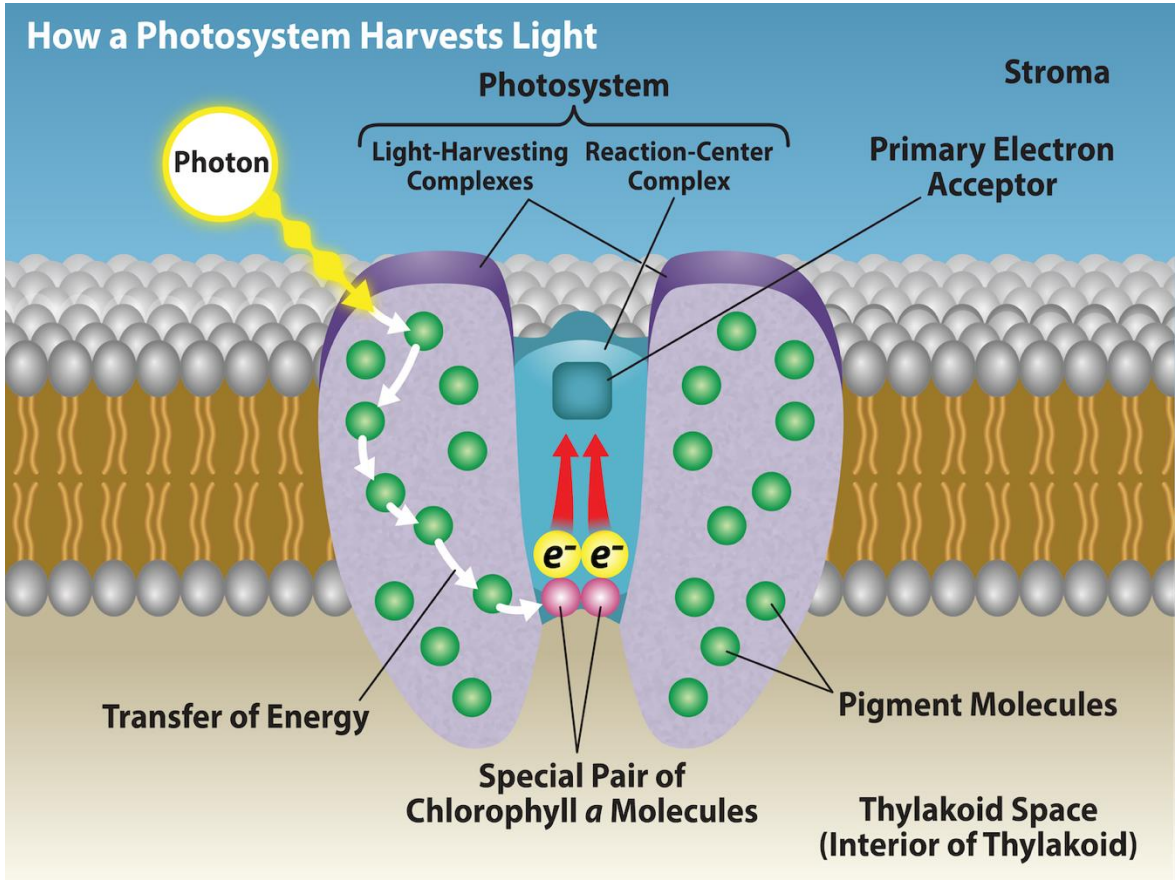
Chlorophyll a/b protein complexes (LHC)

Surround reaction centers

Contain chlorophyll a, chlorophyll b and carotenoids

Absorb light across a broad spectrum

Transfer **excitation energy to the reaction center**



Where Is Light Absorbed in Photosynthesis?

Pigment–Protein Complexes

Component	Function	Pigment Composition
Antenna complex (LHC)	Light capture	Chl a, Chl b, carotenoids
Reaction center (CP)	Charge separation	Chl a (special pair)

Photosynthetic Unit

A **photosynthetic unit** is the **smallest functional unit** in the thylakoid membrane capable of:

Absorbing light

Transferring excitation energy

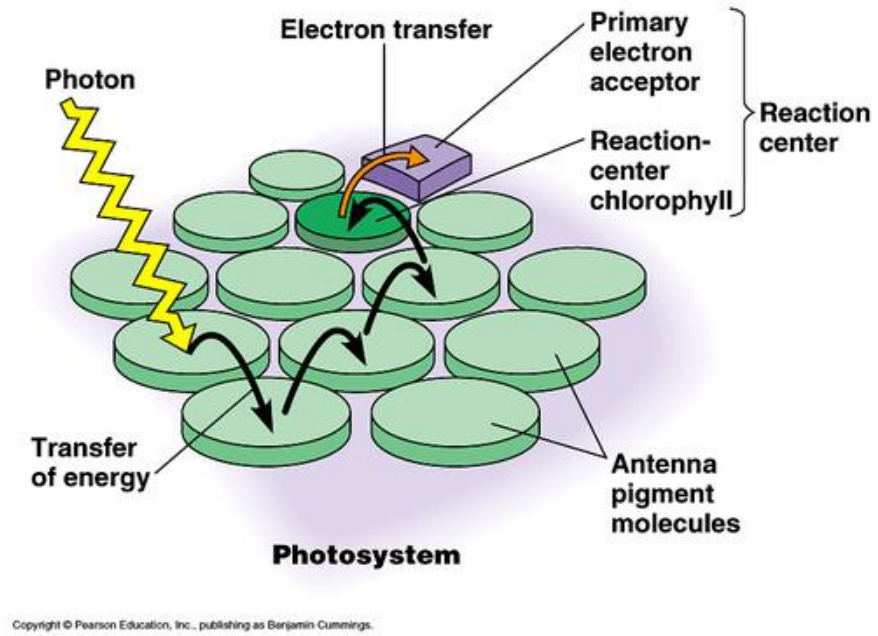
Performing primary photochemistry

Photosynthetic Unit = **LHC** (Antenna) + **CP** (Reaction Center)

A photosynthetic unit consists of an LHC antenna system functionally coupled to a CP core complex, enabling one photochemical event per absorbed photon.

Photosynthetic Unit

Photosystem	LHC Type	CP Type	Reaction Center
PSII	LHCII	CPa	P680
PSI	LHCI	CPI	P700



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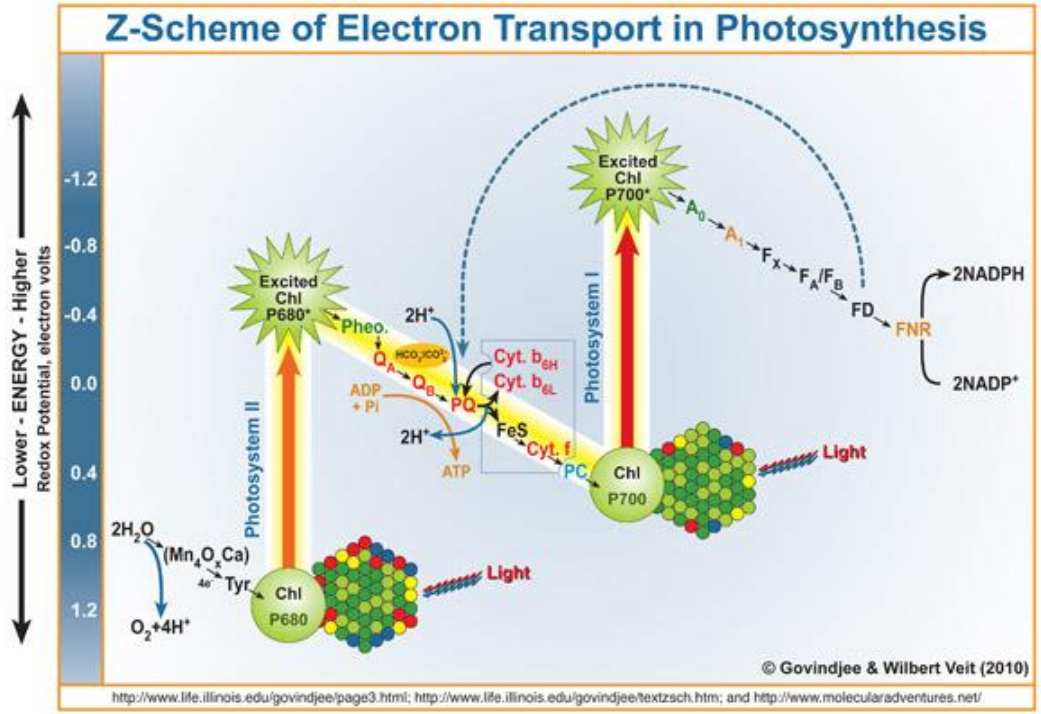


Photosynthetic Unit

Reaction Center (Core of Photochemistry)

Special pair chlorophyll a

PSII: P680

PSI: P700

Primary electron donor (P)

Primary electron acceptor (A)

Secondary electron donor (D)

Component	Role	Example
Primary donor (P)	Excited chlorophyll	P680(PSII), P700(PSI)
Primary acceptor (A)	First electron acceptor	PSII: pheophytin; PSI: A_0 (chlorophyll)
Secondary donor (D)	Replaces lost electron	PSII: H_2O (via OEC); PSI: plastocyanin

Primary Reaction (原初反应)

The **primary reaction** is the initial photochemical event in photosynthesis in which **excitation energy, delivered from the antenna (LHC), is converted into stable chemical energy via charge separation in the reaction center (CP).**

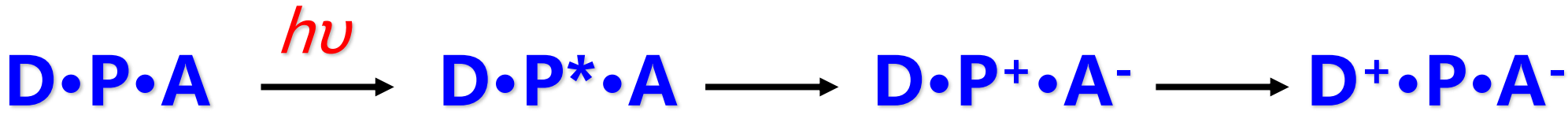
Characteristics:

- **Extremely fast** (~picoseconds)
- **Temperature-independent** (photophysical process)
- **High quantum efficiency (~1 under optimal conditions)**

Process:

- Excitation of reaction center chlorophyll
- Charge separation
- Electron transferred to primary acceptor

Primary Reaction (原初反应)



Level	Donor	Acceptor	Meaning
Primary (immediate)	P680 / P700	Primary acceptor (A)	First charge separation
Secondary (chain)	Electron carriers	Next carriers	Electron transport chain
Ultimate (overall)	H_2O	$NADP^+$	Net photosynthetic flow

Energy Transfer in Antenna Pigments

Antenna pigments absorb photons and become excited.

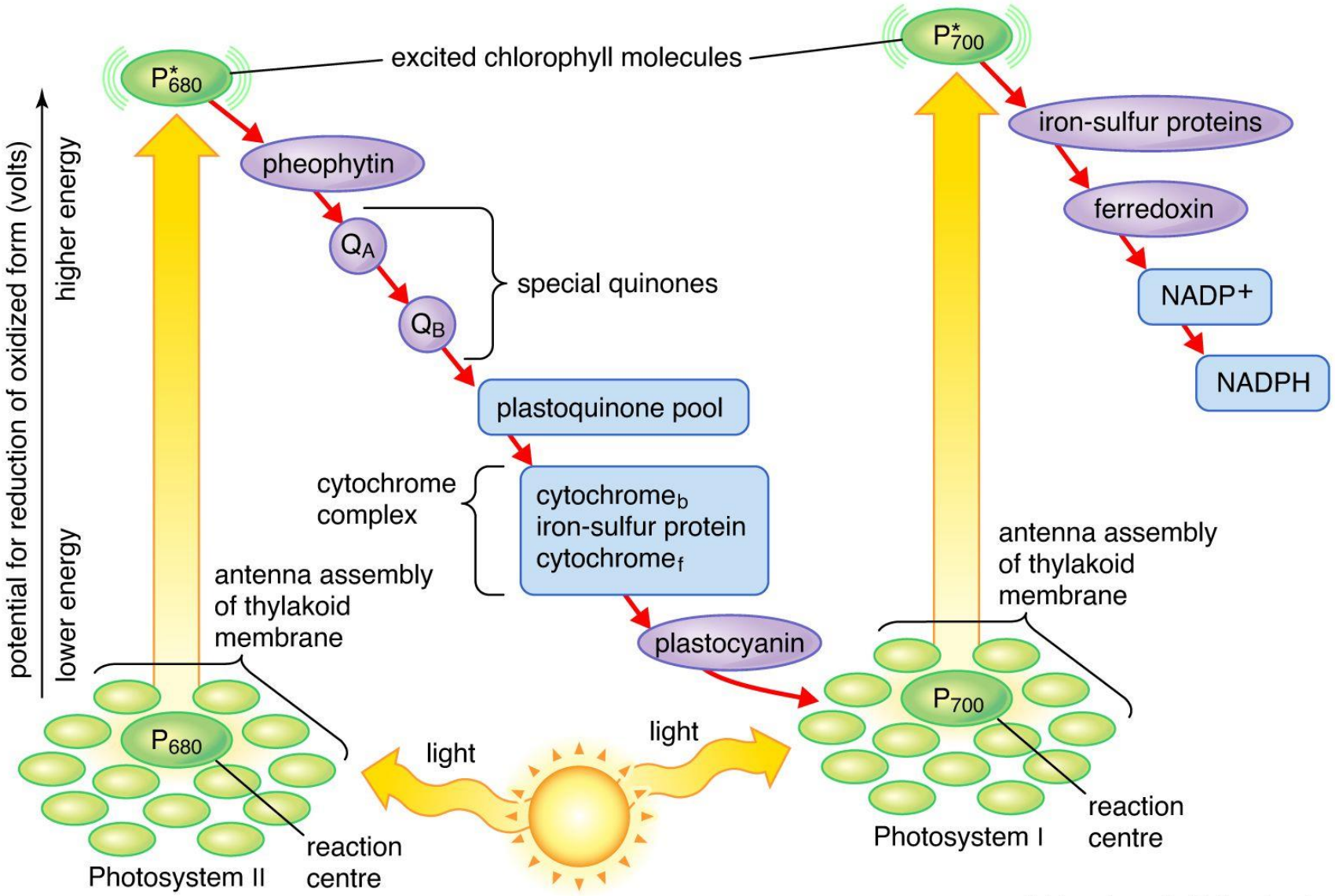
The excitation energy is transferred to neighboring pigments via:

Exciton transfer / 激子传递

Resonance energy transfer (FRET-like mechanism) / 共振传递

An exciton is a quasi-particle representing an excited state consisting of an electron–hole pair, capable of transferring energy without transferring net charge.

Photosynthetic electron pathway



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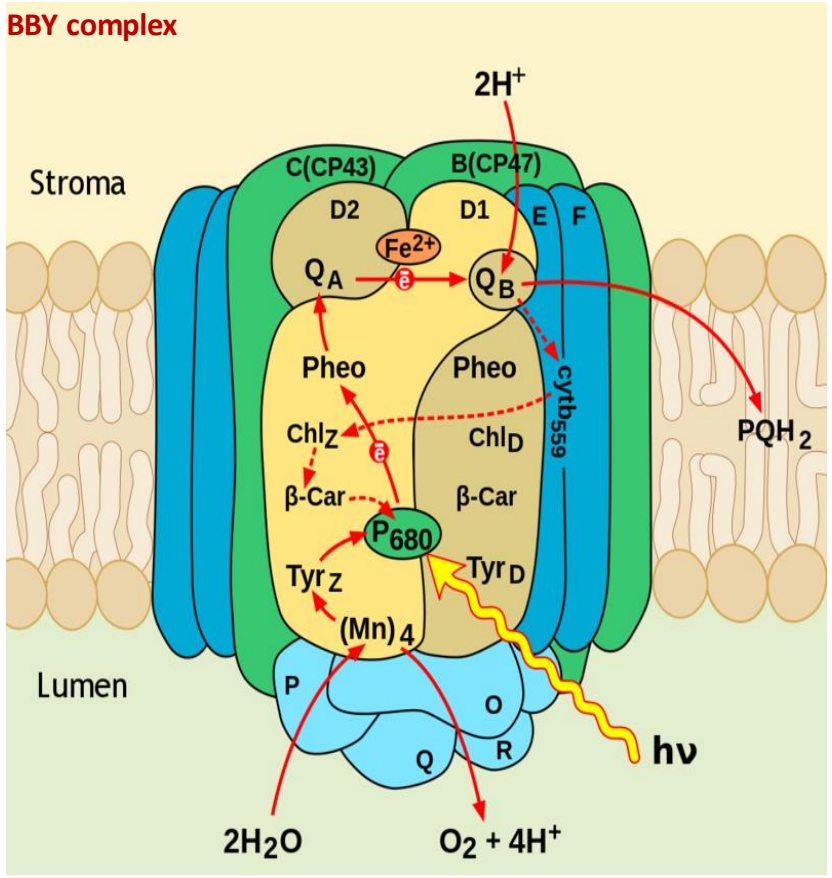
Photosynthetic electron pathway

Photosystem II (PSII) Complex



Also known as the BBY complex (core PSII reaction center preparation)

Located in the thylakoid membrane (mainly grana)

Approximate size: ~17–20 nm

Central function: Initiates electron flow by oxidizing water and reducing plastoquinone

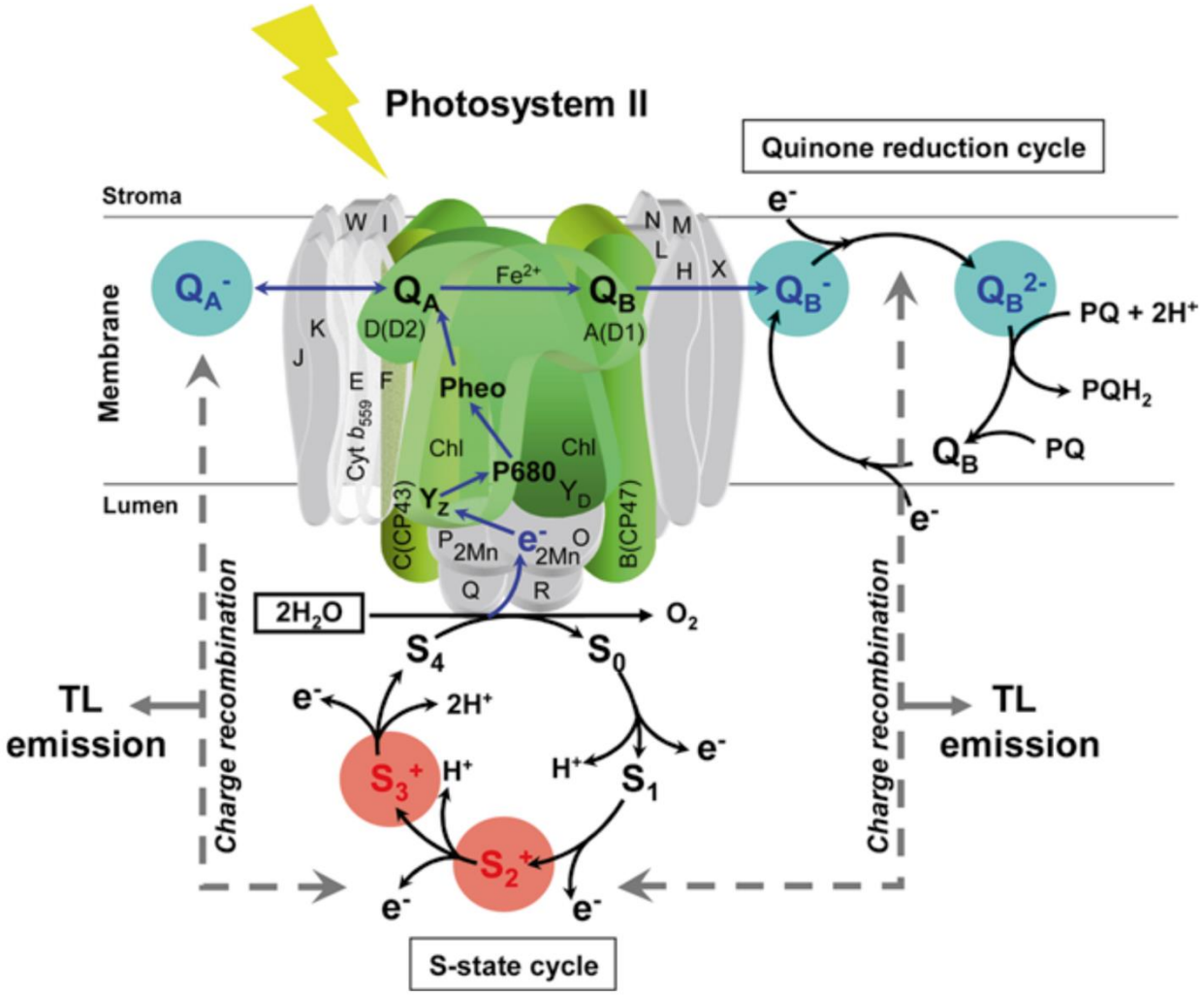
Reaction center: P680 (bound by D1 and D2)

Primary acceptor: Pheophytin (Pheo)/去镁叶绿素

Secondary acceptors： Q_A, Q_B (plastoquinones)

Photosynthetic electron pathway

Photosystem II (PSII) Complex



Primary Reaction in PSII

1. Light excites **P680 → P680***
2. Electron transferred to **pheophytin (Pheo)**
3. Then to **Q_A → Q_B → plastoquinone (PQ → PQH_2)**

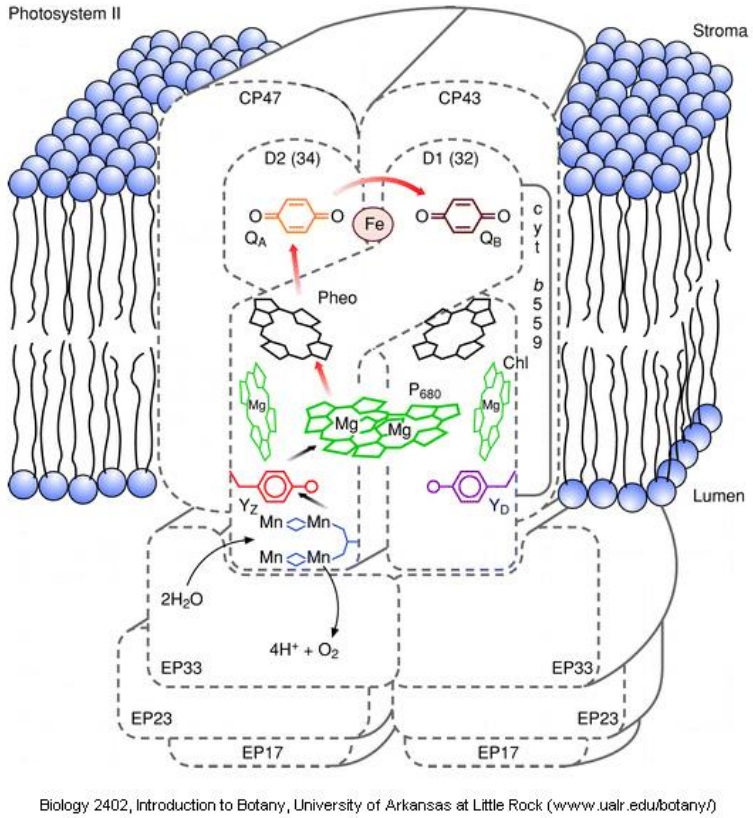
Electron Replacement

1. $P680^+$ is highly oxidizing
2. Re-reduced via:
    1. Y_Z (or tyr_Z; tyrosine residue)
    2. Then Mn cluster extracts electrons from H_2O

Photosynthetic electron pathway

Photosystem II (PSII) Complex

Oxygen-evolving complex (OEC) / 放氧复合体



Biology 2402, Introduction to Botany, University of Arkansas at Little Rock (www.ualr.edu/botany/)

Water Splitting (OEC)

Located on **lumen side**

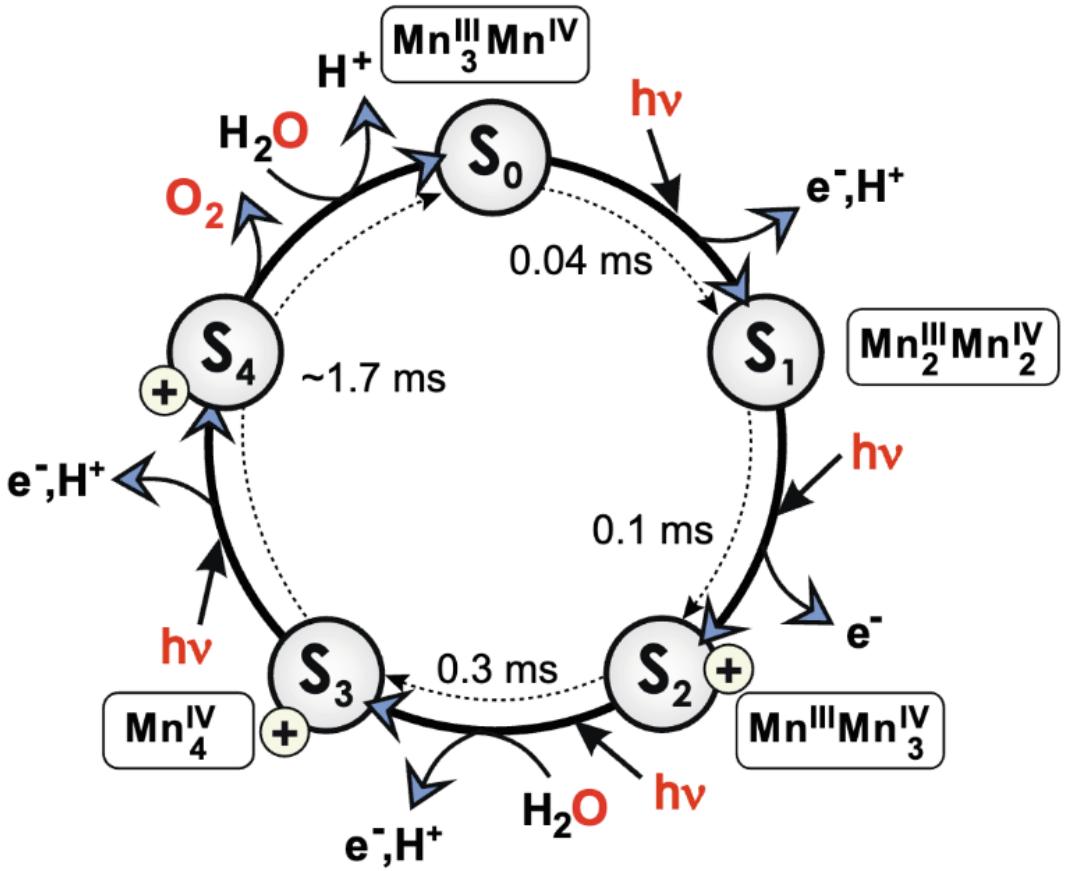
Contains: **Mn_4Ca cluster** / 锰稳定蛋白

Extract electrons from water to replace electrons lost by $P680^+$

- **O_2 (released)**
- **Protons (H^+) into lumen**

Photosynthetic electron pathway

Photosystem II (PSII) Complex



OEC: Kok Cycle (S-State Cycle)

By Kok (1970)

The OEC cycles through five oxidation states:

$$S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4$$

Each step is driven by one photon absorbed by P680

Photosynthetic electron pathway

Photosystem II (PSII) Complex

RESEARCH ARTICLE

An oxyl/oxo mechanism for oxygen-oxygen coupling in PSII revealed by an x-ray free-electron laser

Michihiro Suga[1,2,*,†], Fusamichi Akita[1,2,*]. Keitaro Yamashita[3,‡]. Yoshiki Nakajima[1]. Go Ueno[3]. Hongjie Li[1,4]. Takahiro Yaman...
+ See all authors and affiliations

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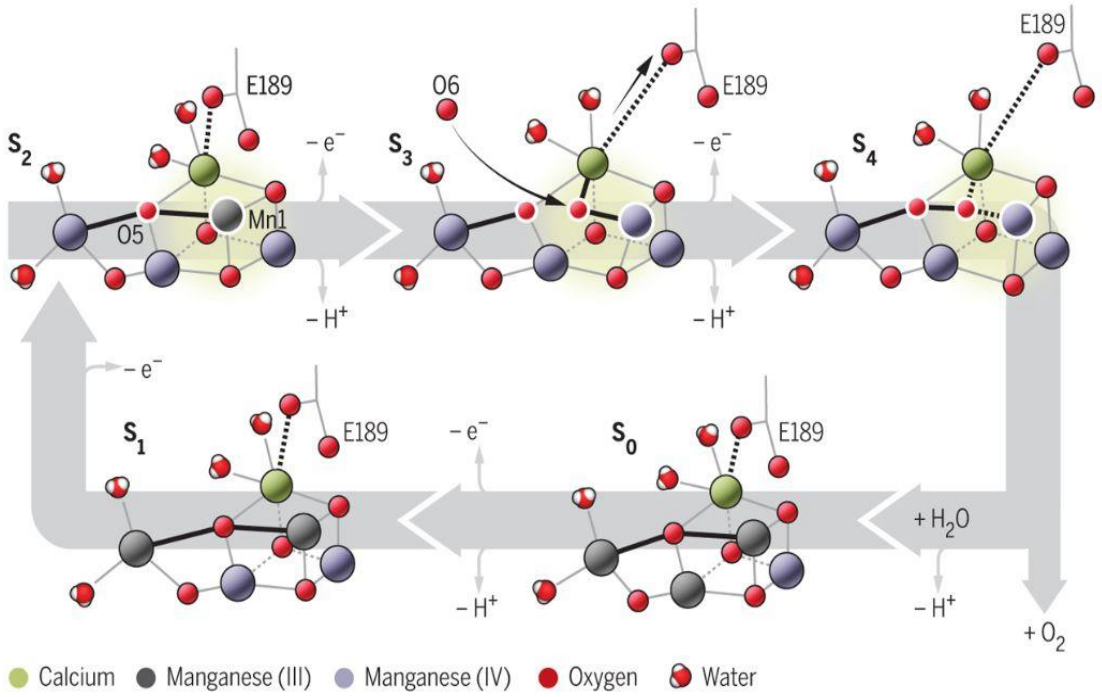
DOI: 10.1126/science.aax6998





Photosynthetic electron pathway

Plastoquinone (PQ；质体醌): Mobile Electron and Proton Carrier

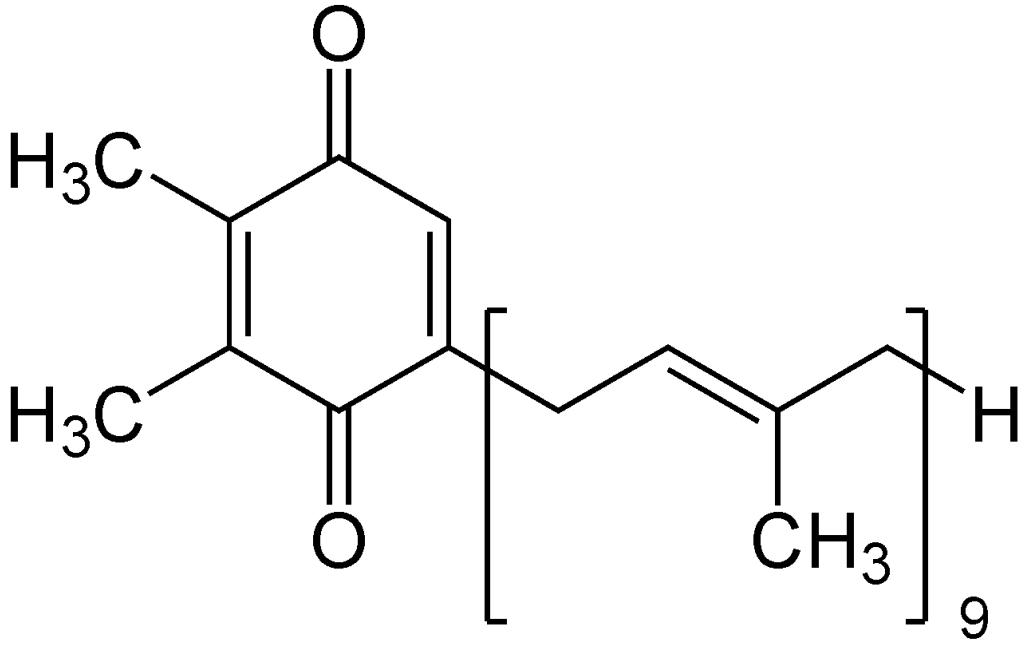
Plastoquinone (PQ) is a lipid-soluble quinone located in the thylakoid membrane.

Functions as a mobile carrier of:

- Electrons (e^-)
- Protons (H^+)

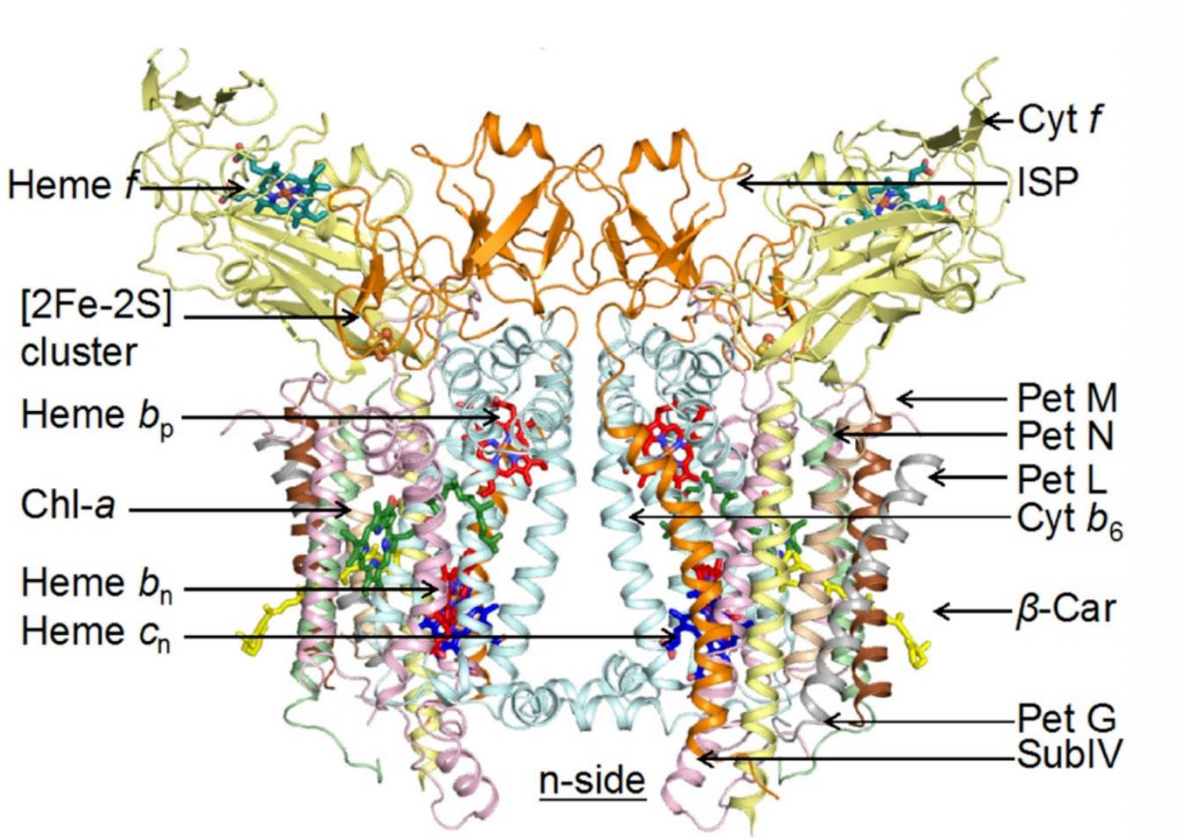
Links Photosystem II (PSII) to the cytochrome b_6f complex / 细胞色素b_6f

Reduced form: PQH_2 (plastoquinol, 还原态醌), PQH^- (plastosemiquinone; 半醌)



Photosynthetic electron pathway

Cytochrome b_6f Complex



Located in the thylakoid membrane

Functions as:

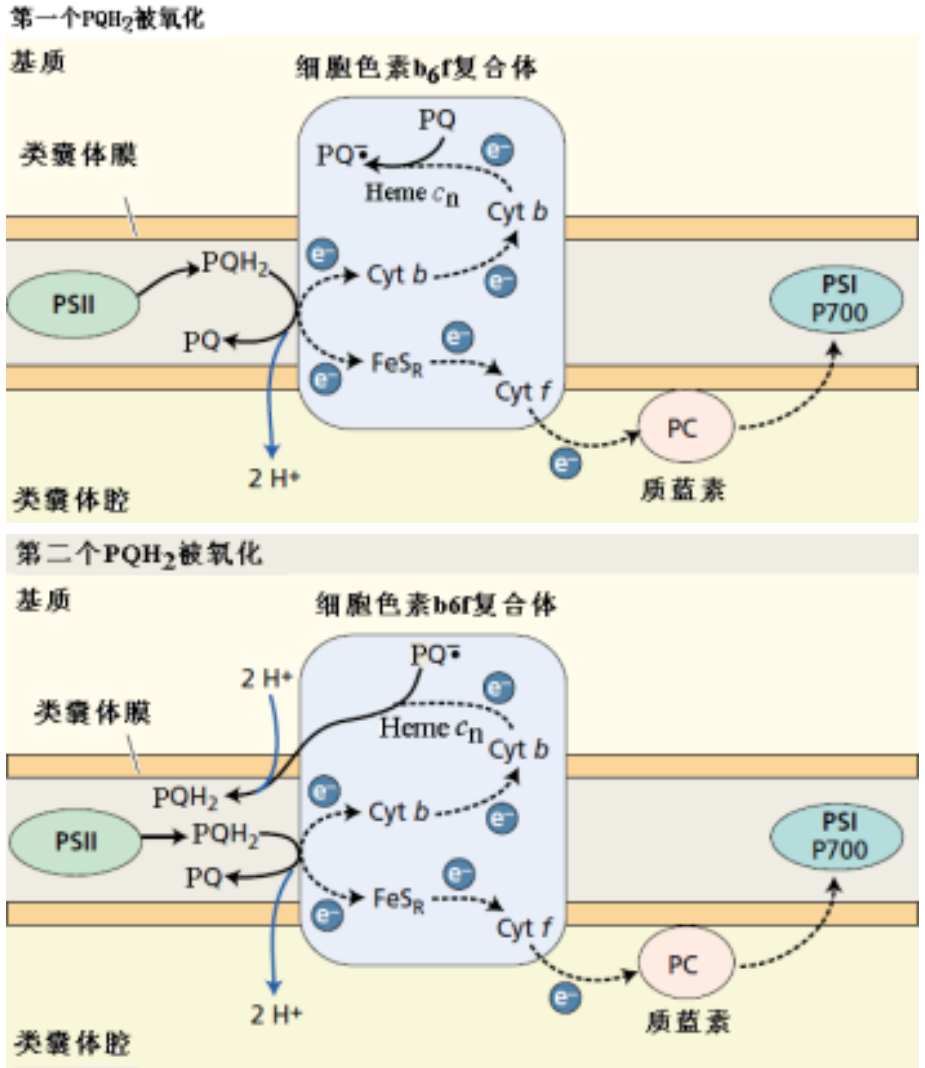
- Electron transfer intermediate
- Proton translocation system

Electron Flow Through Cyt b_6f

- Input: PQH_2 (from PSII)
- Output: Plastocyanin (PC) → PSI

Photosynthetic electron pathway

Cytochrome b_6f Complex



Q-Cycle Mechanism

First PQH_2 Oxidation (at Q_o site)

$PQH_2 \rightarrow PQ + 2e^- + 2H^+$ (to lumen)

Electron split:

- Path 1: Rieske → Cyt f → PC → PSI (P700)
- Path 2: Cyt b_6 → Q → reduces PQ → PQH^-

Second PQH_2 Oxidation

Repeats same process:

- Another $2H^+$ released into lumen
- Second electron: reduces PQH^- → PQH_2

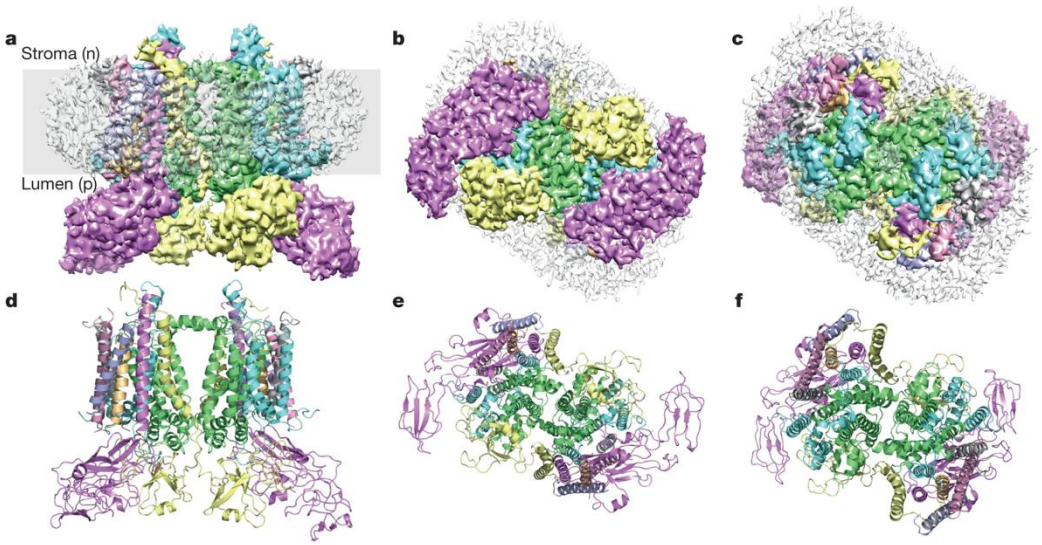
Requires: $2H^+$ uptake from stroma

nature

Article | Published: 13 November 2019

Cryo-EM structure of the spinach cytochrome b_6f complex at 3.6 Å resolution

Lorna A. Malone, Pu Qian, Guy E. Mayneord, Andrew Hitchcock, David A. Farmer, Rebecca F. Thompson, David J. K. Swainsbury, Neil A. Ranson, C. Neil Hunter & Matthew P. Johnson





Key Photosynthesis Complex Viewed in Spinach

Findings fuel hopes for improved food-crop efficiency

Dr. Matt Johnson, reader in Biochemistry at the University of Sheffield and one of the supervisors of the study added: "Cytochrome b6f is the **beating heart** of photosynthesis which plays a crucial role in regulating photosynthetic efficiency.

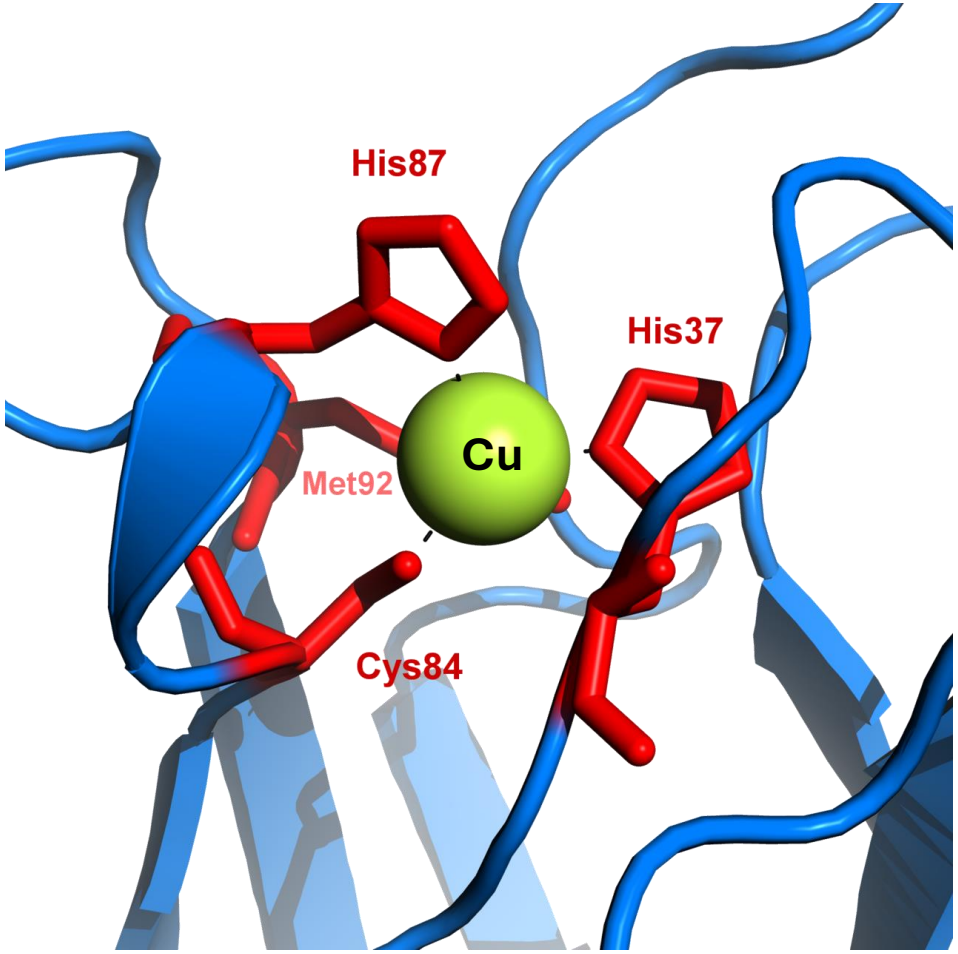
Photosynthetic electron pathway

Plastocyanin (PC): Mobile Electron Carrier to PSI 质蓝素

Plastocyanin (PC) is a small, soluble copper-containing protein

Located in the thylakoid lumen

Functions as a mobile electron carrier

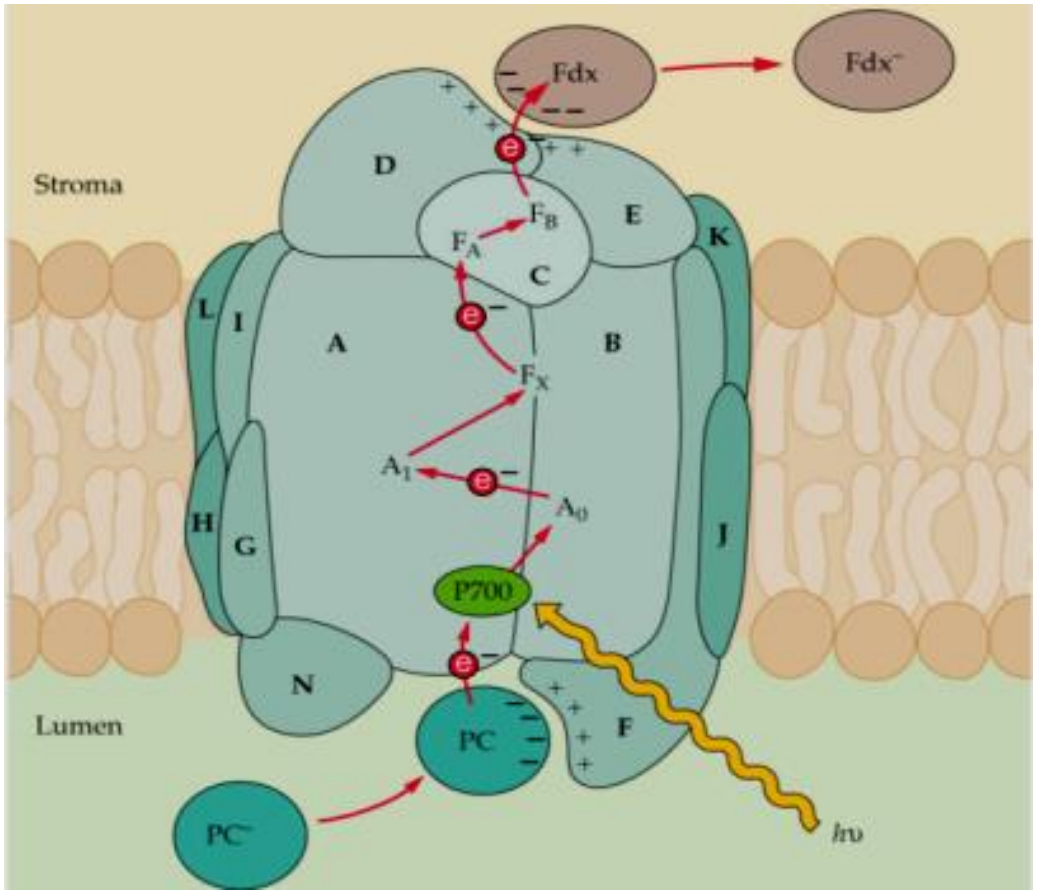


Redox states:

- ✓ **Cu^{+} (reduced form)**
- ✓ **Cu^{2+} (oxidized form)**

Photosynthetic electron pathway

Photosystem I (PSI): Light Reaction and $NADP^+$ Reduction



PSI is a large pigment–protein complex embedded in the thylakoid membrane

Enriched in stroma lamellae (non-appressed regions)

Convert light energy into reducing power (NADPH)

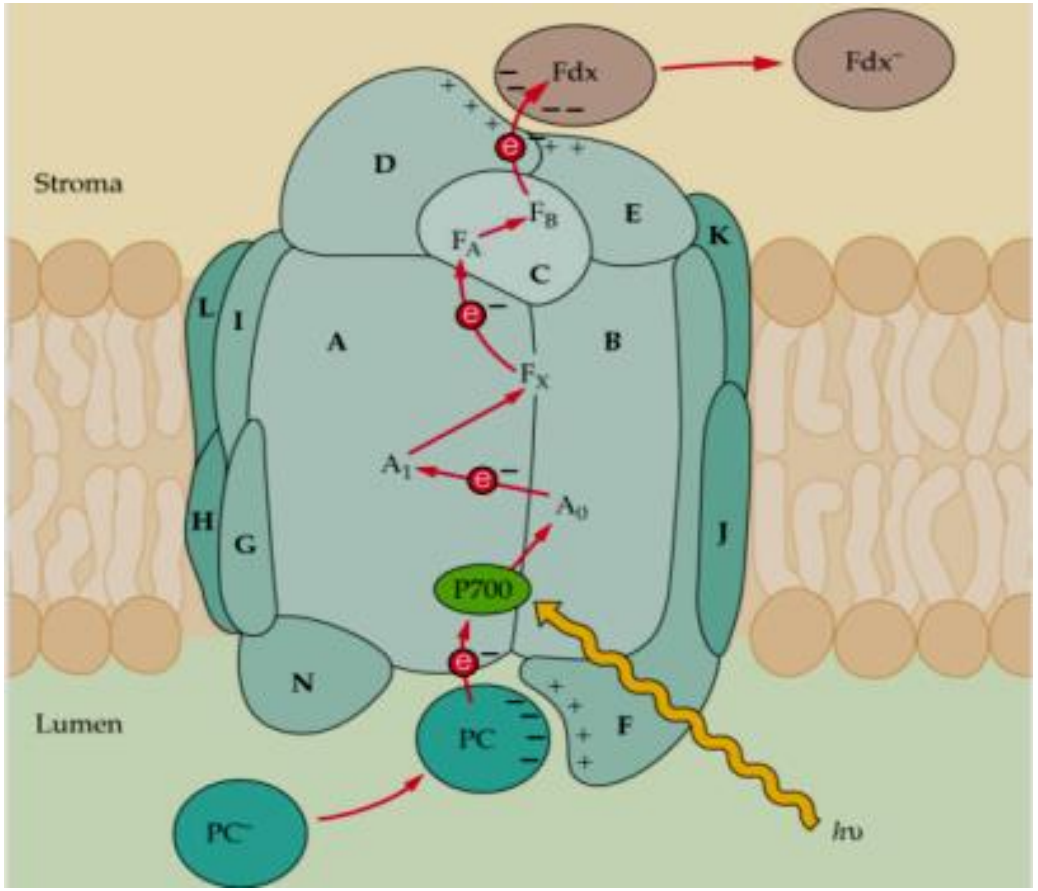
Reaction center: P700

Electron carriers:

- A_0 (chlorophyll a), primary acceptor
- A_1 (phylloquinone/维生素K)
- Fe–S clusters (F_x, F_a, F_b)

Photosynthetic electron pathway

Photosystem I (PSI): Light Reaction and NADP⁺ Reduction



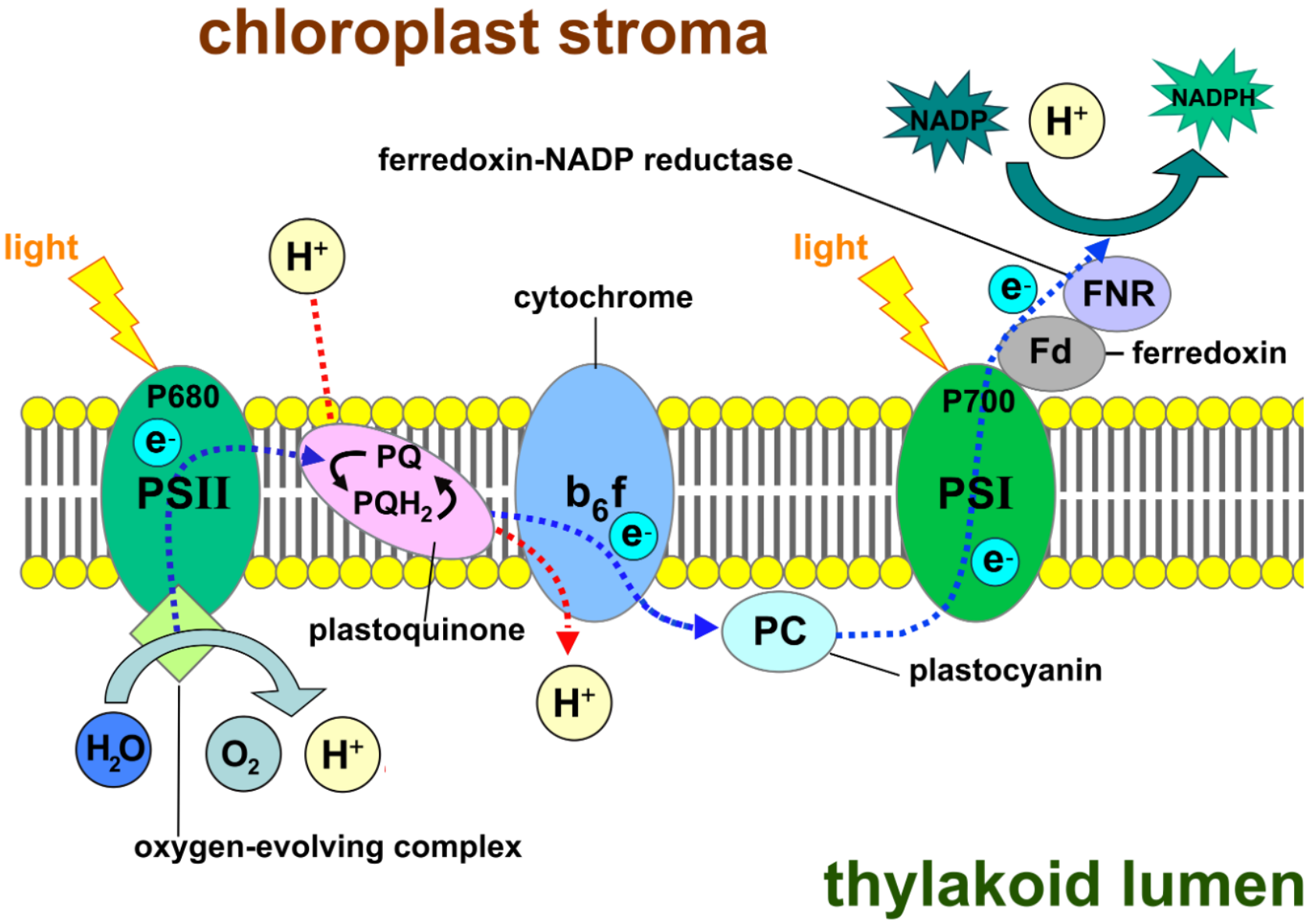
P700⁺ is reduced by **Plastocyanin (PC)**

Electrons exit PSI via Ferredoxin (Fd)

Then Ferredoxin–NADP⁺ reductase (FNR) catalyzes:

$$NADP^+ + 2e^- + H^+ \rightarrow NADPH$$

Photosynthetic electron pathway



Photosynthetic electron pathway

Photosynthetic electron transport operates in three modes:

1. **Linear (noncyclic) electron flow / 非环式电子传递**
2. **Cyclic electron flow / 环式电子传递**
3. **Pseudocyclic electron flow (Mehler reaction / 米歇尔反应) / 假环式电子传递**

Photosynthetic electron pathway

Linear (noncyclic) electron flow

$H_2O \rightarrow PS\,II \rightarrow PQ \rightarrow Cytb_6/f \rightarrow PC \rightarrow PS\,I \rightarrow Fd \rightarrow FNR \rightarrow NADP^+$

For 4 electrons transferred:

- 2 H_2O split → 1 O_2 released
- 2 $NADP^+$ → 2 NADPH
- ~8 H^+ accumulated in lumen
- ATP produced via chemiosmosis

Key Features

- Involves both PSII and PSI
- 8 photons → 1 O_2
- Produces: ATP + NADPH + O_2

Photosynthetic electron pathway

Cyclic Electron Flow (Around PSI)

PS I →Fd→(NADPH→PQ)→Cytb6/f→PC→PS I

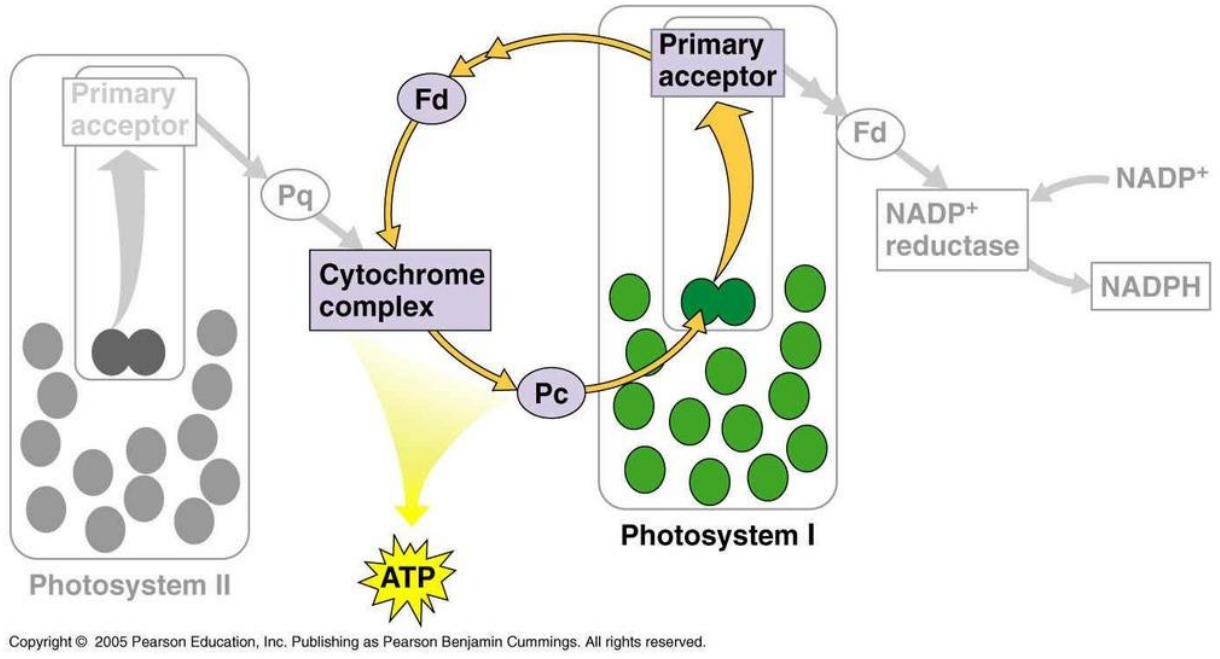
Produce ATP only

No NADPH production and O_2 evolution

Balances ATP/NADPH ratio

Activated when:

- **NADPH is abundant**
- **ATP demand is high**



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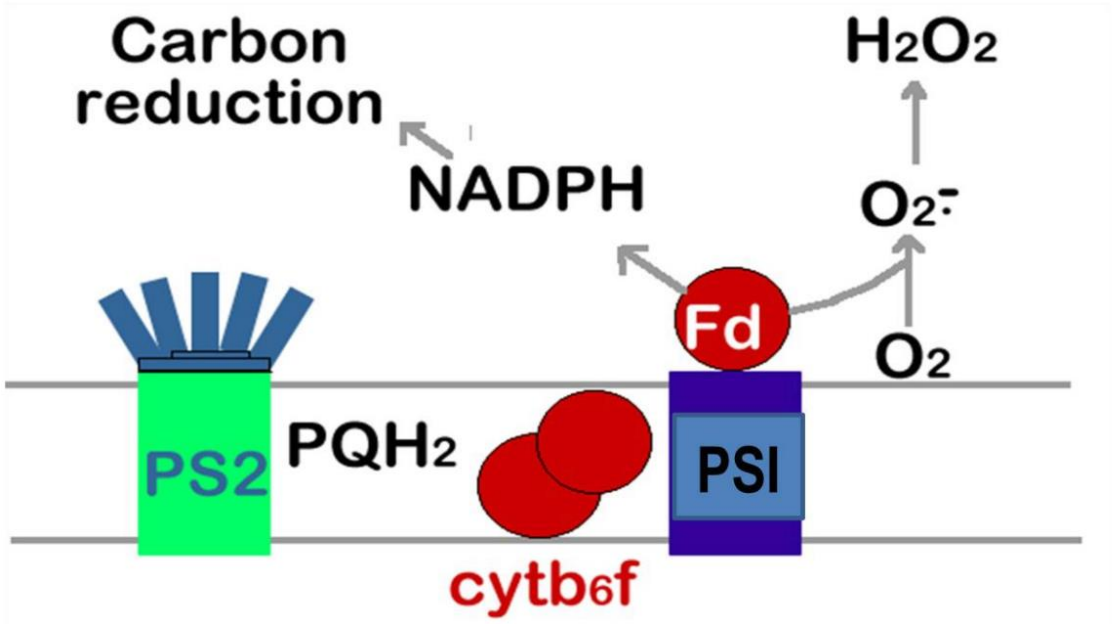
Photosynthetic electron pathway

Pseudocyclic Electron Flow (Mehler Reaction)

H_2O→PSⅡ→PQ→Cytb6/f→PC→PS Ⅰ→Fd→O2



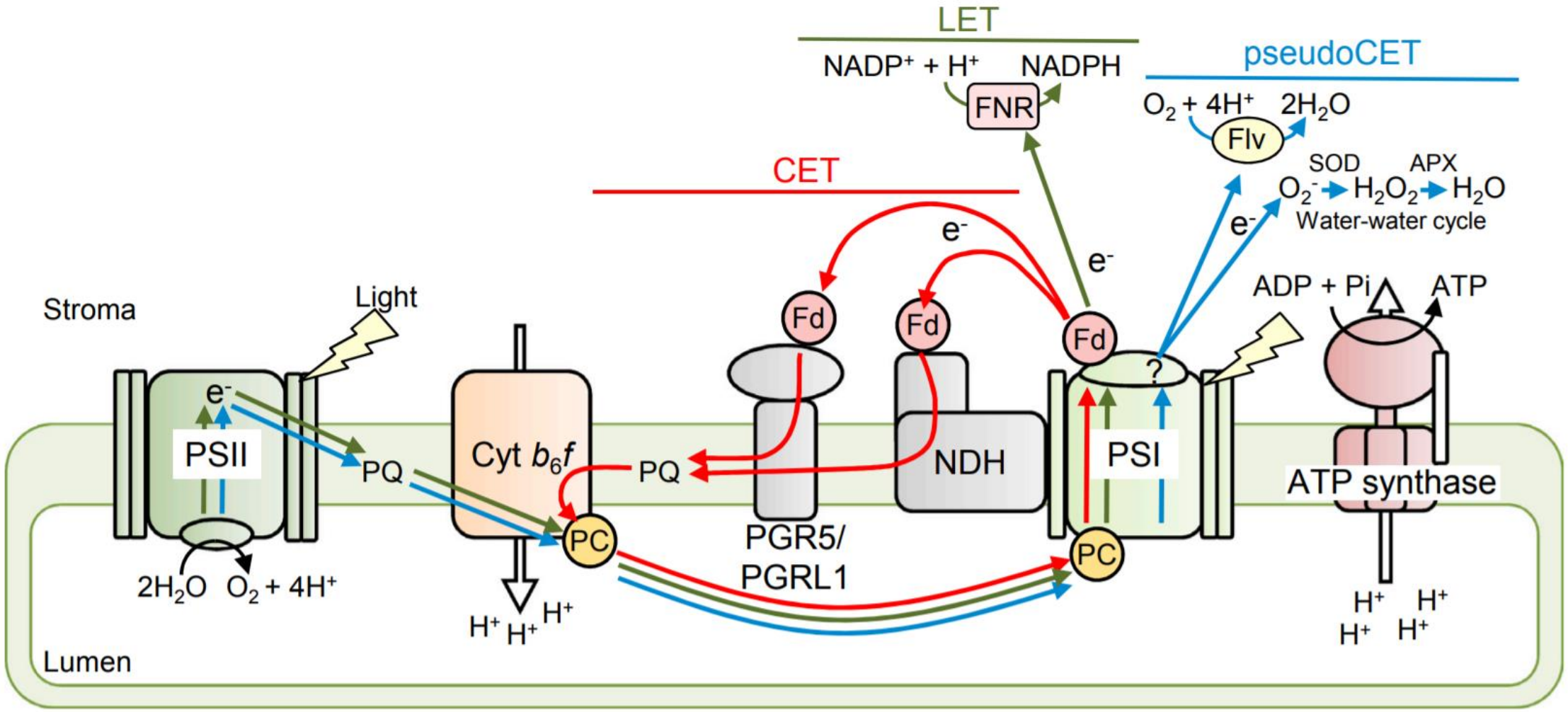
No NADPH produced

O_2 is consumed (not produced overall)

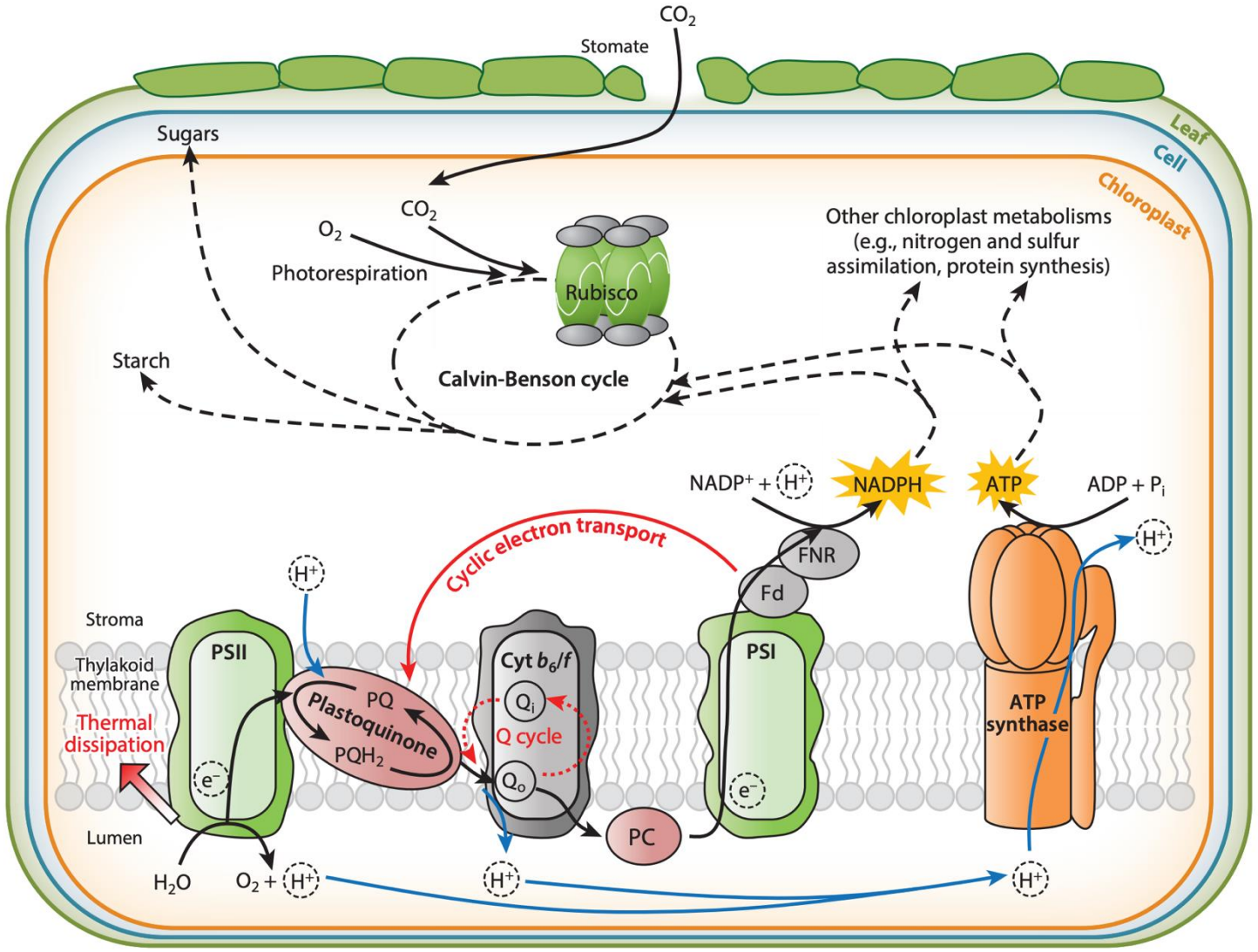
Produces: Reactive oxygen species (ROS) (e.g., superoxide O_2^-)

Can contribute indirectly to: Proton gradient → ATP formation

Photosynthetic electron pathway



Photophosphorylation /光合磷酸化



The process by which light-driven electron transport generates a proton gradient across the thylakoid membrane, which is then used to synthesize ATP from ADP and Pi via ATP synthase.

Protons (H^+) accumulate in the thylakoid lumen via:

1. Water splitting (PSII)
2. Plastoquinone (PQ cycle)
3. Cytochrome b_6f (Q-cycle)

Photophosphorylation /光合磷酸化

Types of Photophosphorylation

(1) Noncyclic Photophosphorylation

Pathway: **PSII + PSI**

Produces: **ATP, NADPH**, **O_2**

The Main pathway for photosynthesis

(2) Cyclic Photophosphorylation

Pathway: **PSI only**

Produces: **ATP only**

Adjusts **ATP/NADPH balance**

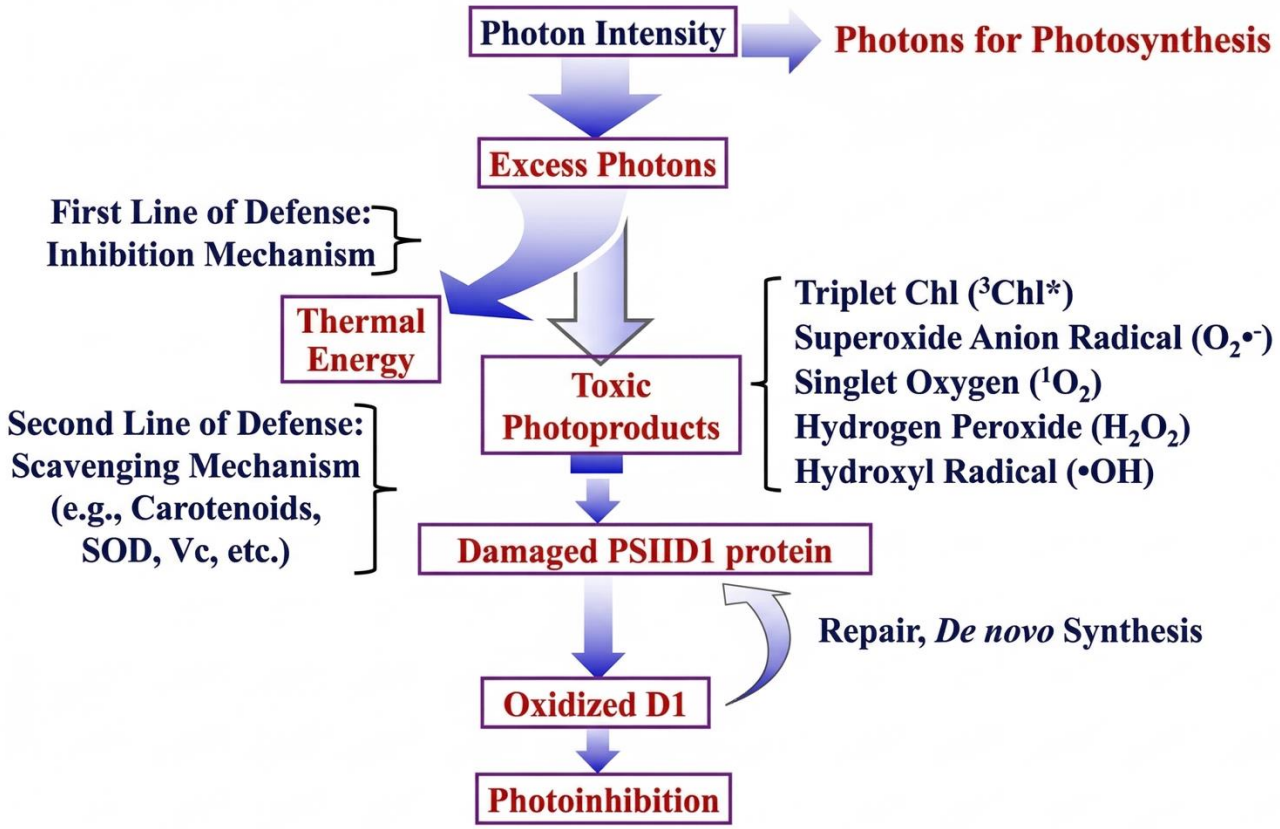
(3) Pseudocyclic photophosphorylation

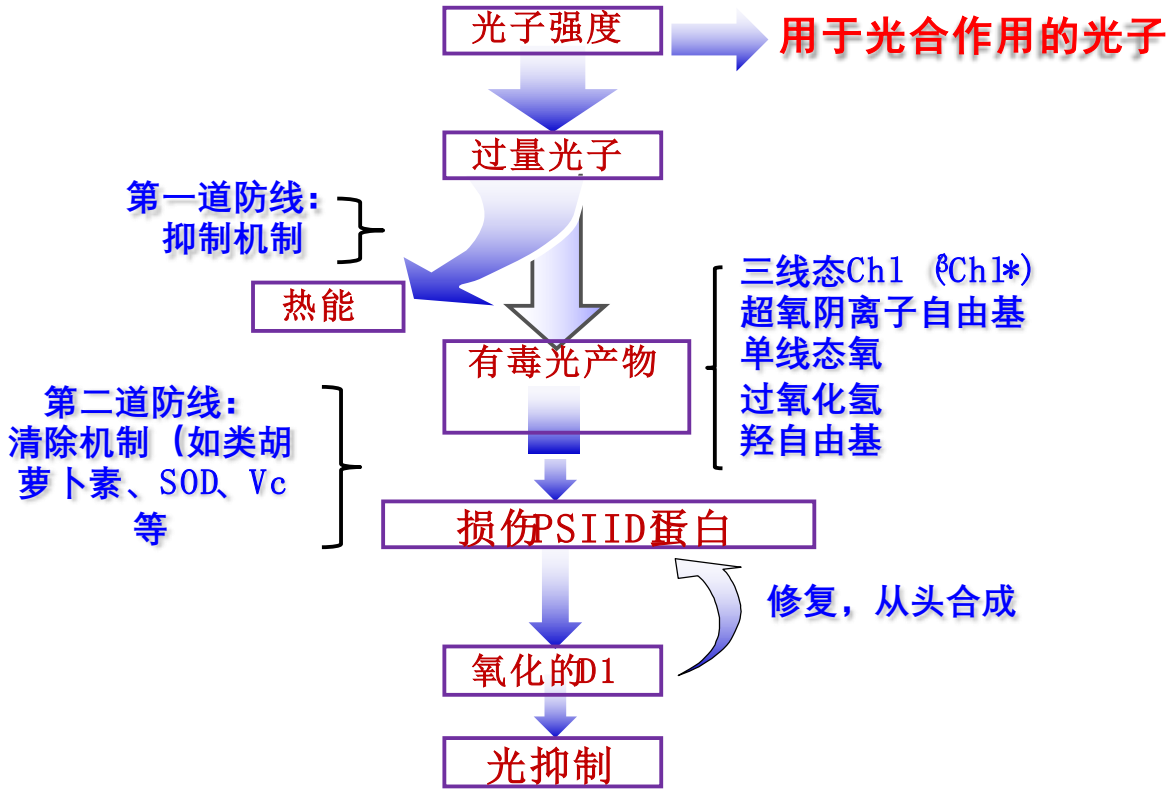
Pathway: **PSII + PSI**

Produces: **ATP only;** O_2 is evolved at PSII but consumed downstream (no net O_2 production in the complete water–water cycle)

Photoprotection

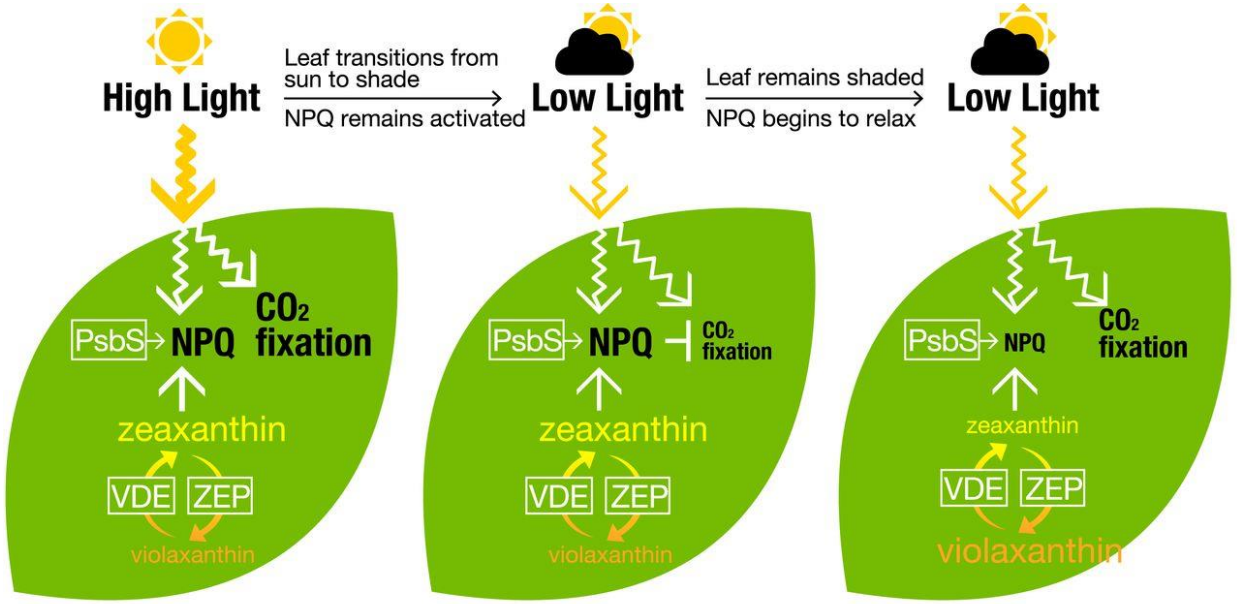
Light Energy Distribution and Photoprotection





Light reaction and crop improvement

Improving photosynthesis and crop productivity by accelerating recovery from photoprotection



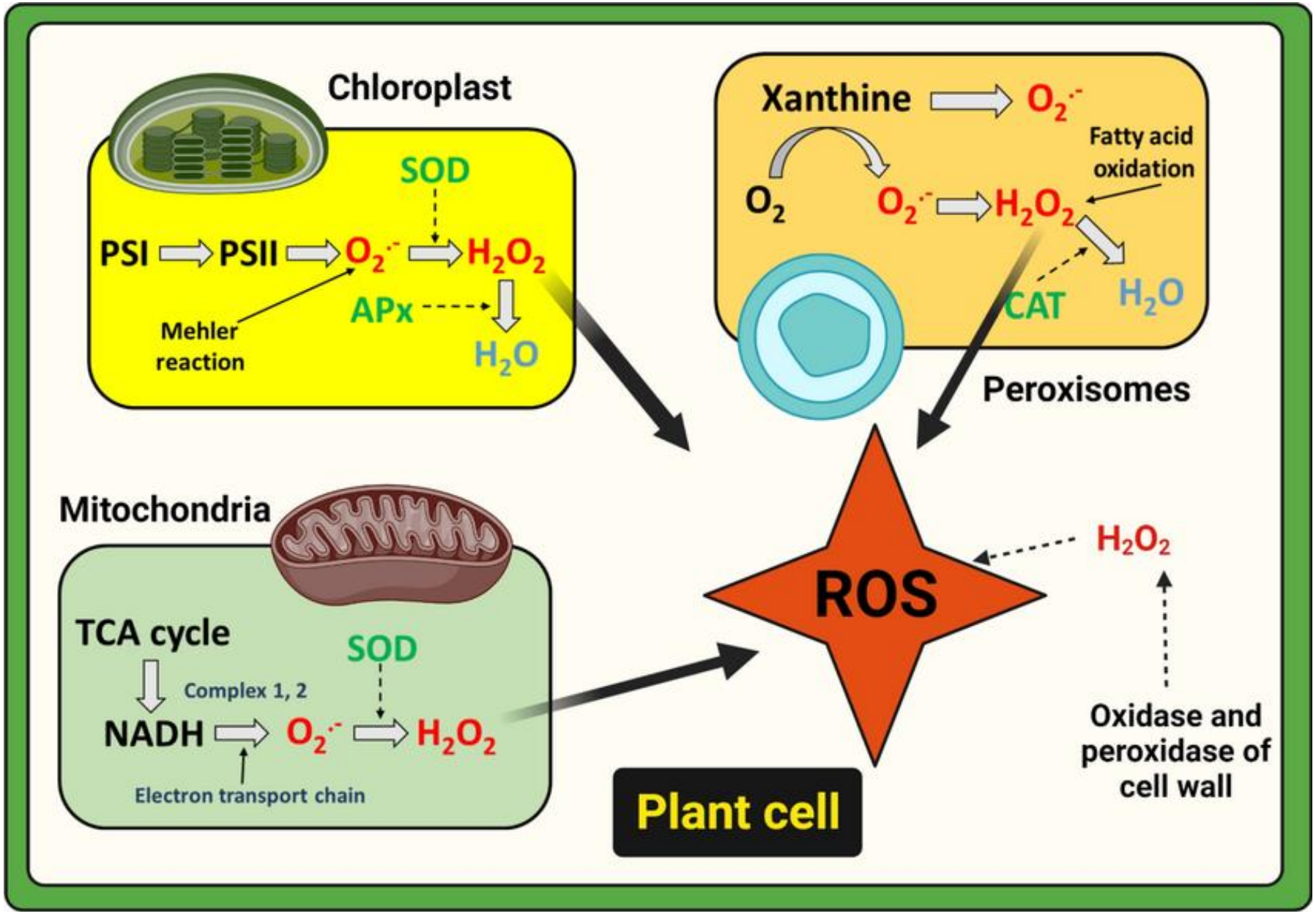
ZEP speeds up NPQ relaxation
VDE balances ZEP activity during NPQ induction
PsbS adjusts NPQ level to maintain WT amplitude

2016 Science, 10.1126/science.aai8878

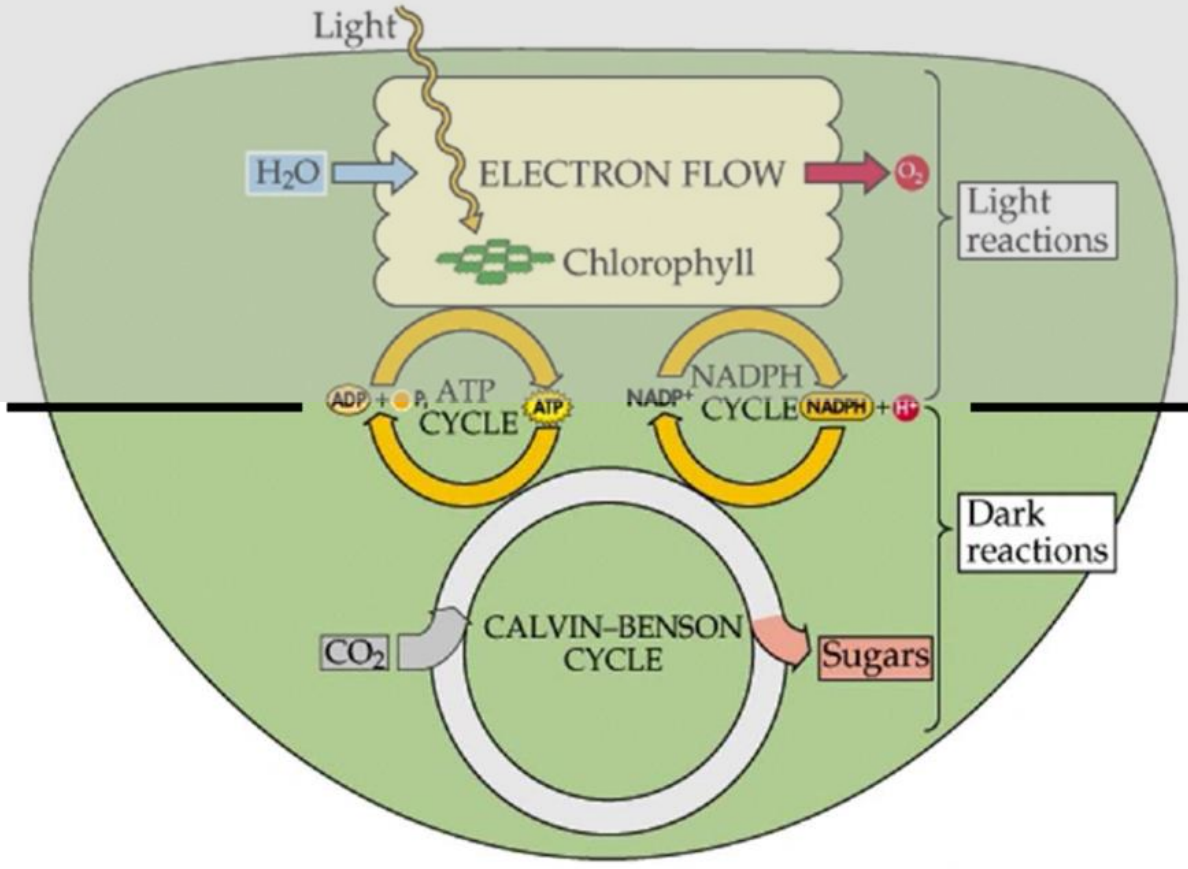
2022 Science, 10.1126/science.adc9831



Sources of Reactive Oxygen Species (ROS) in Plants



A two(=multi)part photosynthetic process:



1) **Light-dependent reactions**
PHOTOCHEMISTRY.
Light energy captured by chlorophyll is (PARTLY) used for ATP and NADPH synthesis from ADP and $NADP^+$.

2) **Light-independent reactions**
. **BIOCHEMISTRY**.
ATP and NADPH are used to reduce and fix CO_2 generating sugars in the C-B-B cycle.

Carbon Assimilation in Photosynthesis

Carbon assimilation (CO_2 assimilation): The process by which plants use ATP and NADPH (from light reactions) to convert CO_2 into carbohydrates.

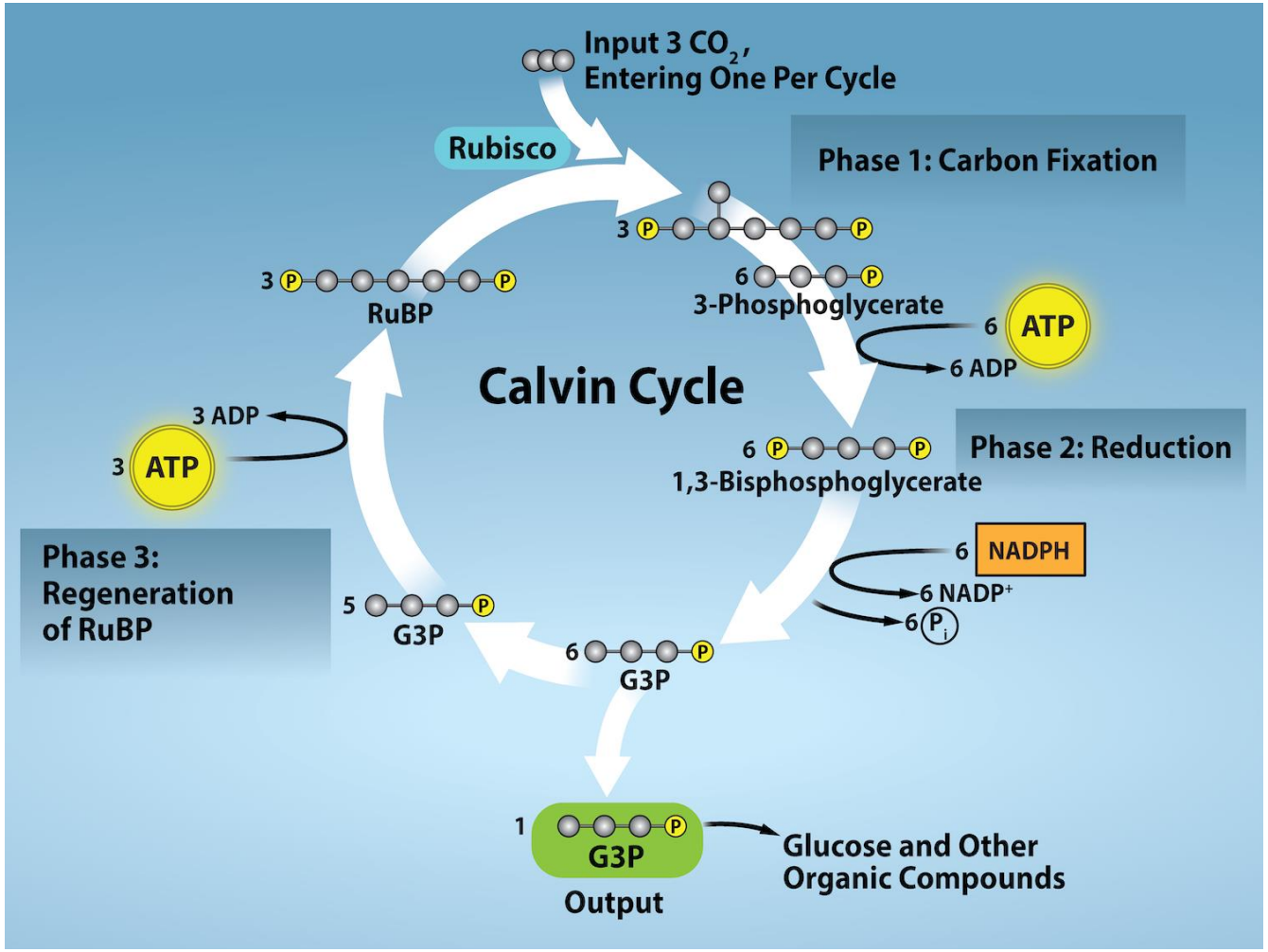
Occurs in: Chloroplast stroma

Major Carbon Fixation Pathways

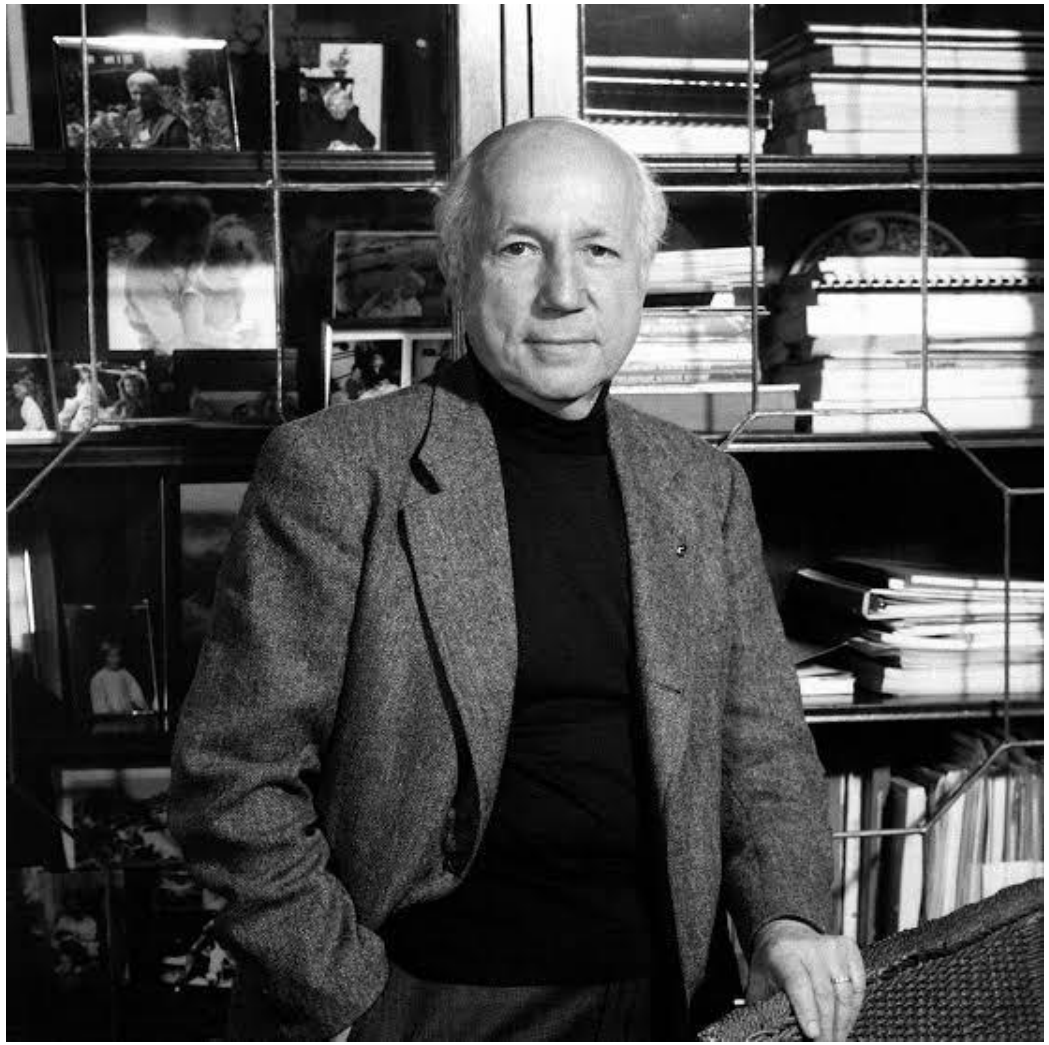
- **C_3 pathway (Calvin cycle)** (most common)
- **C_4 pathway**
- **CAM pathway**

The C_3 Pathway (Calvin–Benson Cycle)

A photosynthetic carbon fixation pathway in which ribulose-1,5-bisphosphate (RuBP) acts as the CO_2 acceptor, and the first stable product formed is the three-carbon compound 3-phosphoglycerate (PGA).



Discovery



Nobel Prize in Chemistry 1961



Photo: Berkeley, CA. Nobel Foundation archive

Melvin Calvin

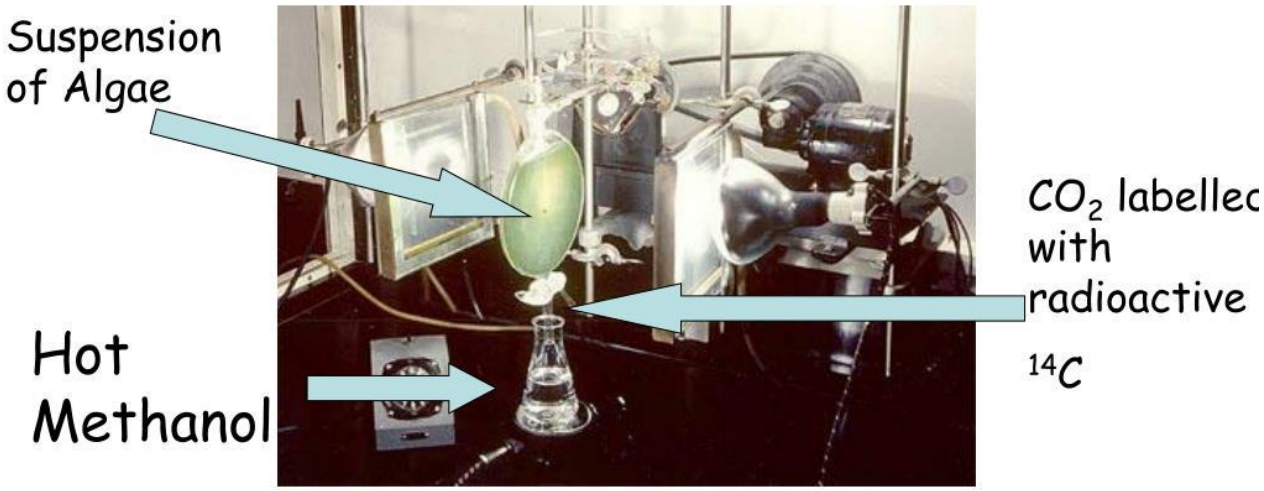
Prize share: 1/1

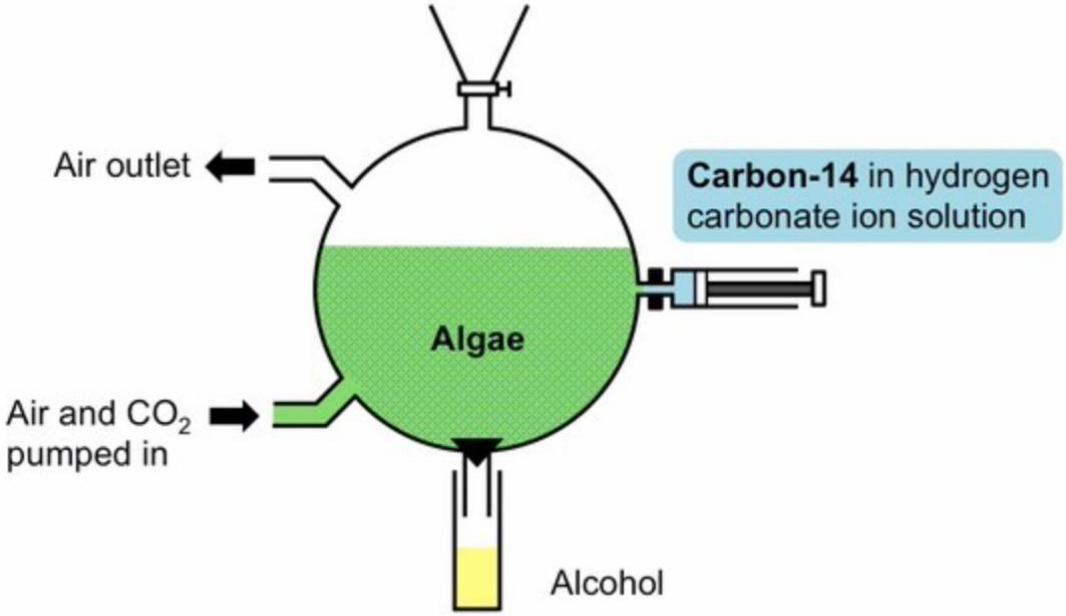
The Nobel Prize in Chemistry 1961 was awarded to Melvin Calvin "for his research on the carbon dioxide assimilation in plants"

Melvin Calvin, (1911-1997)

Discovery

Calvin's Experiment – the light independent reaction of photosynthesis





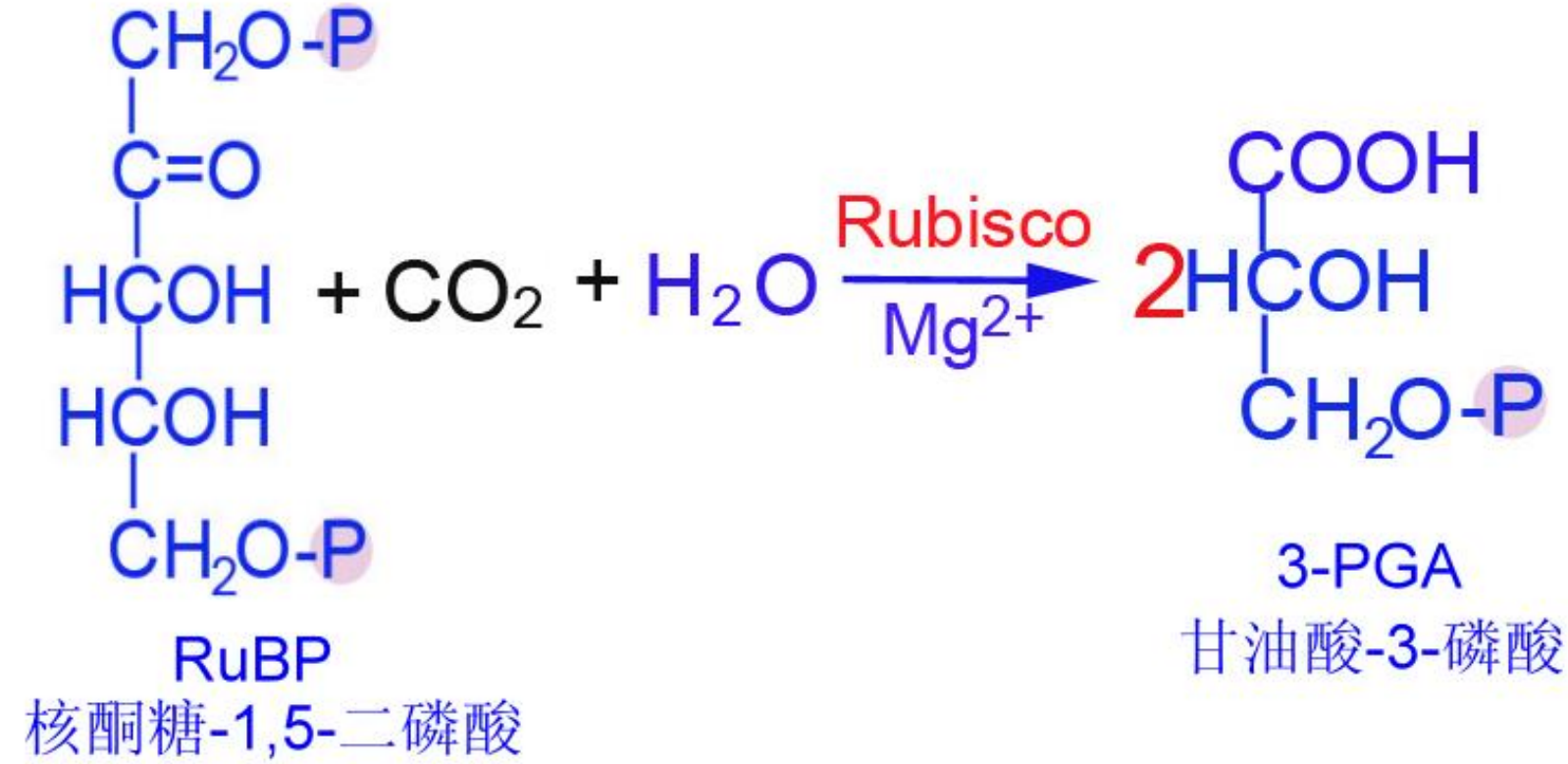
Step 1: Expose algae to **$^{14}CO_2$ under light**

Step 2: Stop reaction rapidly using **hot methanol (quenching)**

Step 3: Analyze labeled compounds via **chromatography**

The C_3 Pathway (Calvin–Benson Cycle)

Step 1: CO_2 Fixation / CO_2 固定



Ribulose 1,5-bisphosphate

3-Phosphoglycerate

PGA contains 3 Carbon atoms, and this defines the pathway as C3

The C_3 Pathway (Calvin–Benson Cycle)

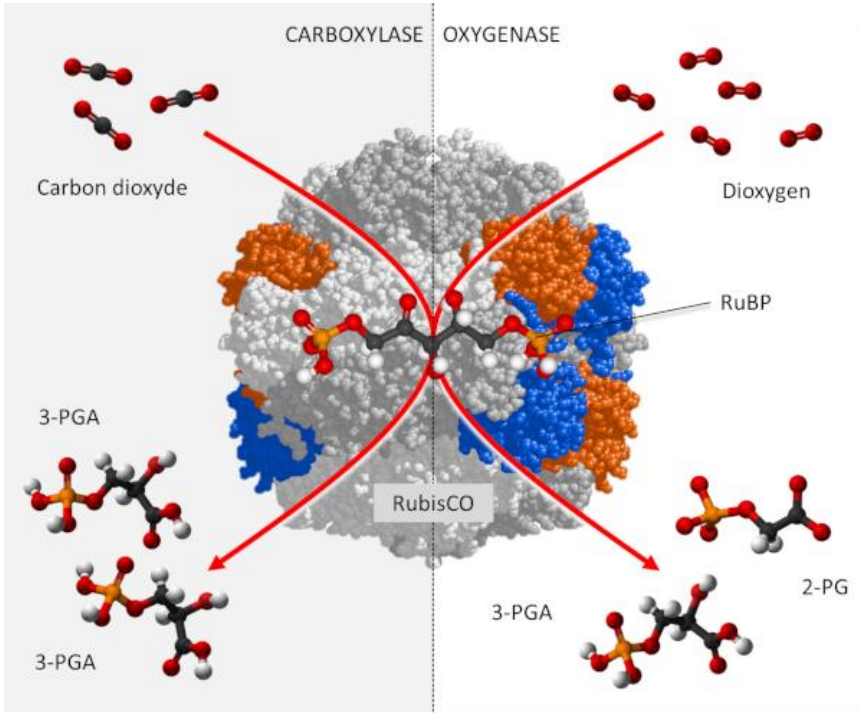
Step 1: CO_2 Fixation / CO_2 固定

RuBisCO: Ribulose-1,5-bisphosphate carboxylase/oxygenase

L_8S_8 complex (16 subunits)

Large subunits (L, ~55–56 kDa), which encoded by chloroplast genome, and contain active sites

Small subunits (S, ~14 kDa), which encoded by nuclear genome, plays as Regulatory/structural role

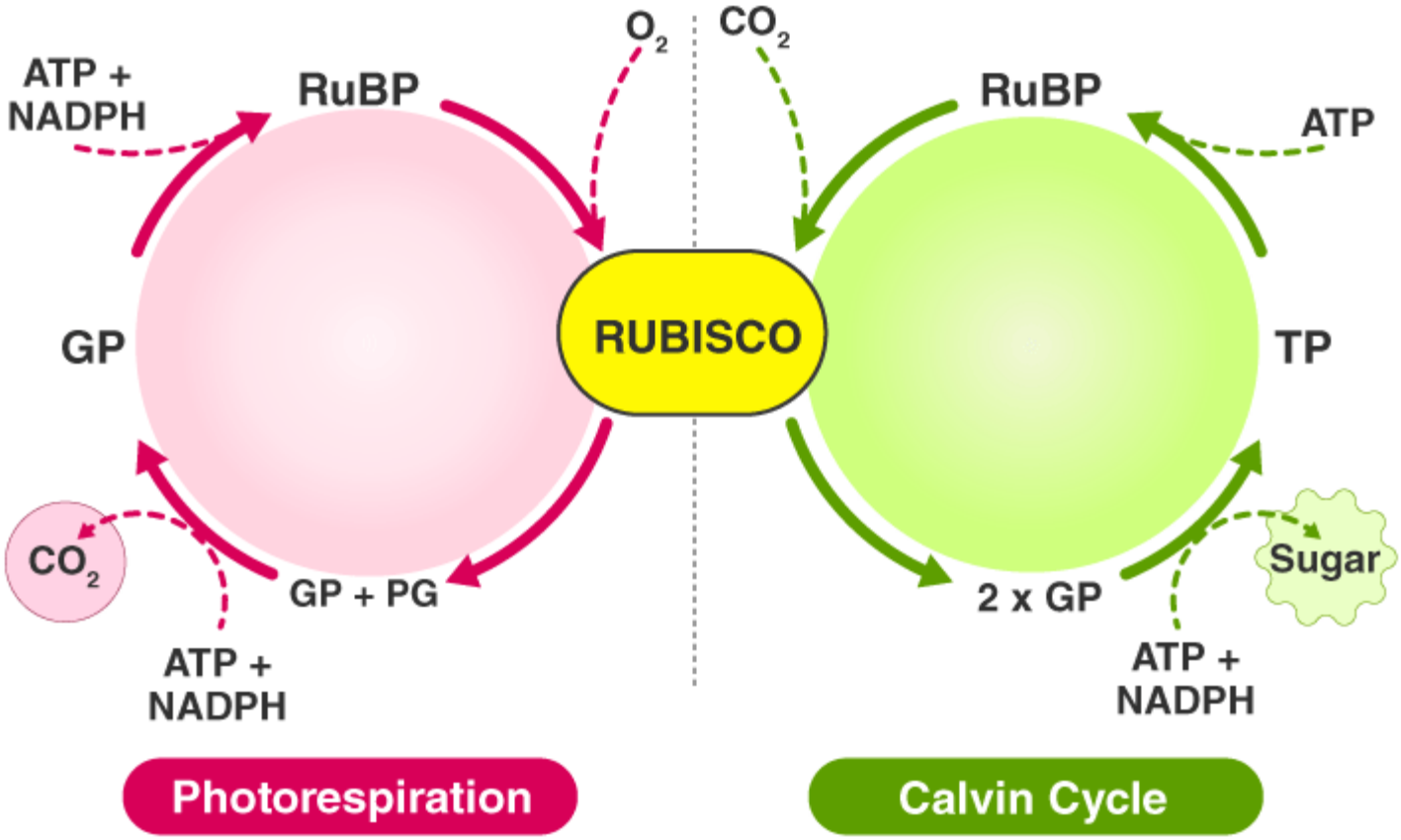


RuBisCO accounts for >40% of soluble leaf protein

The C_3 Pathway (Calvin–Benson Cycle)

Step 1: CO_2 Fixation / CO_2 固定

RuBisCO: Ribulose-1,5-bisphosphate carboxylase/oxygenase



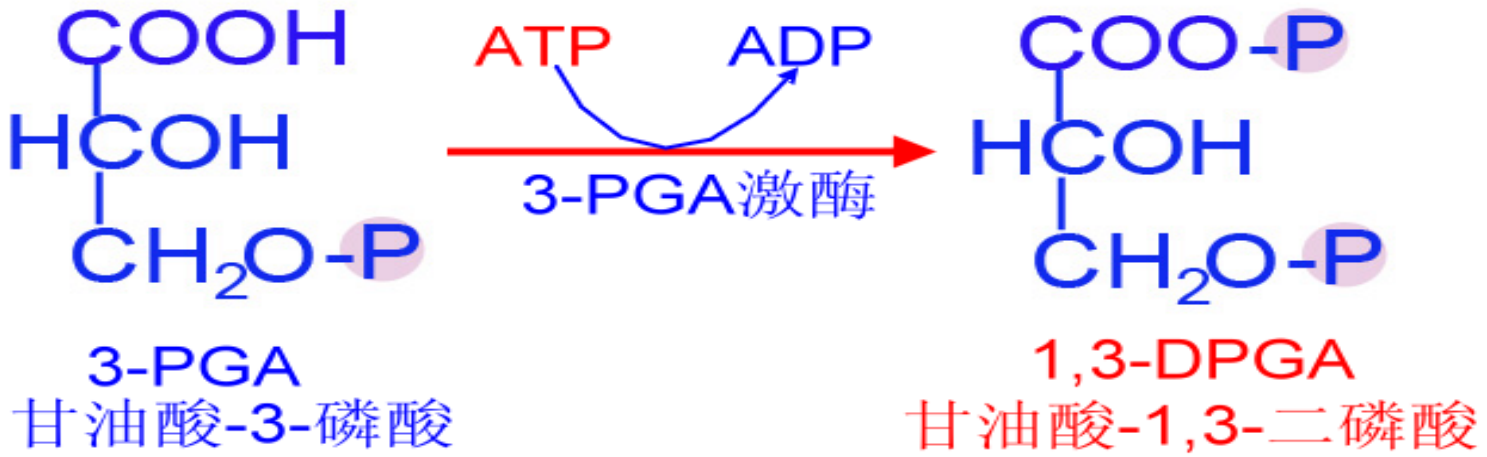
Carboxylase Activity

vs

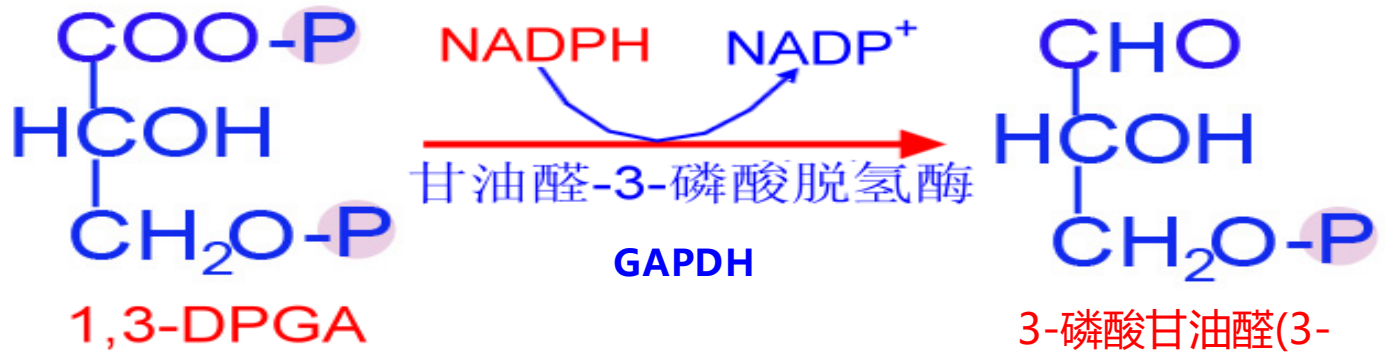
Oxygenase Activity

The C_3 Pathway (Calvin–Benson Cycle)

Step 2: Reduction / 还原



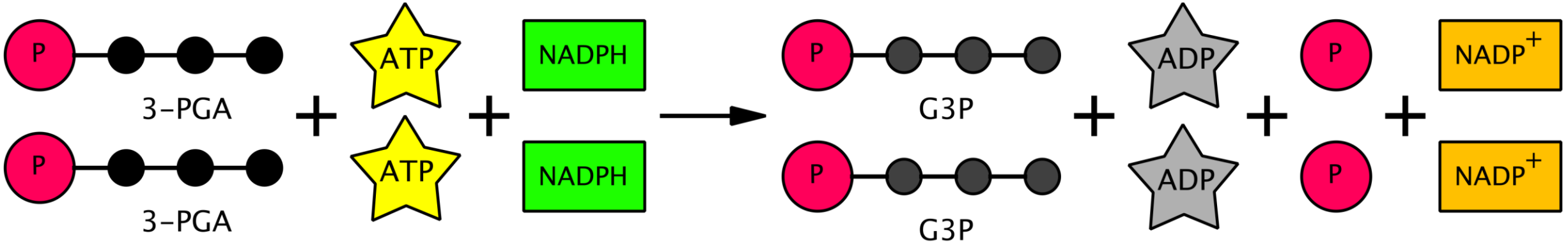
3-Phosphoglycerate **1,3-Bisphosphoglycerate**



1,3-Bisphosphoglycerate **Glyceraldehyde 3-phosphate**

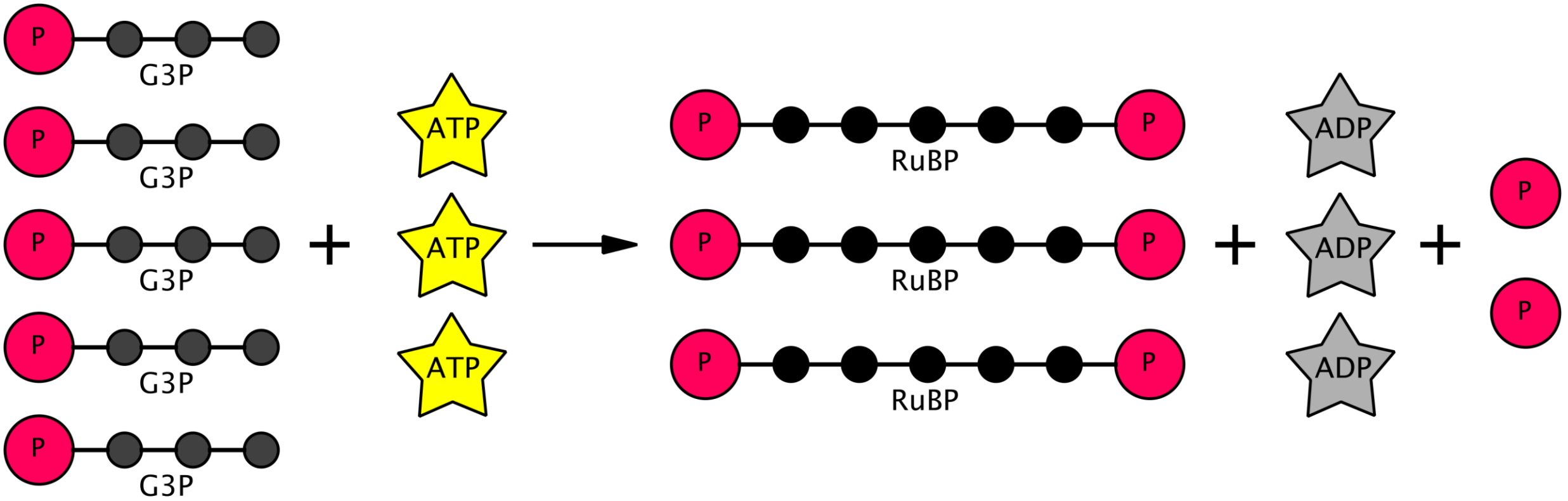
The C_3 Pathway (Calvin–Benson Cycle)

Step 2: Reduction / 还原



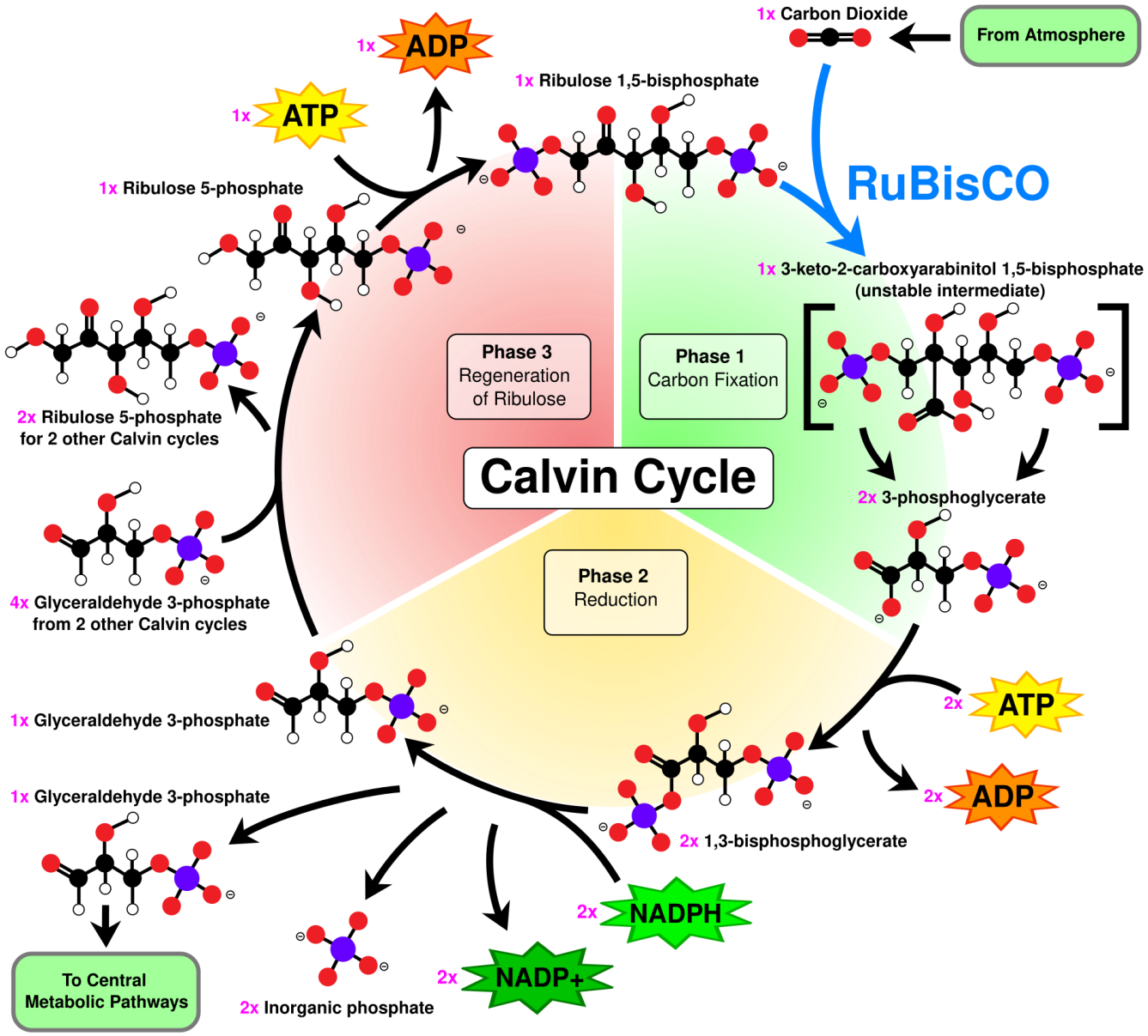
The C_3 Pathway (Calvin–Benson Cycle)

Step 3: RuBP Regeneration / RuBP 再生



Five G3P molecules produce three RuBP molecules, using up three molecules of ATP.

The C_3 Pathway (Calvin–Benson Cycle)



6C sugars (C6H12O6) are not products of the Calvin cycle!

The carbohydrate products of the Calvin cycle are three-carbon sugar phosphate molecules, or "triose phosphates", namely, glyceraldehyde-3-phosphate (G3P)

The sum of reactions in the Calvin cycle

$$3\ CO_2 + 6\ NADPH + 9\ ATP + 6\ H^+$$



$$G3P + 6\ NADP^+ + 9\ ADP + 3\ H_2O + 8\ Pi$$

For every 1 mol CO_2 assimilated, the Calvin cycle consumes: **3 mol ATP + 2 mol NADPH**

Reduction of 3 mol CO_2 produces: 1 mol triose phosphate as net output.

Regulation of the C_3 Pathway (Calvin Cycle)

1. Autocatalytic Regulation (Self-Regulation)/ 自动催化调节

The cycle maintains a steady-state pool of intermediates (especially RuBP)

Regeneration of RuBP ensures continuous CO_2 fixation

Flux depends on: Availability of intermediates and enzyme activities

2. Light Regulation/ 光调节 (关键调控机制)

Light reactions pump H^+ into lumen (pH increase)

Counter-ion movement from lumen into stroma (Mg^{2+} increase)

Key Light-Activated Enzymes: RuBisCO (via RuBisCO activase), GAPDH, FBPase (fructose-1,6-bisphosphatase), and SBPase

3. Regulation of Triose Phosphate Export / 光合产物输出速率的调节

Triose phosphate/phosphate translocator (TPT): Exports G3P/DHAP to cytosol and Imports Pi into chloroplast

C_4 Pathway (Hatch–Slack pathway)

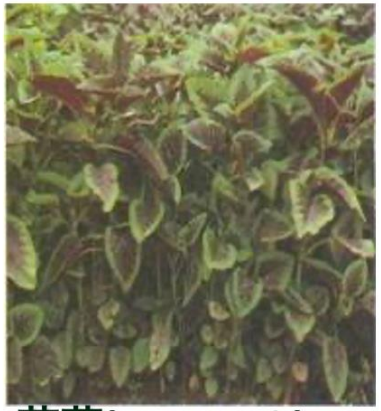
A photosynthetic carbon fixation pathway in which phosphoenolpyruvate (PEP) acts as the initial CO_2 acceptor, forming a four-carbon compound (oxaloacetate, OAA), followed by transport and decarboxylation to supply CO_2 to the Calvin cycle.



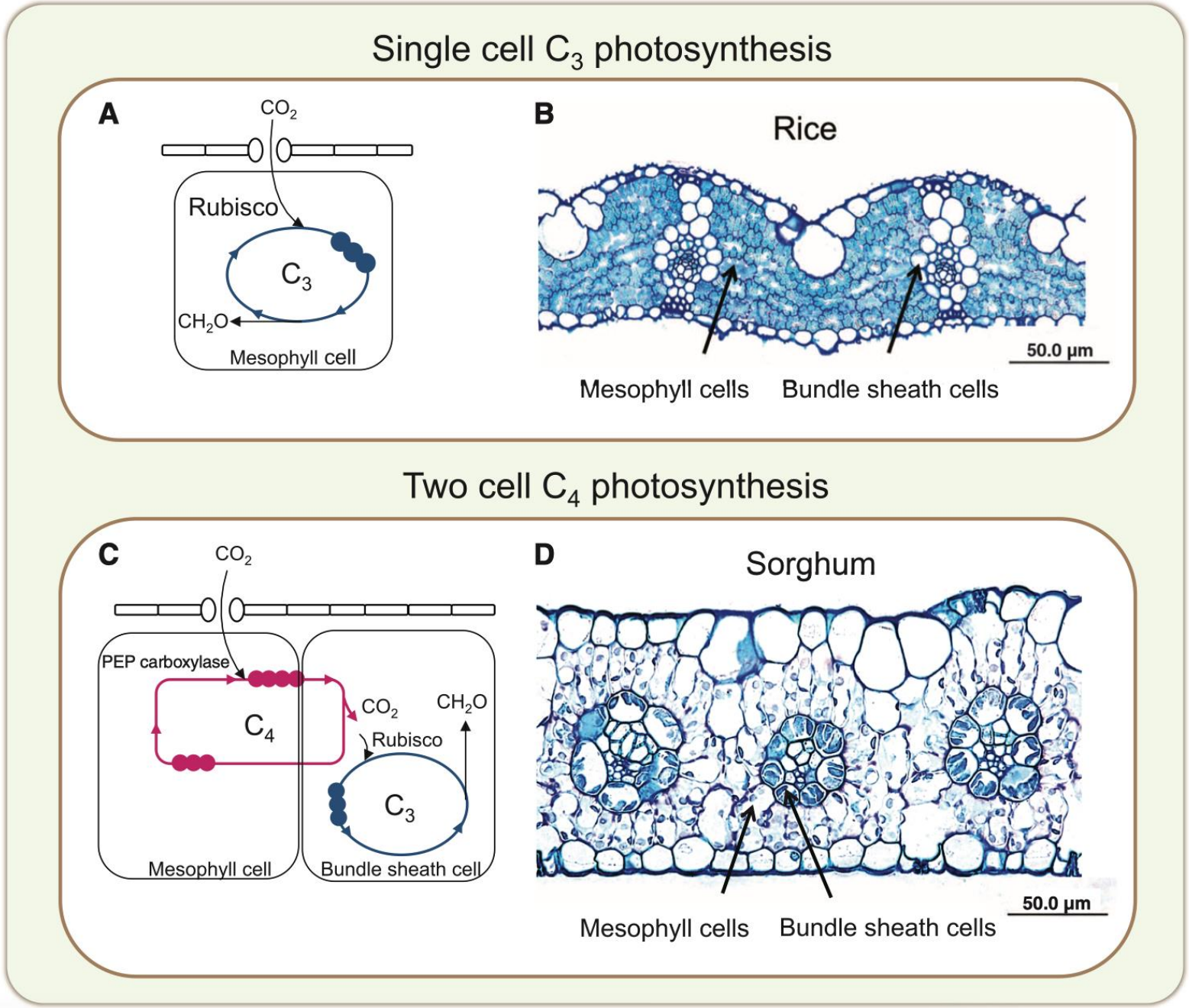


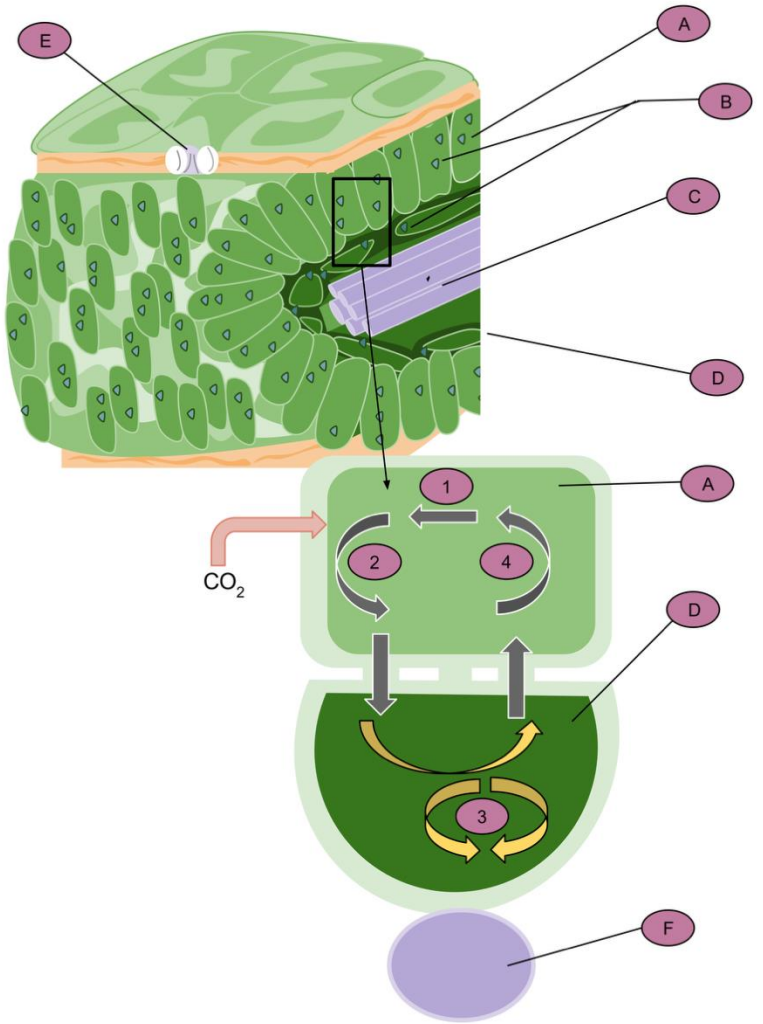



甘蔗(sugarcane)


苋菜(amaranth)

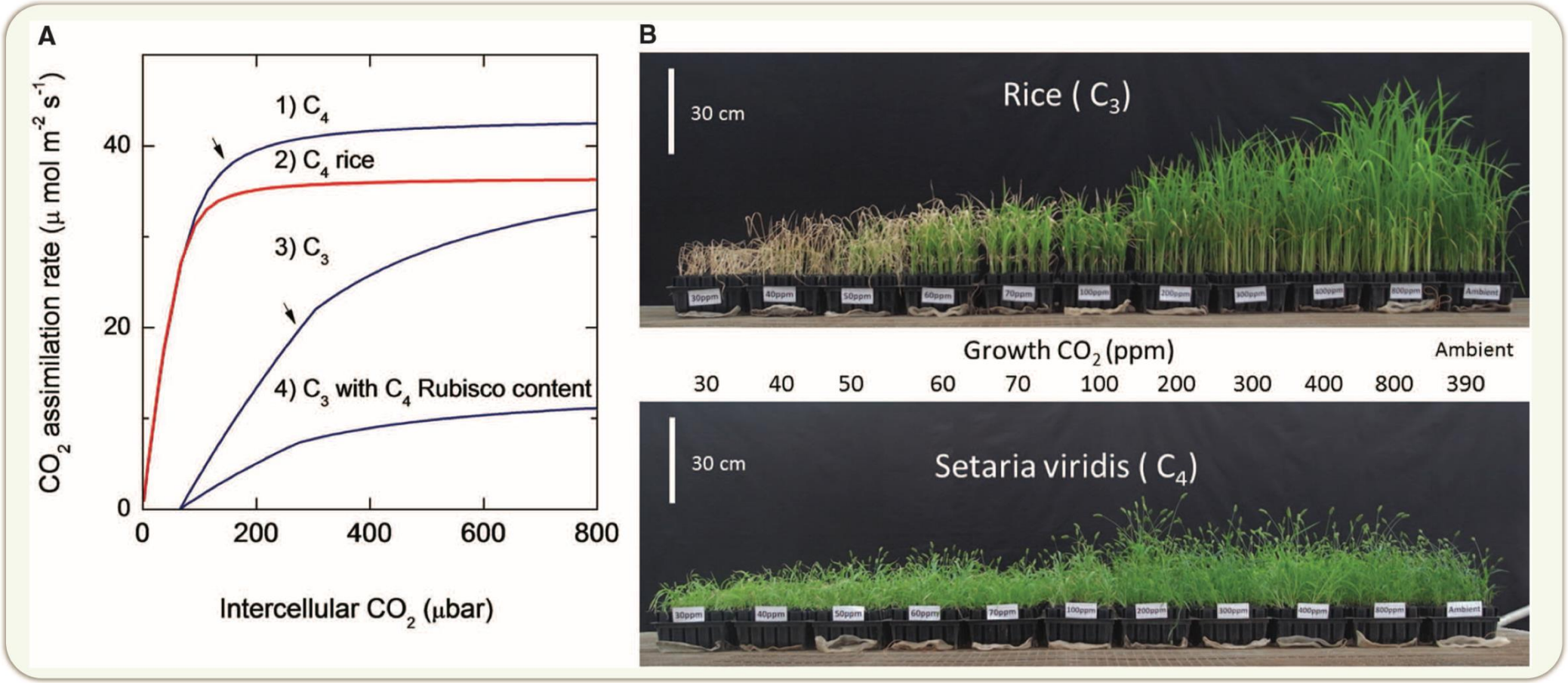






Caemmerer et al., 2012

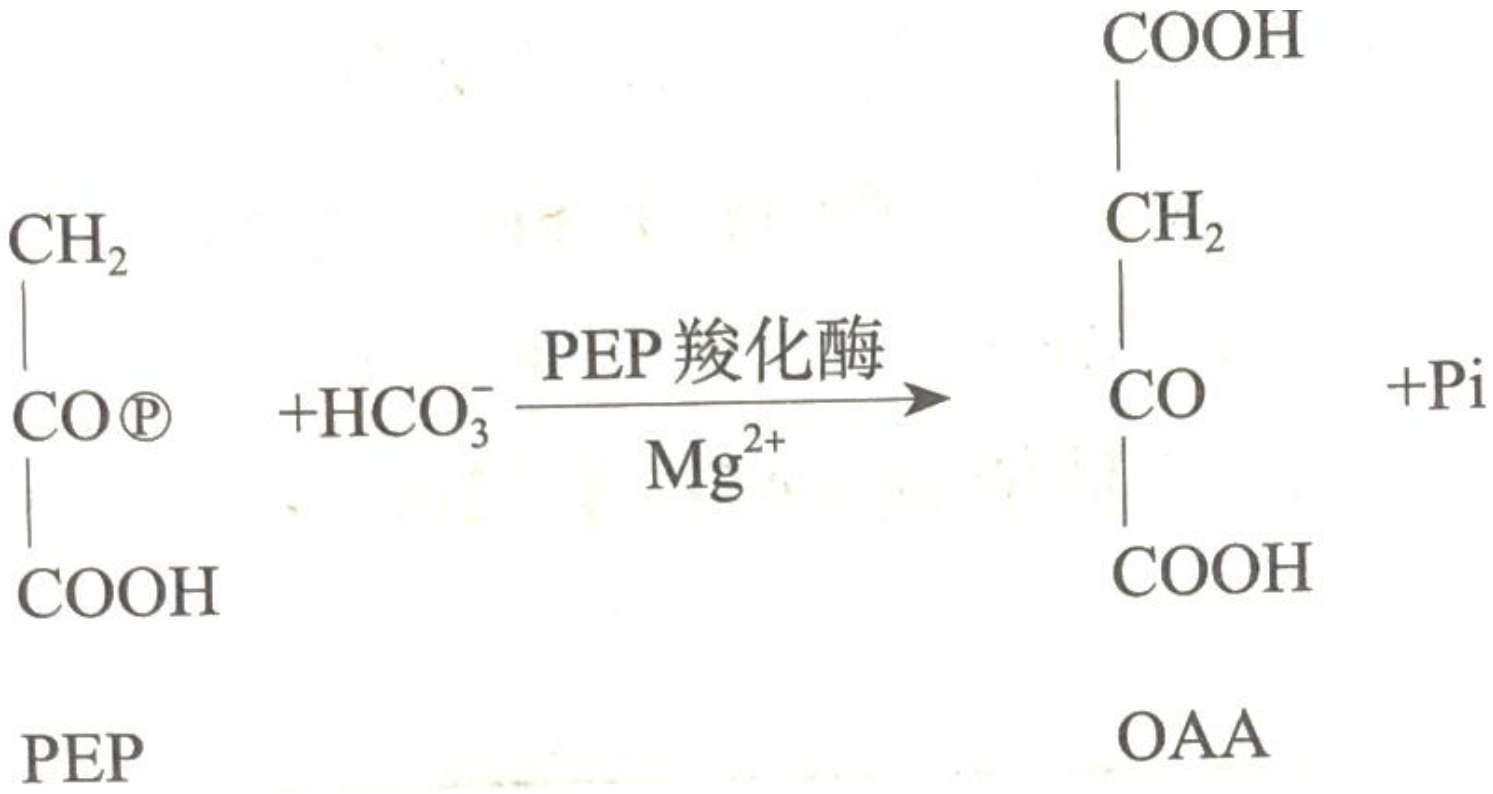
Plant Metabolism



Caemmerer et al., 2012

C_4 Pathway (Hatch–Slack pathway)

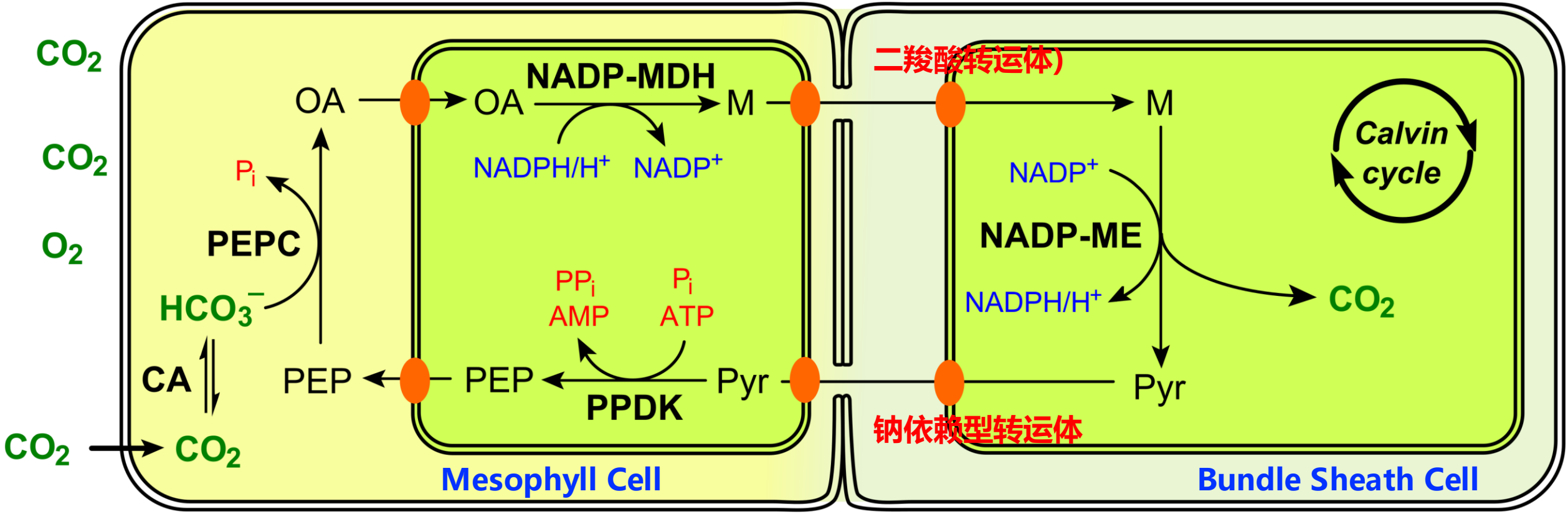
Step 1: CO_2 Fixation in Mesophyll



C_4 Pathway (Hatch–Slack pathway)

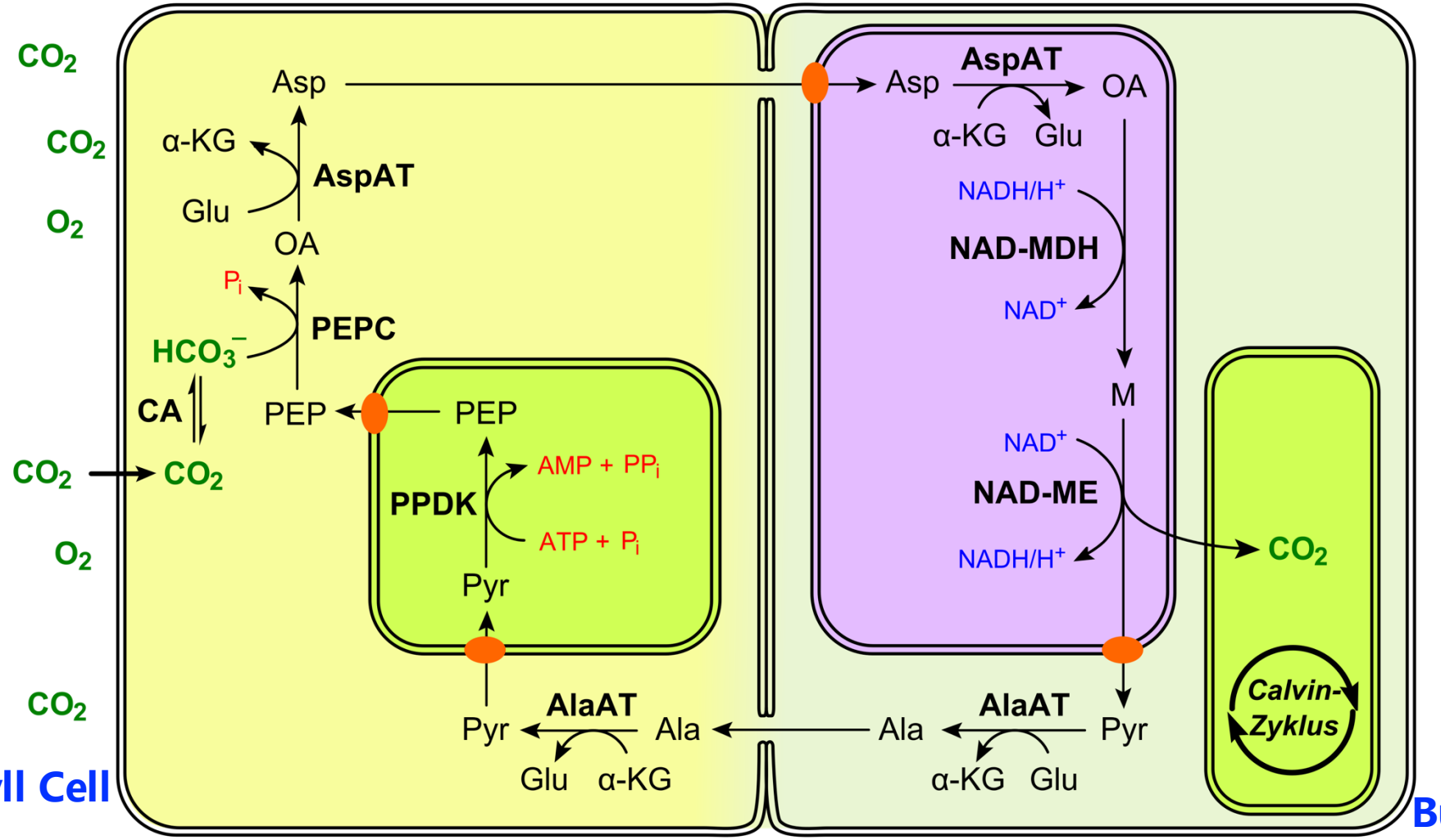
NADP-ME / NADP-苹果酸酶型

Corn, Sugarcane, Sorghum



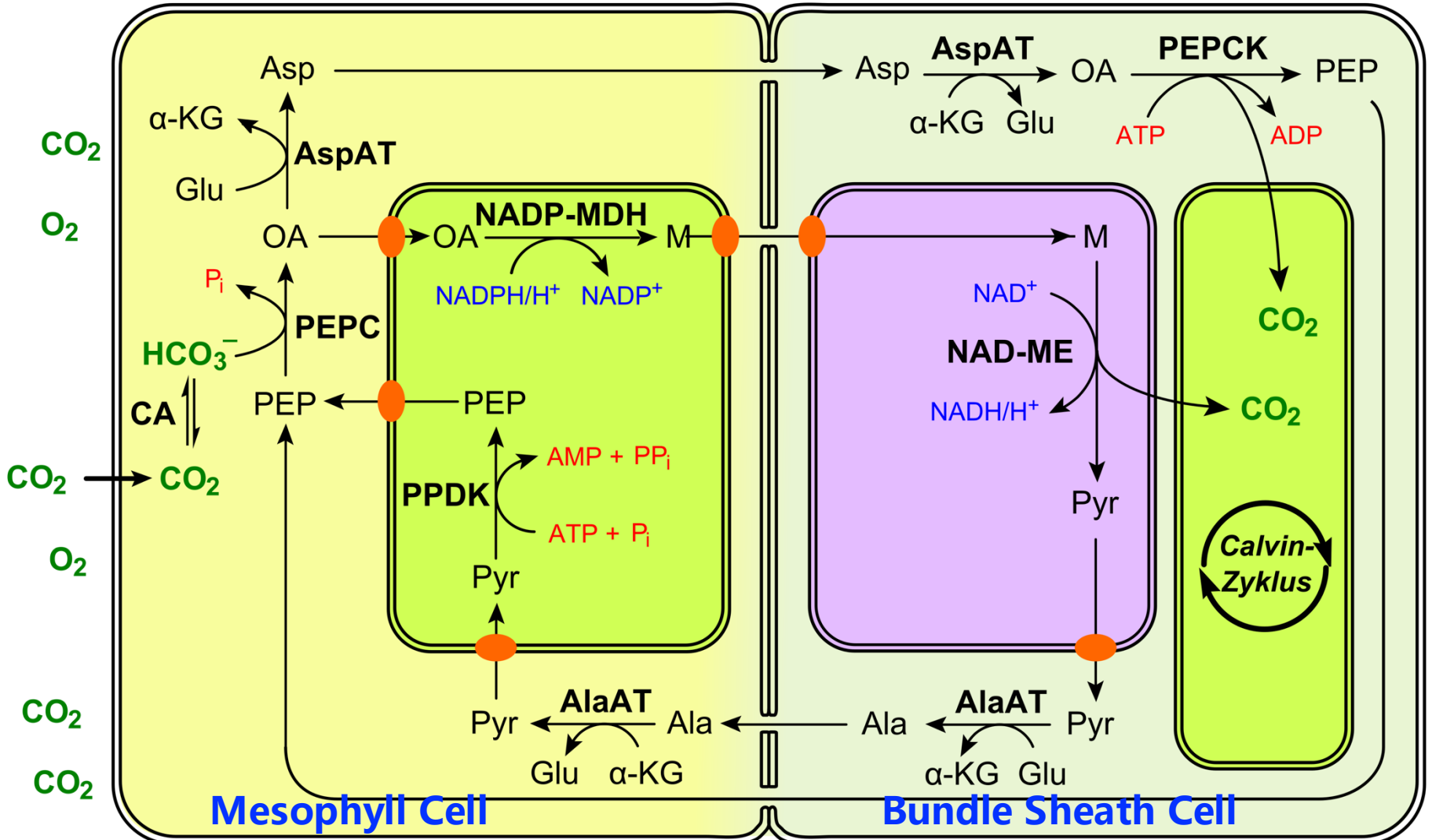
C_4 Pathway (Hatch–Slack pathway)

NAD-ME / NAD - 苹果酸酶型



C_4 Pathway (Hatch–Slack pathway)

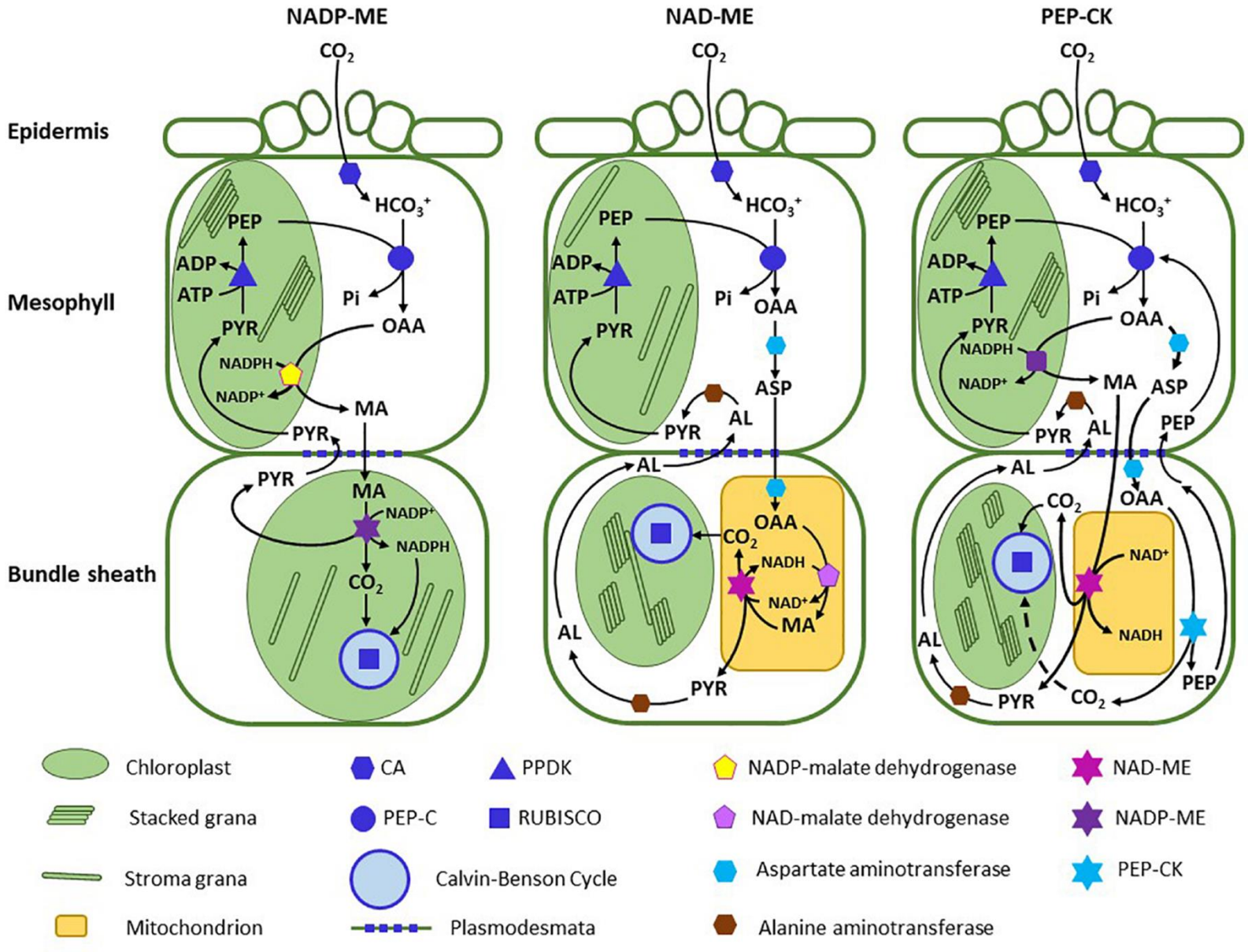
PEPCK / PEP羧化激酶型



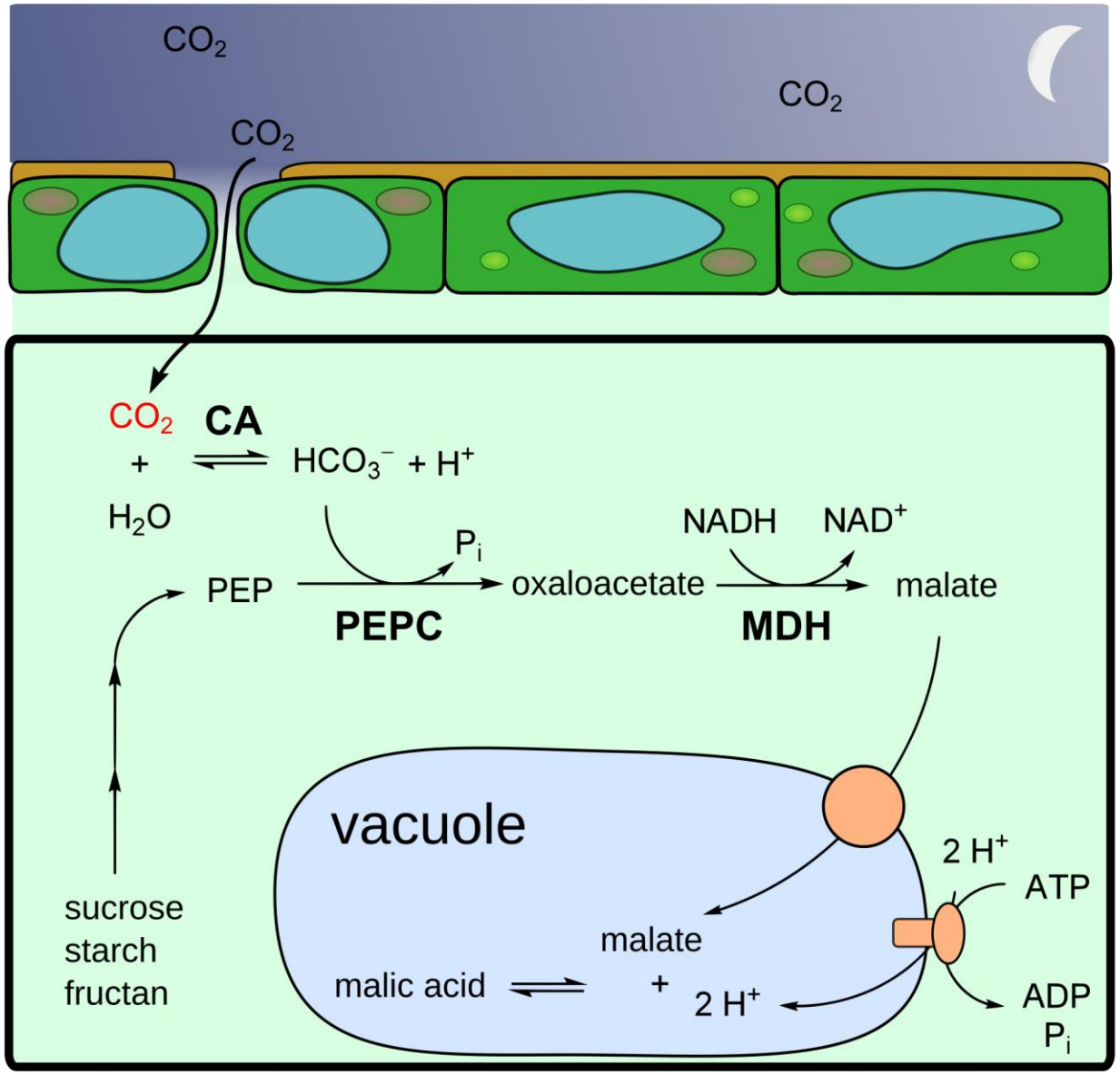
C_4 Pathway (Hatch–Slack pathway)

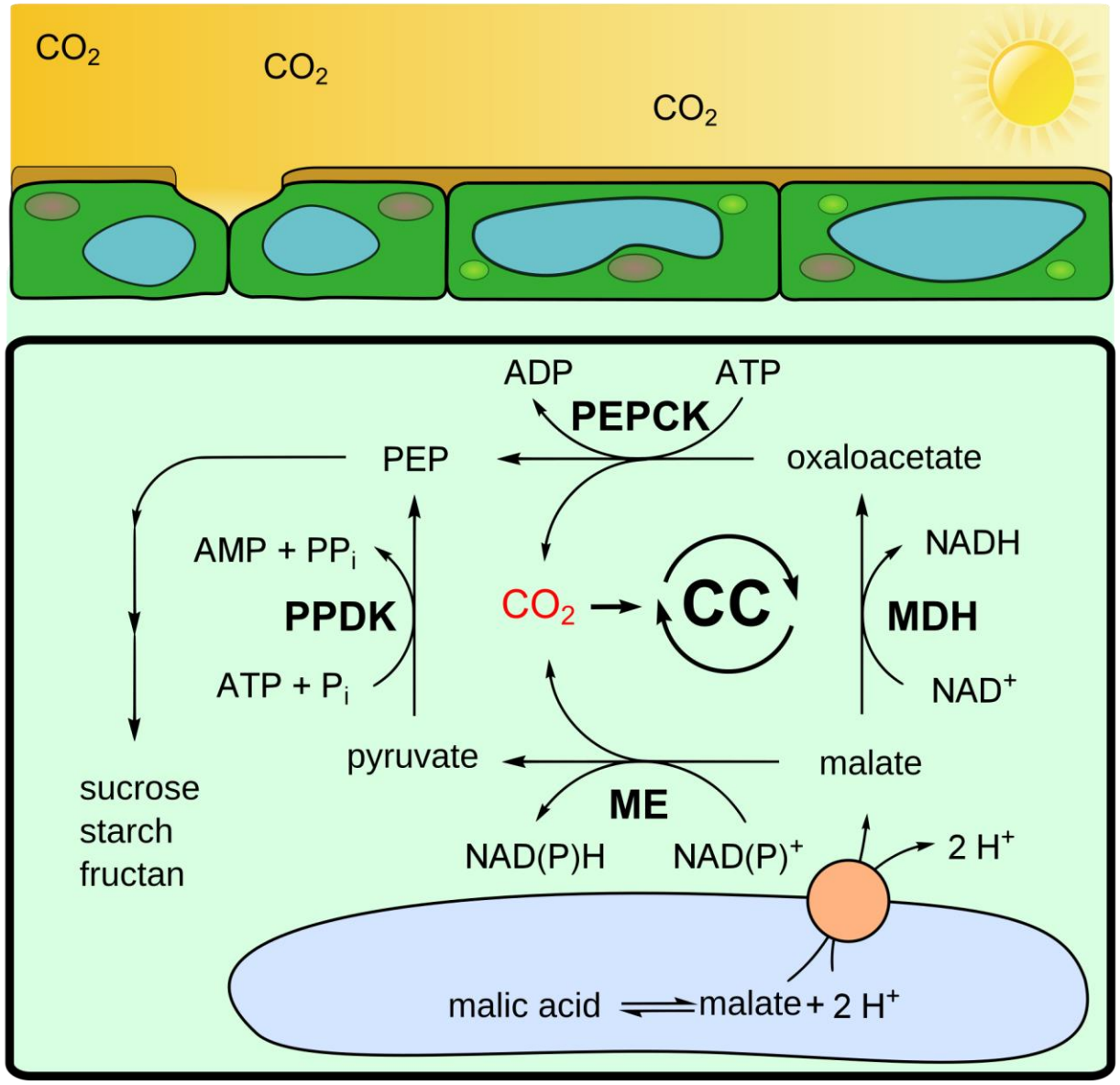
Subtype	BSC release CO_2
NADP-ME	Mal→Mal（叶绿体；$NADP^+$ NADPH）→Pyr+CO_2
NAD-ME	Asp→Mal（线粒体；NAD^+ NADH）→Pyr+CO_2
PEPCK	Asp→OAA（细胞质；ATP ADP）→PEP+CO_2

C_4 Pathway (Hatch–Slack pathway)



CAM photosynthesis / 景天科酸代谢途径

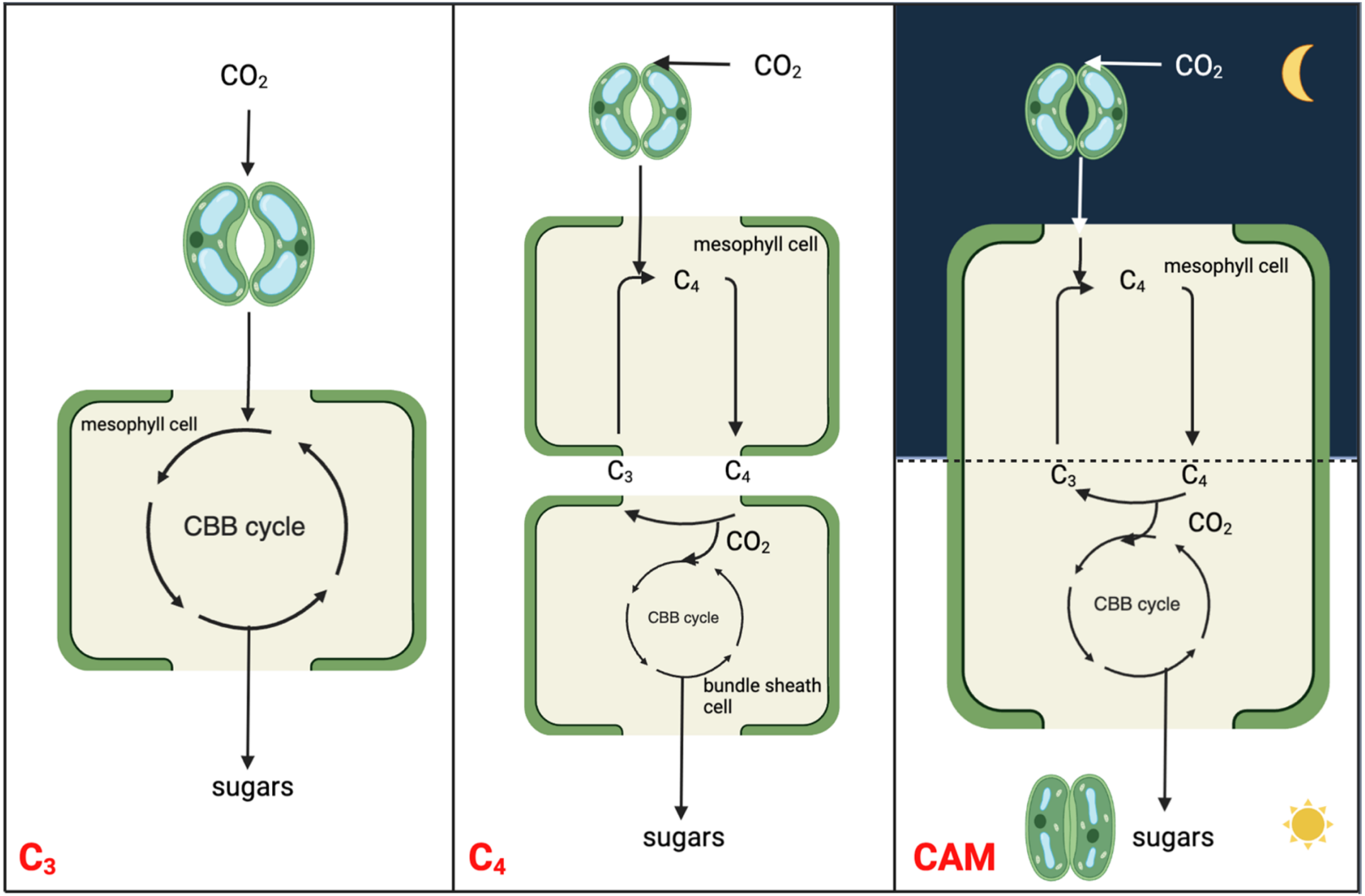




CAM photosynthesis / 景天科酸代谢途径

During the night, CAM plants have their stomata open, which allows CO_2 to enter and be fixed as organic acids by a PEP reaction similar to the C_4 pathway. The resulting Mal are stored in vacuoles for later use.

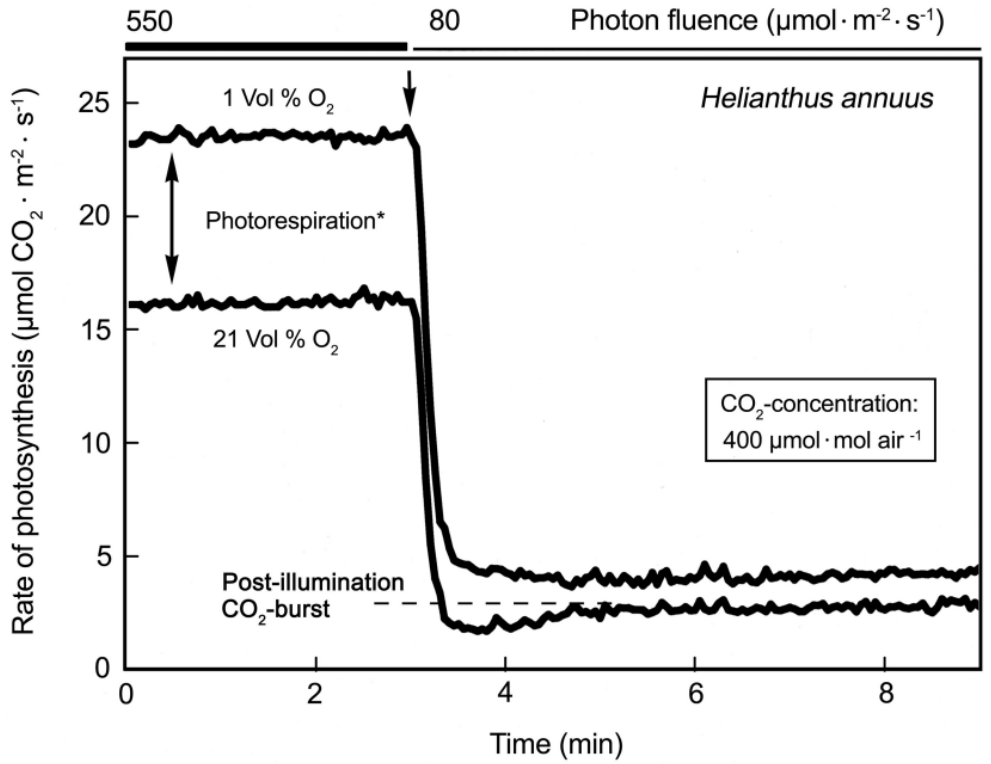
During the day, the stomata close to conserve water, and the CO_2-storing organic acids are released from the vacuoles of the mesophyll cells. An enzyme in the stroma of chloroplasts releases the CO_2, which enters into the Calvin cycle so that photosynthesis may take place.

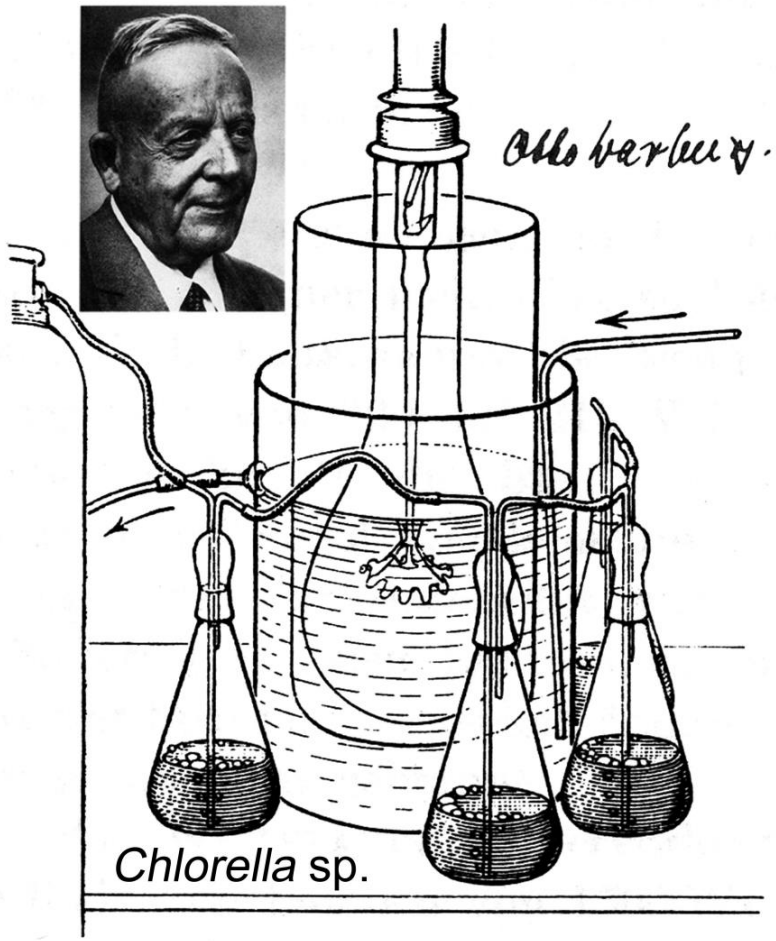

CO_2
mesophyll cell
CBB cycle
sugars
C3
CO_2
mesophyll cell
C_4
C_3
C_4
CO_2
CBB cycle
bundle sheath cell
sugars
C4
CO_2
mesophyll cell
C_4
C_3
C_4
CO_2
CBB cycle
sugars
CAM

Comparison of photosynthetic pathways

Feature	C_3 Plants	C_4 Plants	C_3–C_4 Intermediates	CAM Plants
Bundle Sheath Cells (BSC)	Poorly developed	Well developed	Moderately developed	Poorly developed
Chloroplasts in BSC	Absent (or very few)	Present	Present	Generally absent; cells rich in mitochondria
Leaf Anatomy	Mesophyll cells loosely arranged; **no Kranz anatomy**	Mesophyll cells tightly arranged around BSC; **Kranz anatomy present**	BSC present but thinner cell walls than C_4 plants	Large vacuoles in mesophyll cells
Special Structural Feature	No spatial separation of processes	Clear spatial separation (mesophyll vs bundle sheath)	Partial characteristics of both C_3 and C_4	Temporal separation (night/day metabolism)

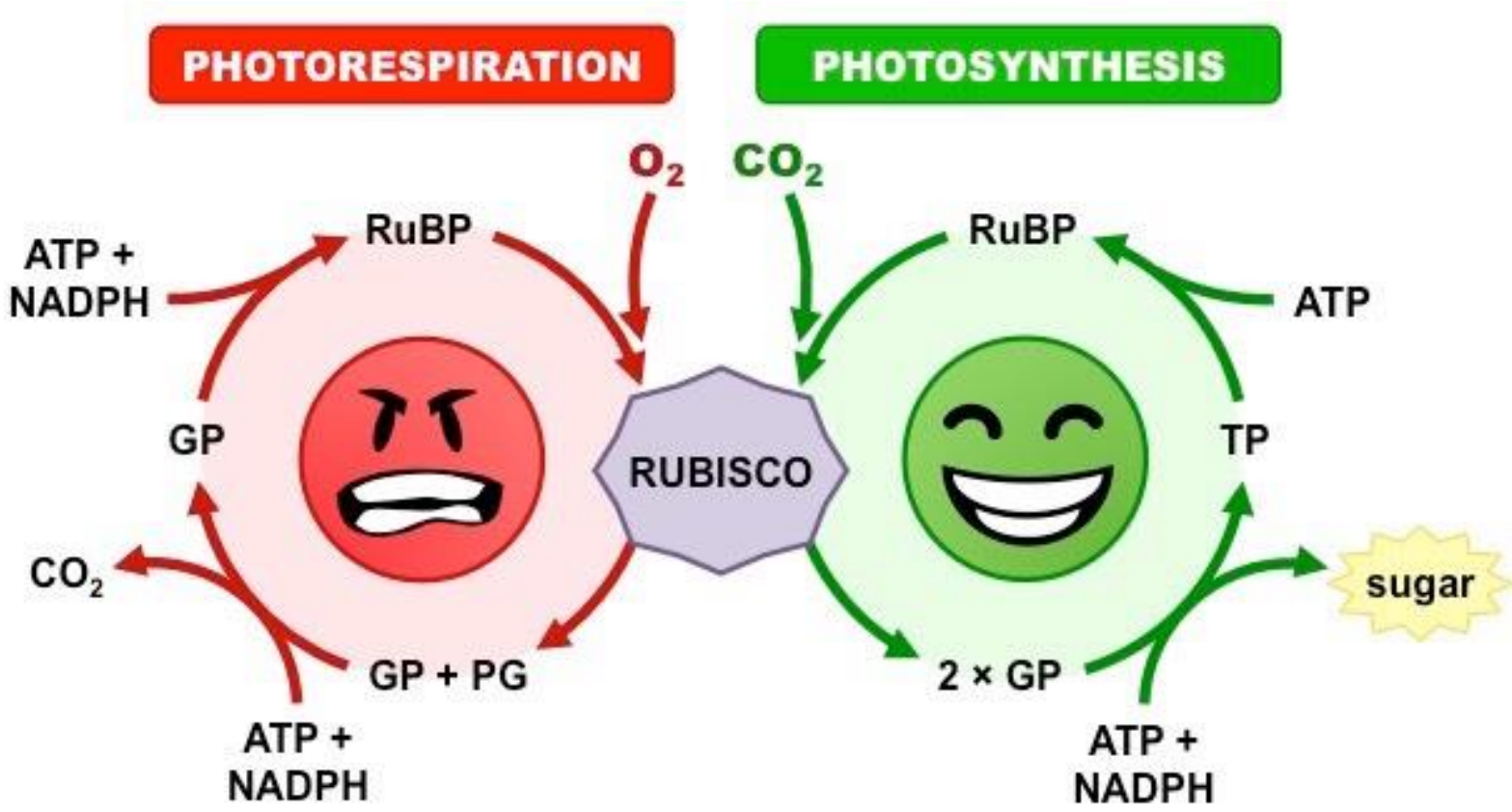
1920, Otto Warburg discovered that in liquid cultures of unicellular green algae (Chlorella sp.) molecular oxygen (O_2) exerts an inhibitory effect on photosynthesis. It is late known due to photorespiration / 光呼吸.

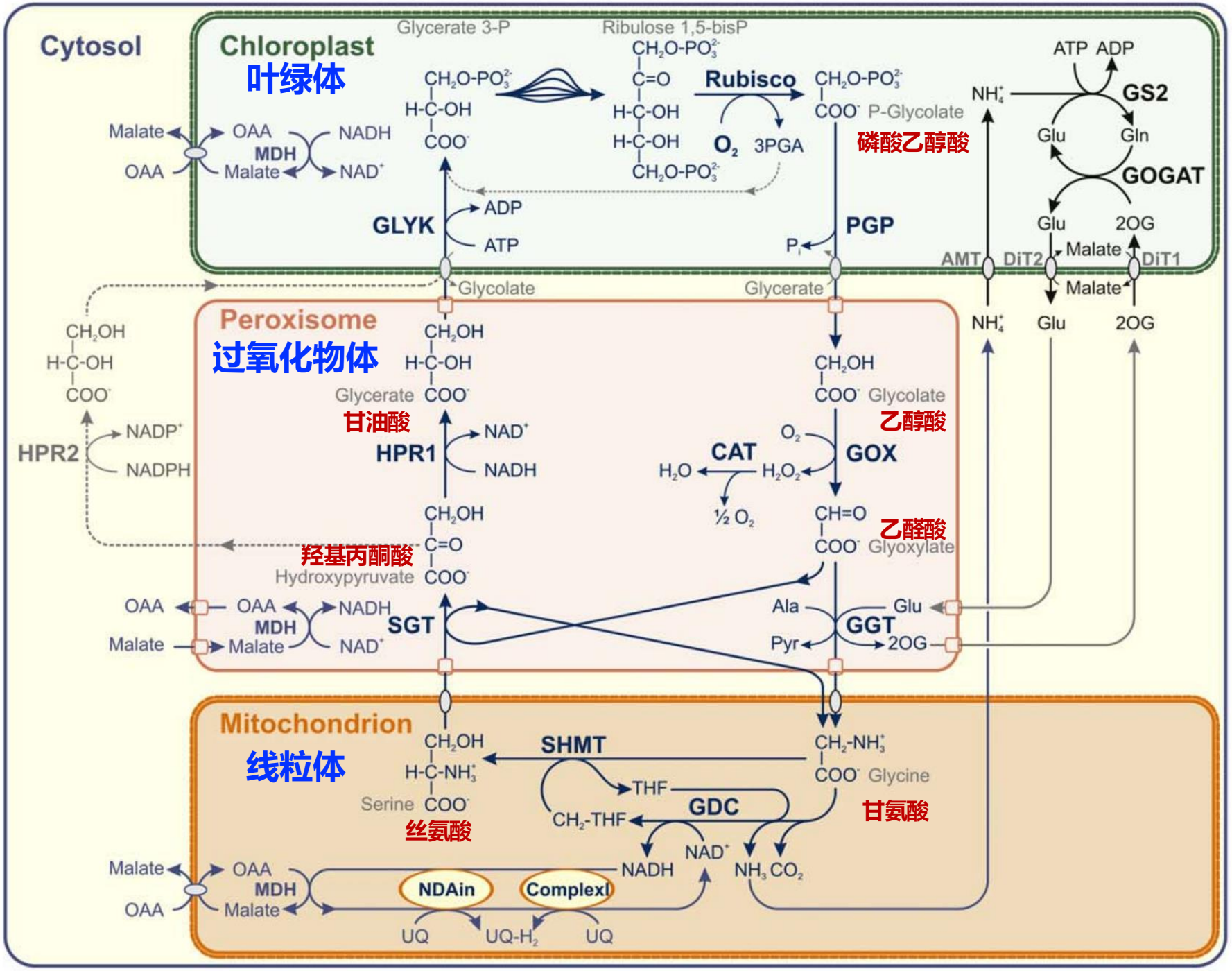




Photorespiration

A light-dependent metabolic process in which RuBisCO oxygenates RuBP, leading to O_2 consumption and CO_2 release, without production of sugars.





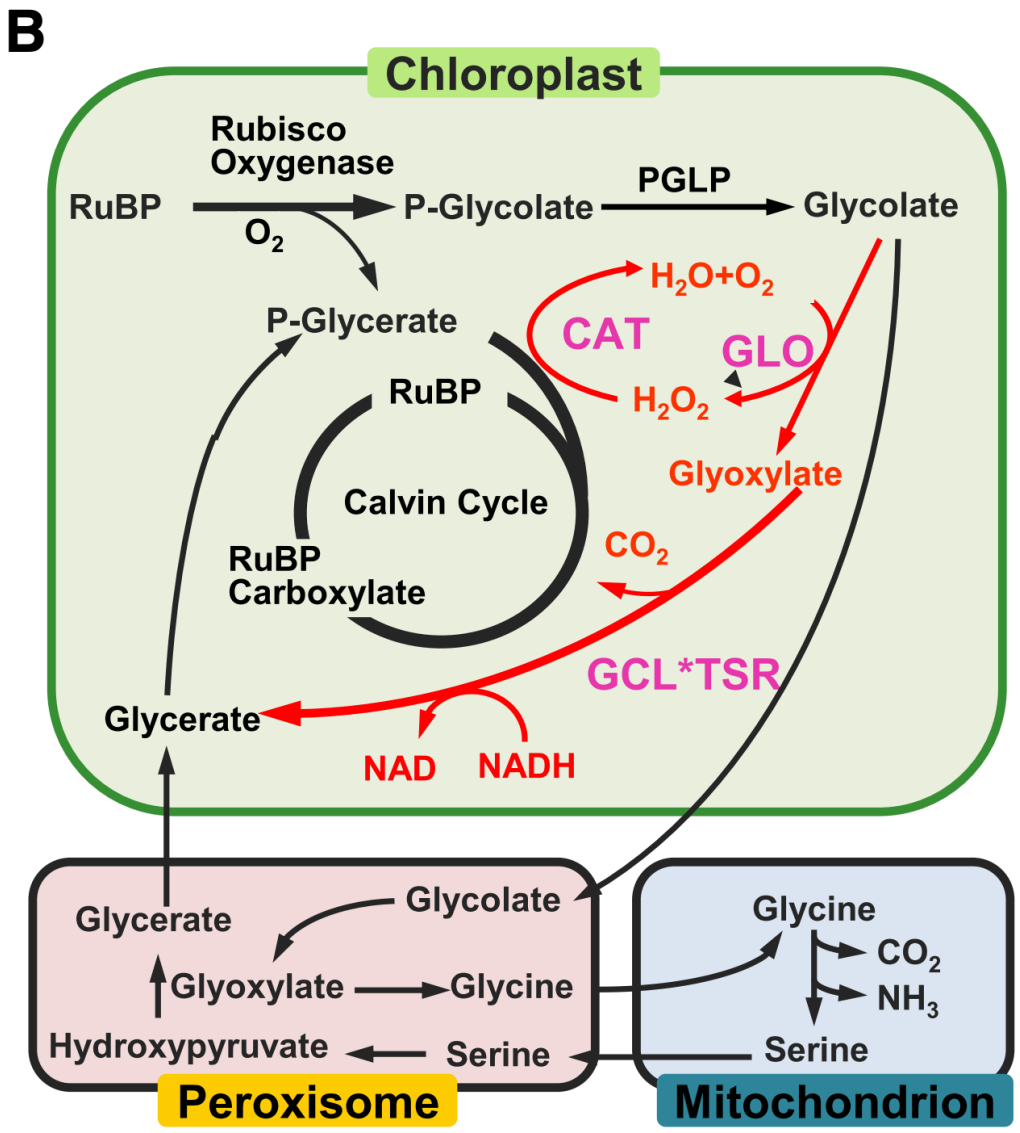
Photorespiration involves **three organelles**: **Chloroplast, Peroxisome, Mitochondrion**

O_2 consumption occurs in **chloroplast and peroxisome**

CO_2 release occurs mainly in **mitochondria**

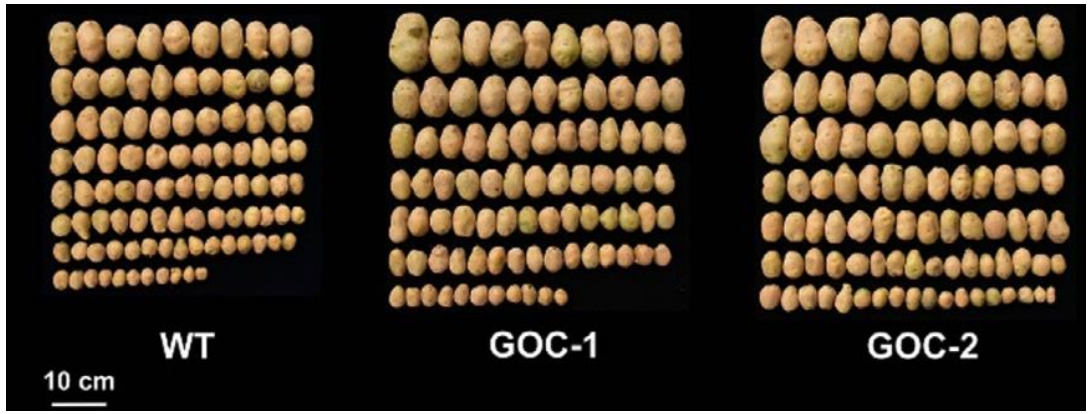
Carbon Loss: For every **2 glycolate molecules 1 CO_2 released (25%)**

Photorespiratory pathway redesign





彭新湘教授



Photorespiration

Physiological Functions of Photorespiration

Removes 2-phosphoglycolate (toxic metabolite)

Maintenance of C_3 Cycle Operation under stresses

Photoprotection: Consumes excess ATP and NADPH

Link to Nitrogen Metabolism: Produces Glycine (Gly), Serine (Ser), and other amino acids

Photosynthesis in plant physiology

Photosynthetic Rate (光合速率): the amount of CO_2 assimilated or O_2 evolved per unit time per unit leaf area.

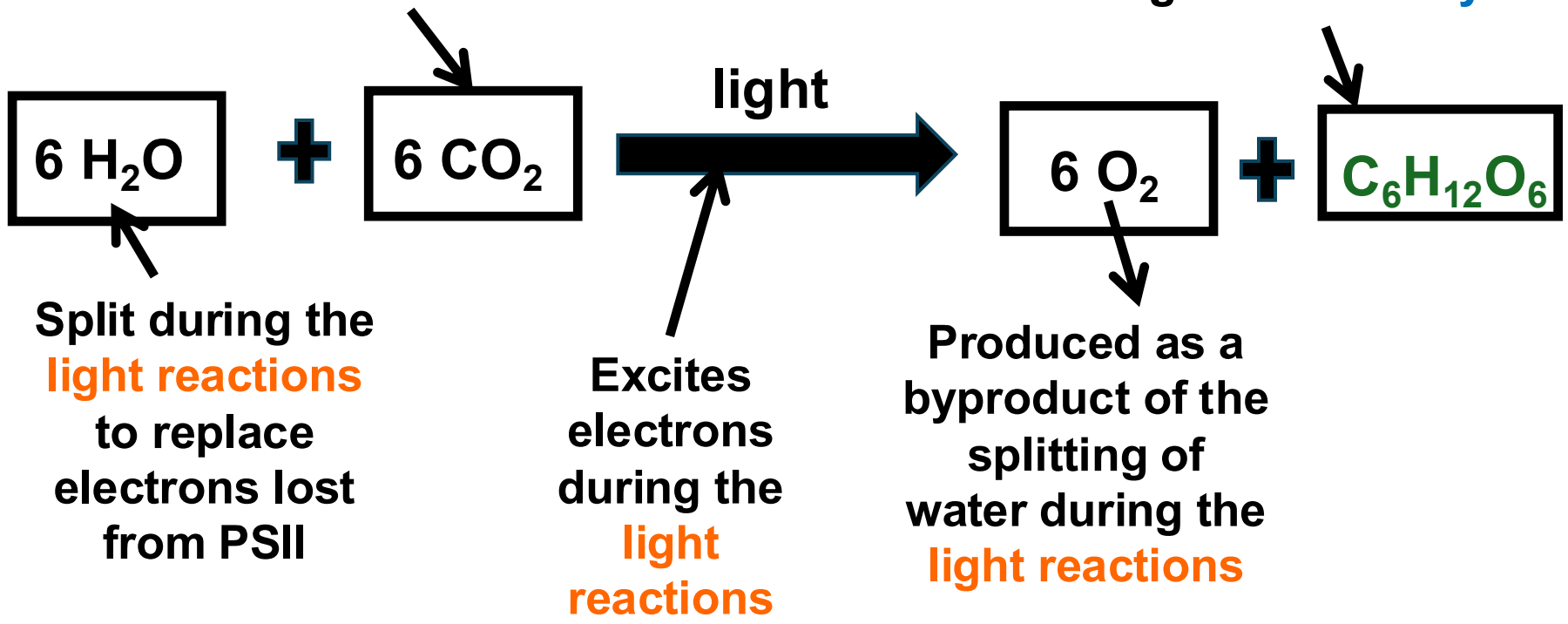
Net vs Gross Photosynthesis

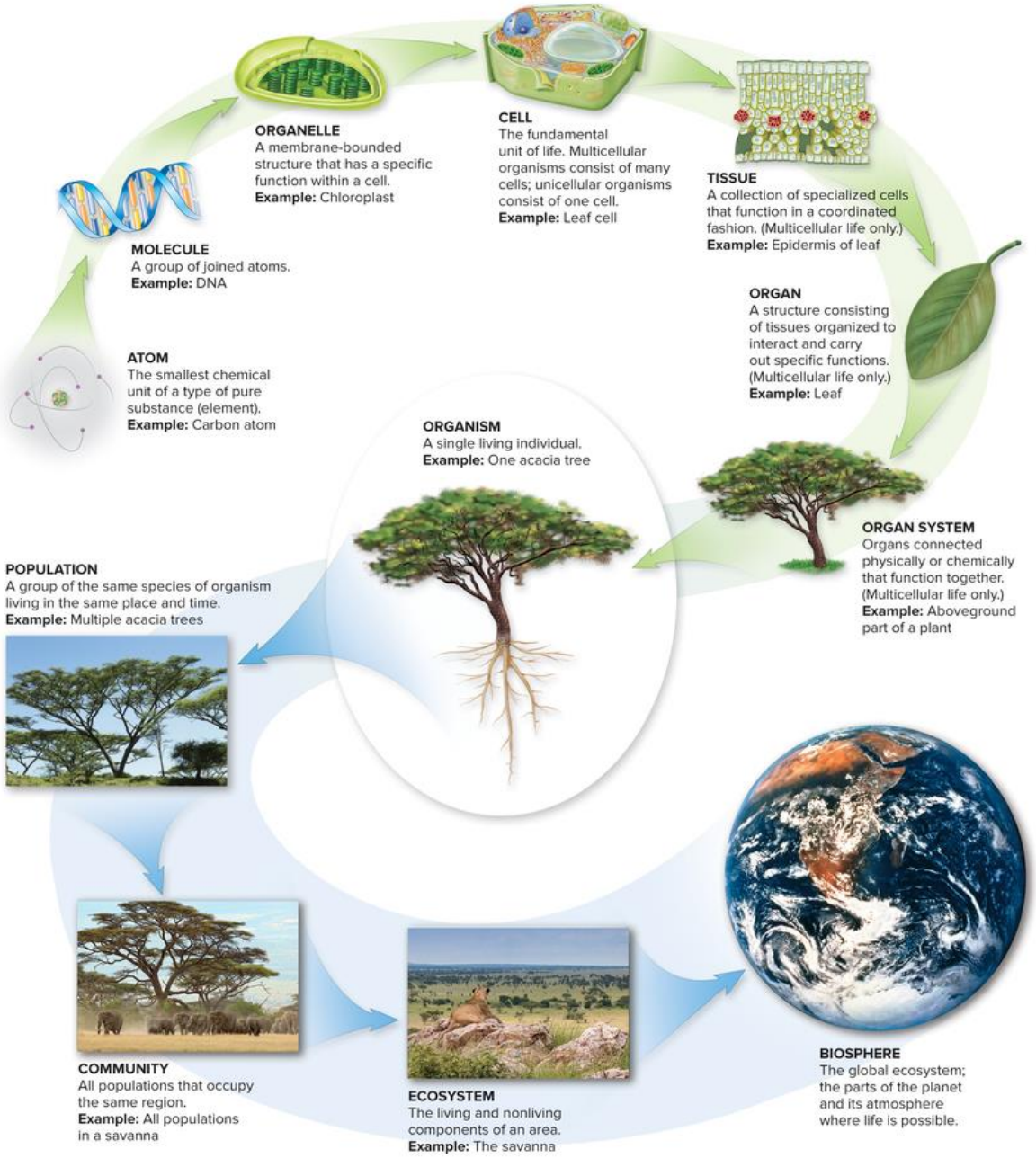
$$P_{net} = P_{gross} - \text{Respiration}$$

Photosynthetic Productivity (NAR): The amount of dry matter produced per unit leaf area per unit time over longer periods.

The photosynthetic equation:

Based on this equation, how could the rate of photosynthesis be measured?





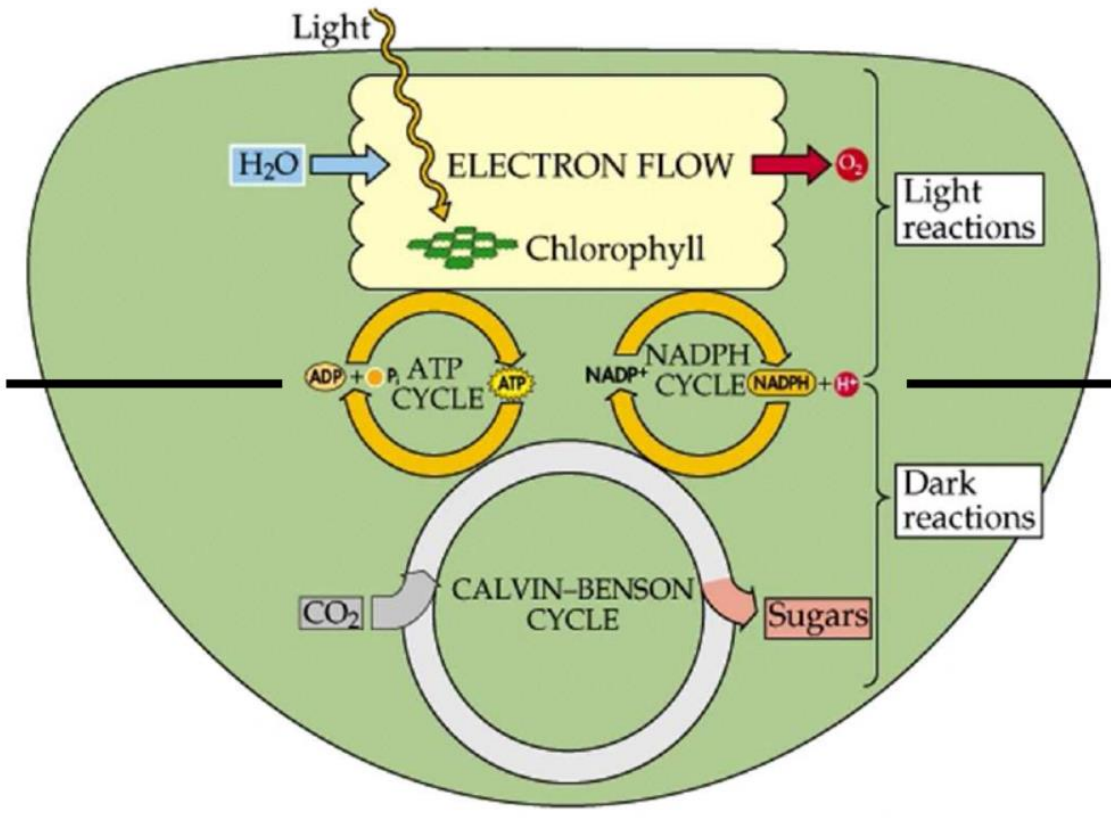
Chemistry or biochemistry approaches in tubes or *in vitro*

We focus on Leaf to canopy scales *in vivo*

Modeling (next part) or Remote sensing

How can we study these two parts of the photosynthesis process *in vivo*?

Chlorophyll fluorescence

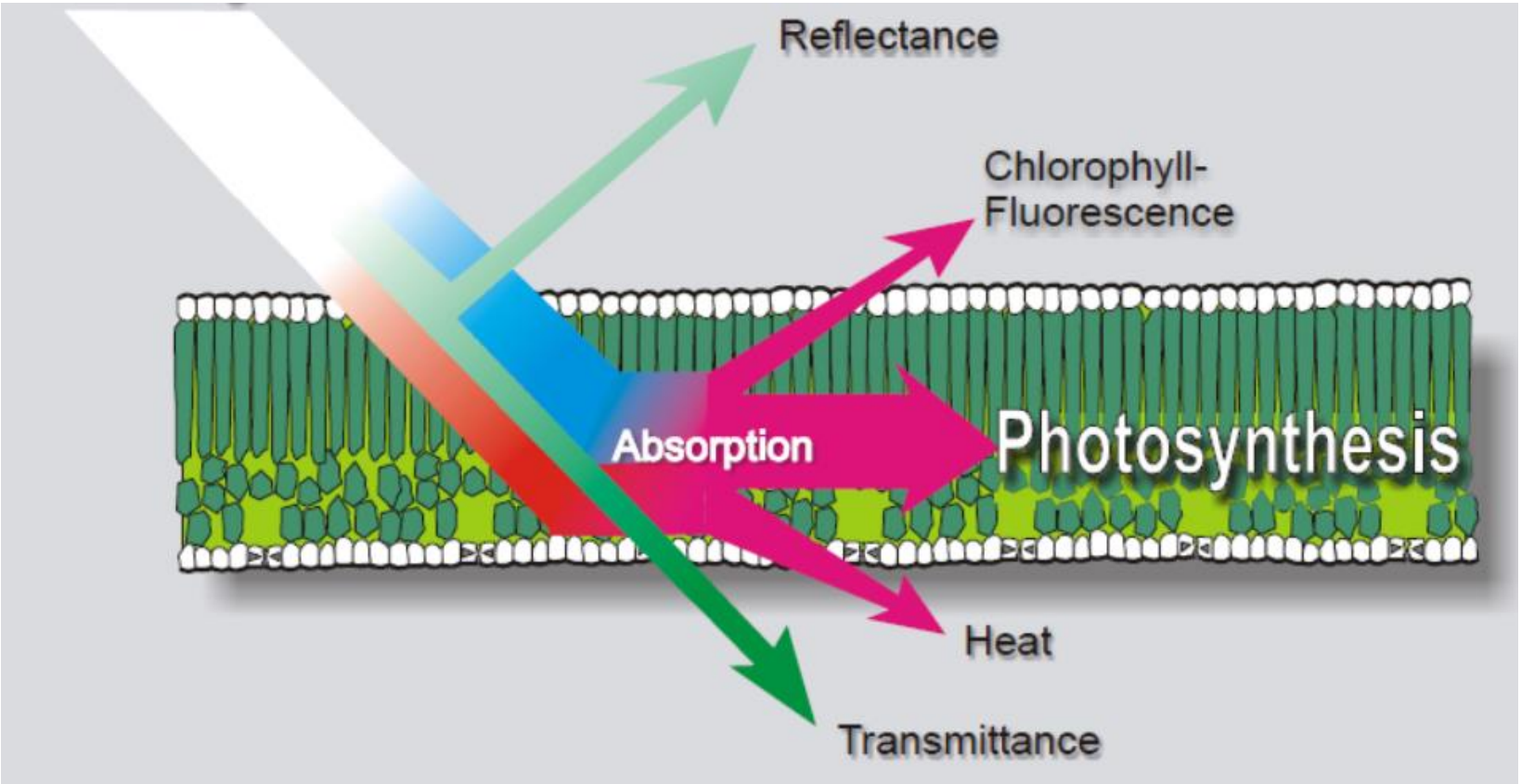


1) **Light-dependent reactions**
PHOTOCHEMISTRY.
Light energy captured by chlorophyll is (PARTLY) used for ATP and NADPH synthesis from ADP and $NADP^+$.

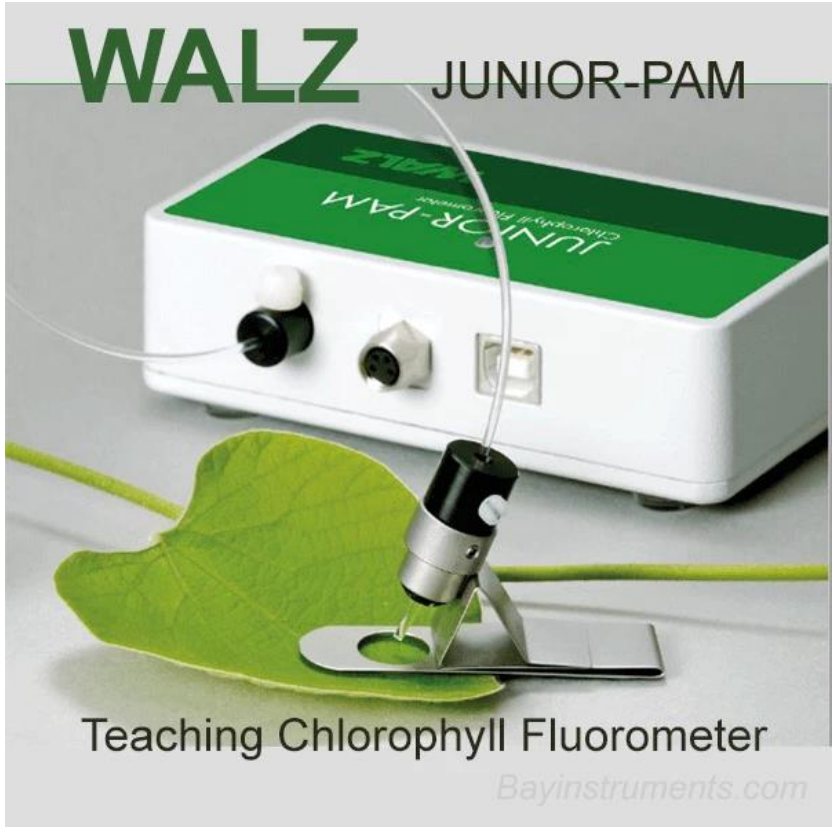
2) **Light-independent reactions**
. **BIOCHEMISTRY**.
ATP and NADPH are used to reduce and fix CO_2 generating sugars in the C-B-B cycle.

Gas exchange

Light absorption index



$$f\left(\begin{array}{l}\text{Photochemistry}\\ \text{Heat dissipation}\\ \text{Intensity of excitation}\end{array}\right)$$

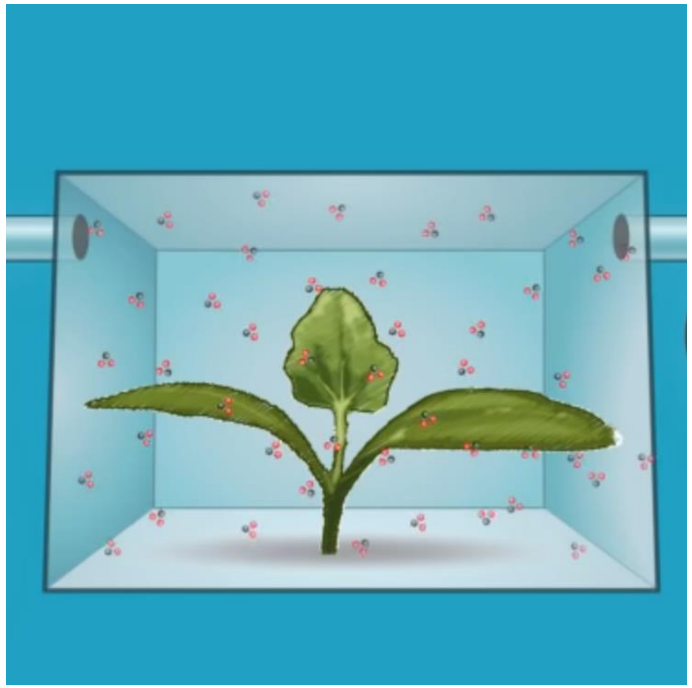

WALZ
JUNIOR-PAM
Teaching Chlorophyll Fluorometer
Bayinstruments.com


WALZ
DUAL PAM 100
P700 and Chlorophyll Fluorescence Measurment





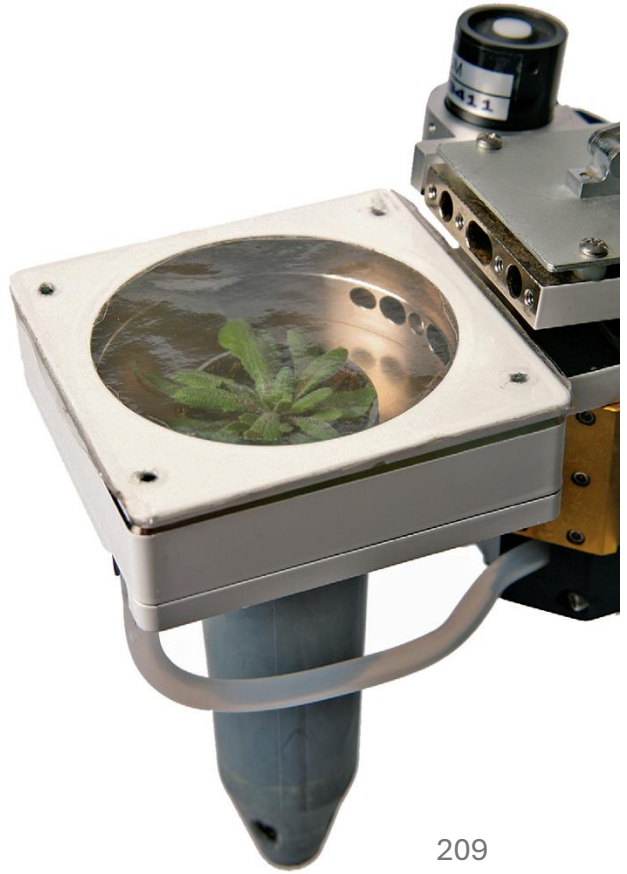






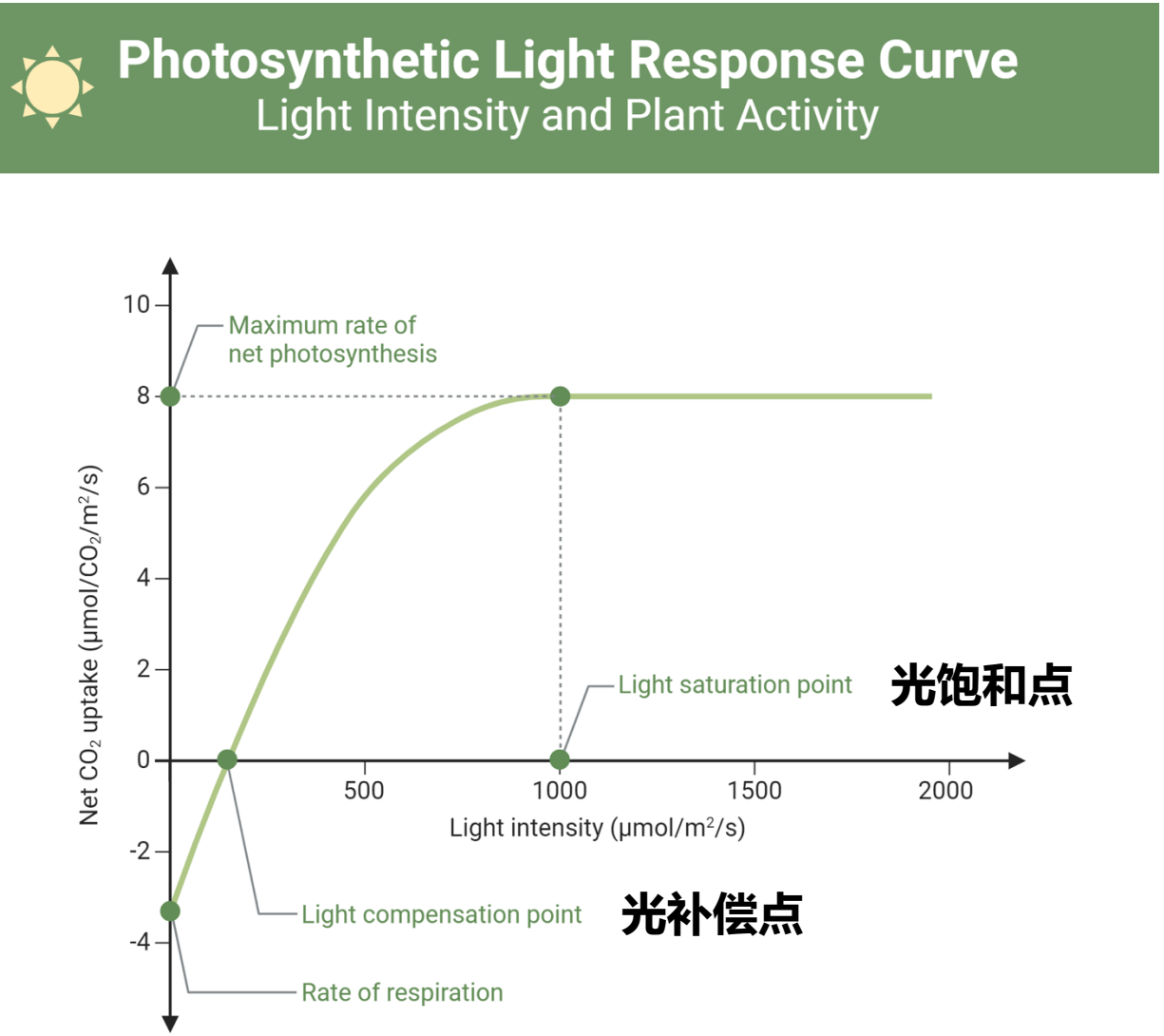






How much CO_2 consumed in unit of time is the net photosynthetic rate (typically normalized by leaf area).

Photosynthesis in plant physiology



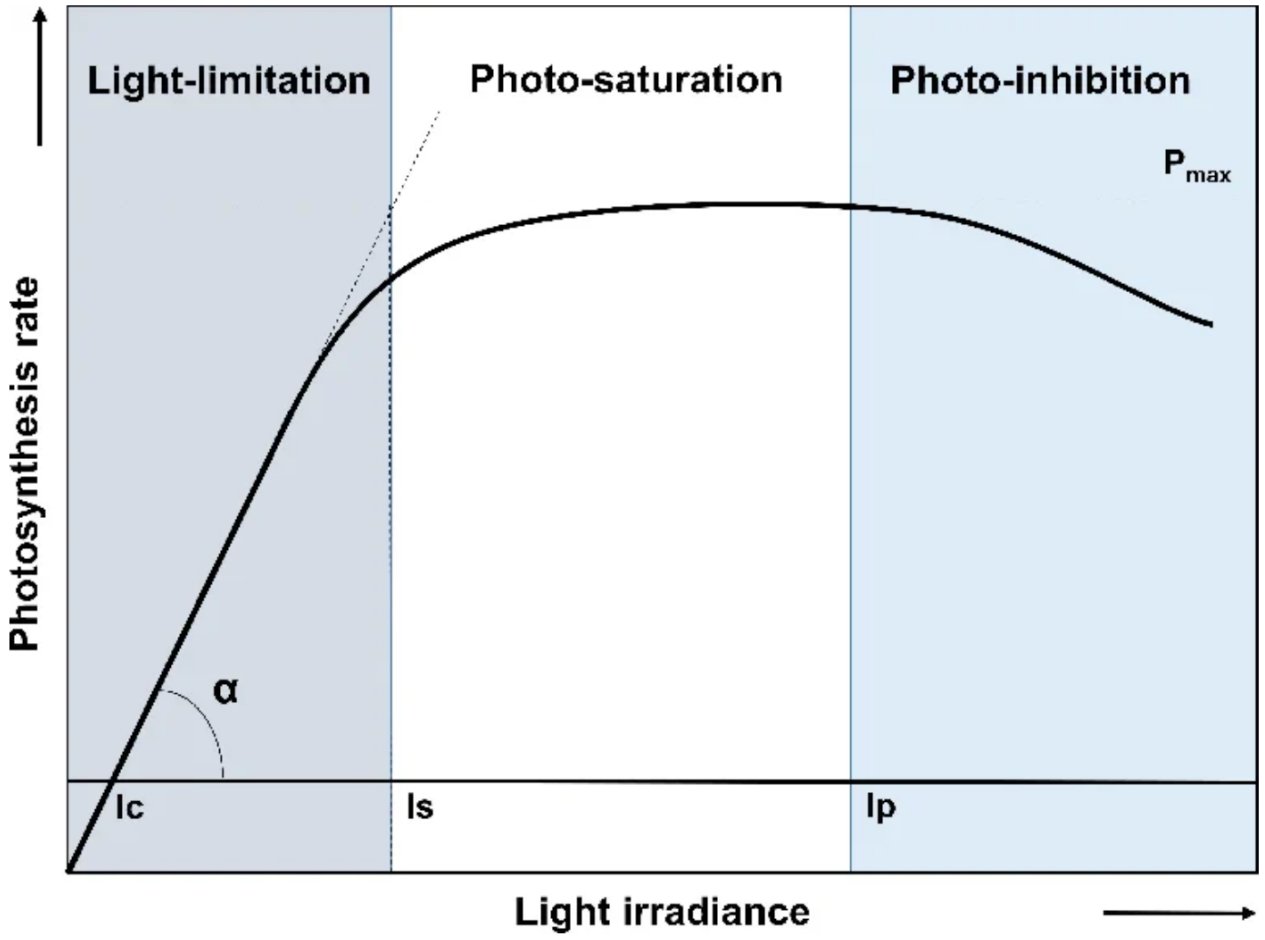
Light Intensity

Light is a primary factor controlling **photosynthetic rate**

Light Compensation Point (光补偿点): The light intensity at which Photosynthesis = Respiration

Light Saturation Point (光饱和点): The light intensity at which photosynthetic rate reaches maximum

Photosynthesis in plant physiology



Light Intensity

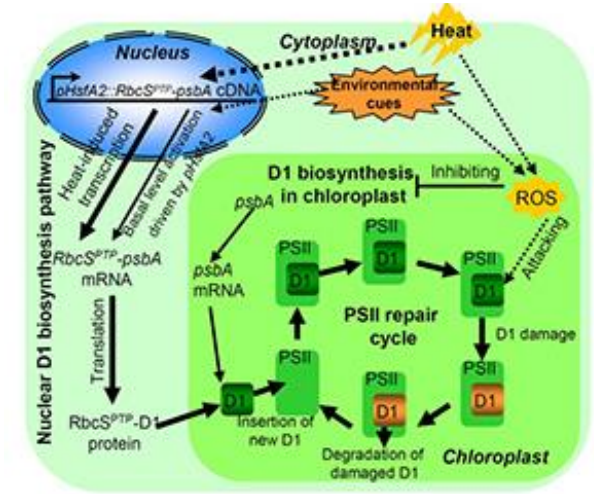
Photoinhibition: A decrease in photosynthetic efficiency caused by excess light energy exceeding the capacity of photochemical utilization and protective mechanisms.

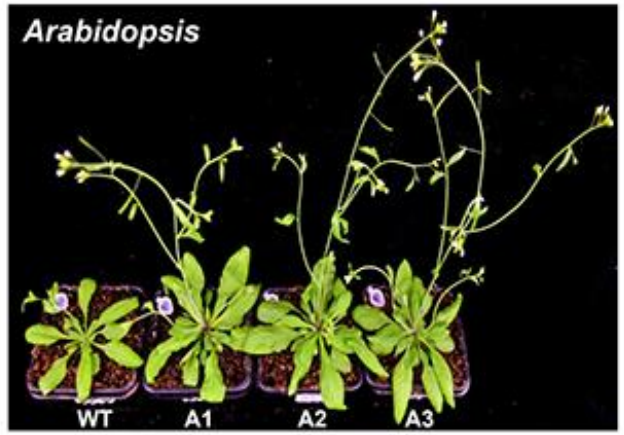
Primarily occurs in PSII, and under special conditions (e.g., low temperature + light stress), PSI can also be affected

ARTICLES
https://doi.org/10.1038/s41477-020-0629-z
nature plants
Check for updates

Nuclear-encoded synthesis of the D1 subunit of photosystem II increases photosynthetic efficiency and crop yield

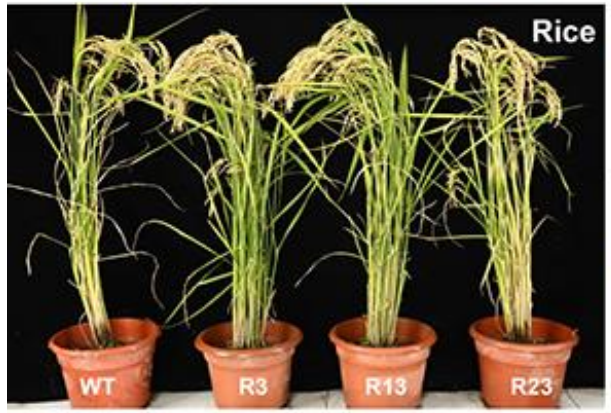
Juan-Hua Chen[1,2,3], Si-Ting Chen[1,3], Ning-Yu He[1], Qing-Long Wang[1], Yao Zhao[1,2], Wei Gao[1,2] and Fang-Qing Guo[1]✉









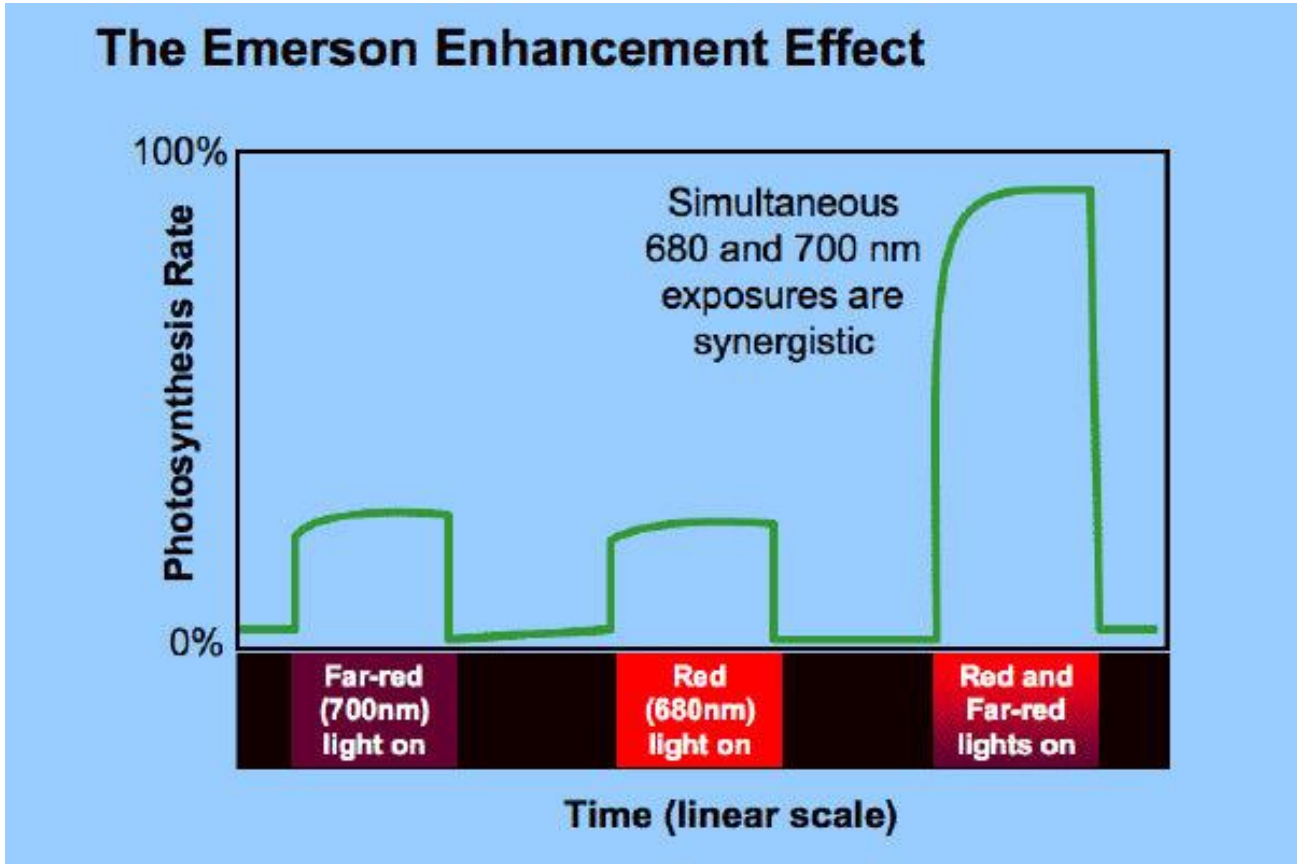




Photosynthesis in plant physiology

Light quality

Emerson Enhancement Effect (爱默生效应)



Observation (Emerson, 1957)

Red light (~650 nm) → moderate photosynthesis

Far-red light (~700 nm) → low photosynthesis

Both together → much higher than sum

Photosynthesis in plant physiology

Light quality

Red Drop Phenomenon (红降现象)

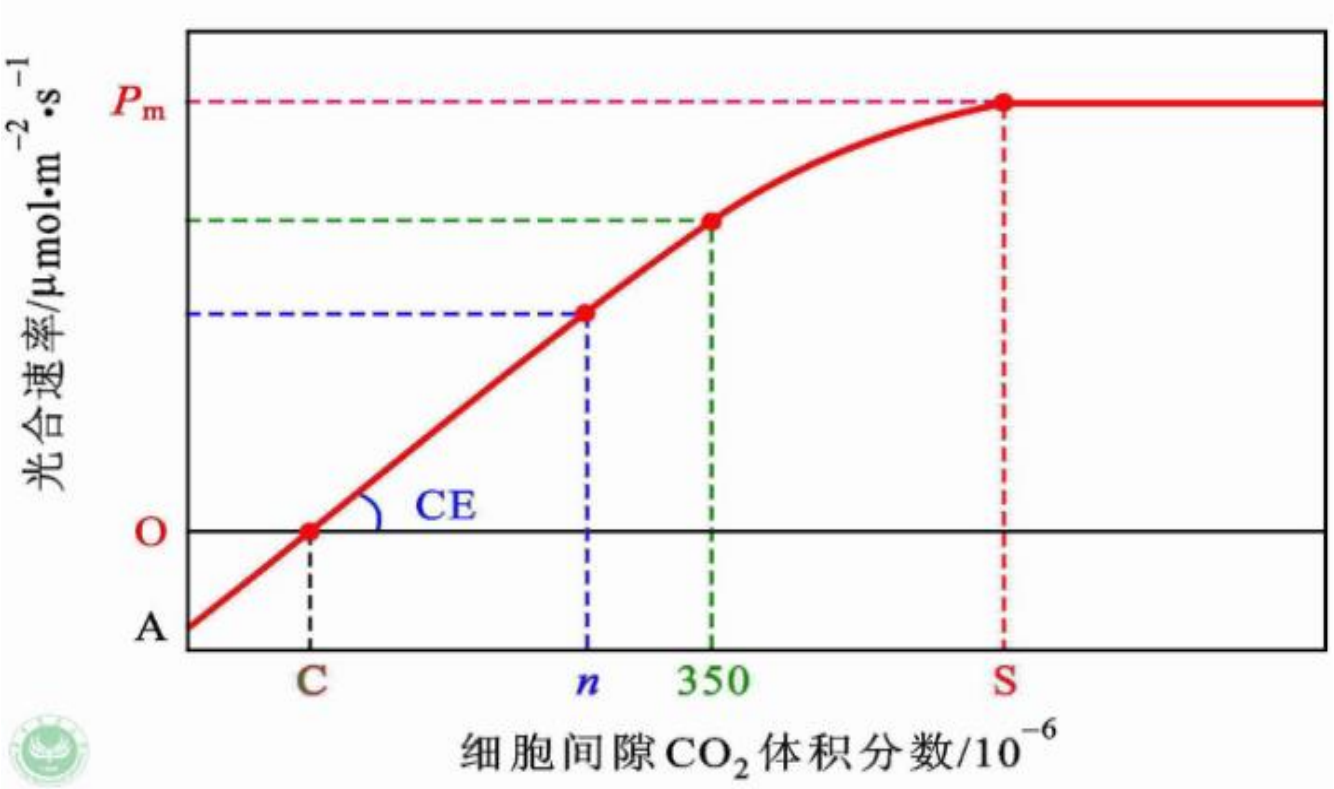
When wavelength > 685 nm (far-red light), the photosynthetic efficiency drops sharply

Quantum Yield (量子产额): The number of O_2 molecules evolved (or CO_2 molecules fixed) per photon absorbed. Typical value is ~1/8 to 1/10 O_2 per photon

Quantum Requirement (量子需要量): The number of photons required to produce 1 O_2, or Fix 1 CO_2. Typical value is 8–10 photons

Photosynthesis in plant physiology

CO_2



Carboxylation Efficiency (CE): Initial slope of CO_2 response curve

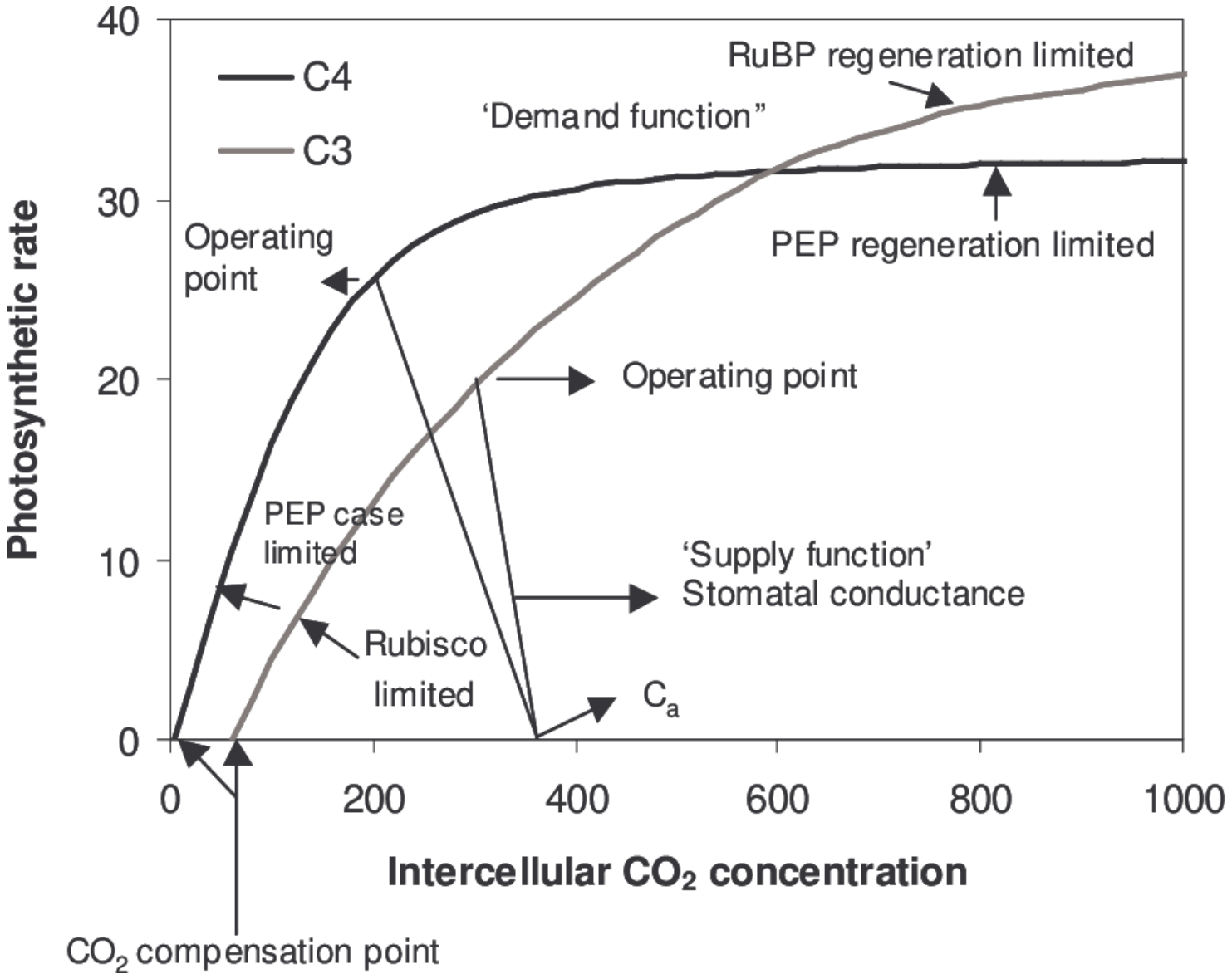
CO_2 Compensation Point

CO_2 Saturation Point

Maximum Photosynthetic Rate (P_m)

Photosynthetic CO_2 response curves (A-Ci curves)

Photosynthesis in plant physiology



CO_2

C_4 plants:

Lower CO_2 compensation point

Higher efficiency at low CO_2

C_3 plants:

Higher compensation point

Stronger CO_2 limitation

Photosynthesis in plant physiology

CO_2

Route of CO_2 Entry in C3

Atmosphere → Stomata → Intercellular space

→ Cytosol → Chloroplast stroma

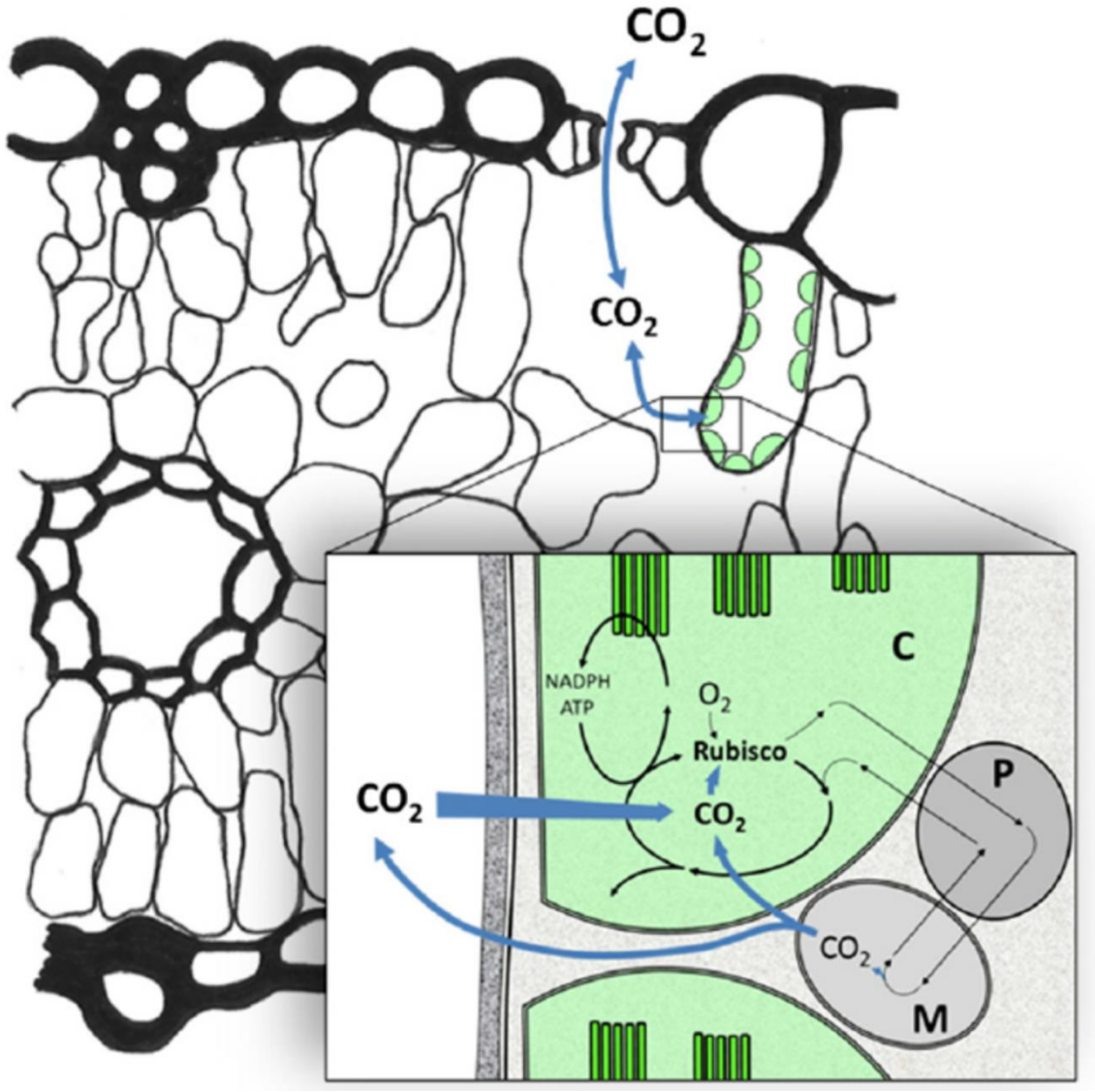
Limiting Factors

Concentration gradient

Diffusion resistance:

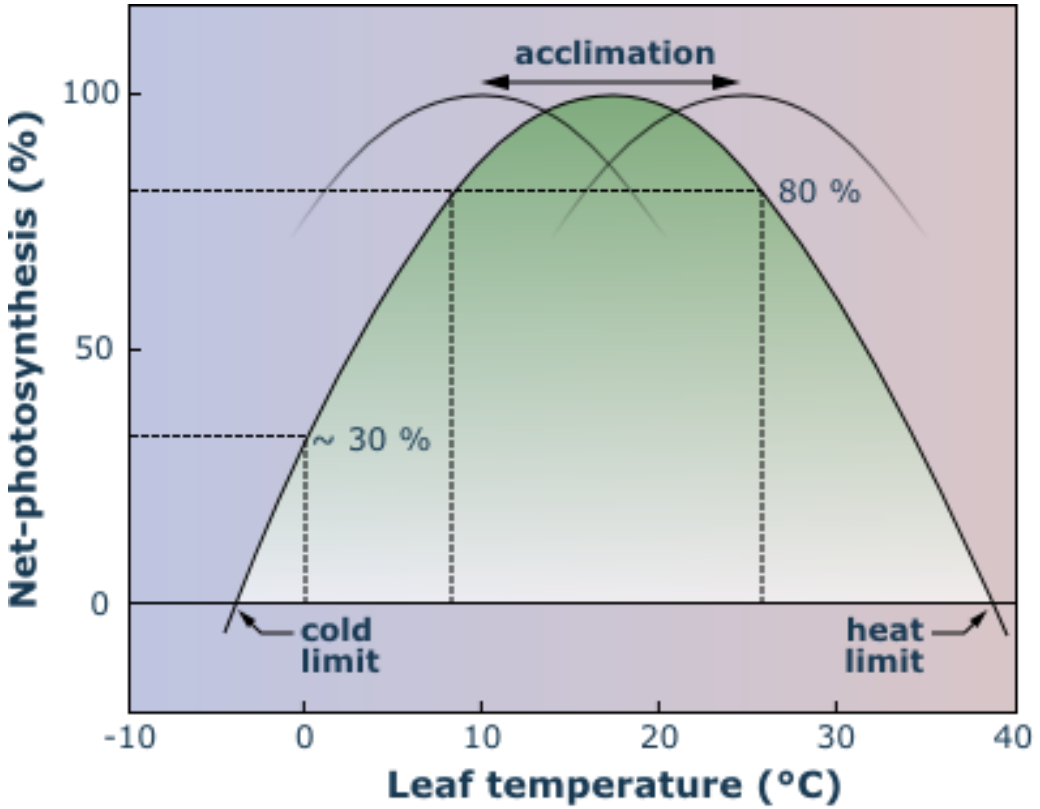
Stomatal resistance

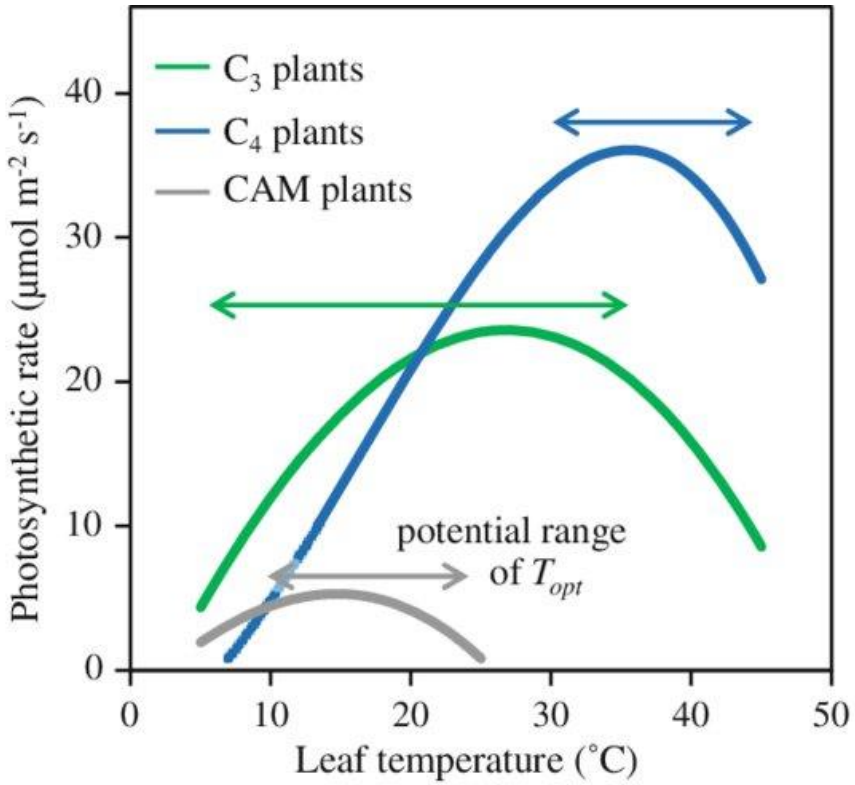
Mesophyll resistance



Photosynthesis in plant physiology

Temperature





Photosynthesis in plant physiology

Temperature

Parameter	Typical Range (C_3 plants)	Definition	Physiological Basis
Minimum temperature (Tmin)	~2–4 °C	Lowest temperature at which photosynthesis can occur	Enzyme activity extremely low; metabolic processes slow
Optimum temperature (Topt)	~20–30 °C	Temperature at which photosynthesis is maximal	Balance of enzyme activity, CO_2 fixation, and low photorespiration
Maximum temperature (Tmax)	~40–45 °C	Highest temperature at which photosynthesis can proceed	Enzyme denaturation, membrane instability, high respiration

Photosynthesis in plant physiology

Mineral Nutrition

Element Group	Elements	Function in Photosynthesis
Structural components	N, P, S, Mg	Chlorophyll, proteins, membranes
Electron transport	Fe, Cu	Components of electron carriers (cytochromes, plastocyanin)
Energy metabolism	Pi	ATP, NADPH, metabolic intermediates
Water splitting	Mn, Cl	Essential for oxygen-evolving complex (OEC)
Regulation	K, Ca	Stomatal movement, metabolite transport

Photosynthesis in plant physiology

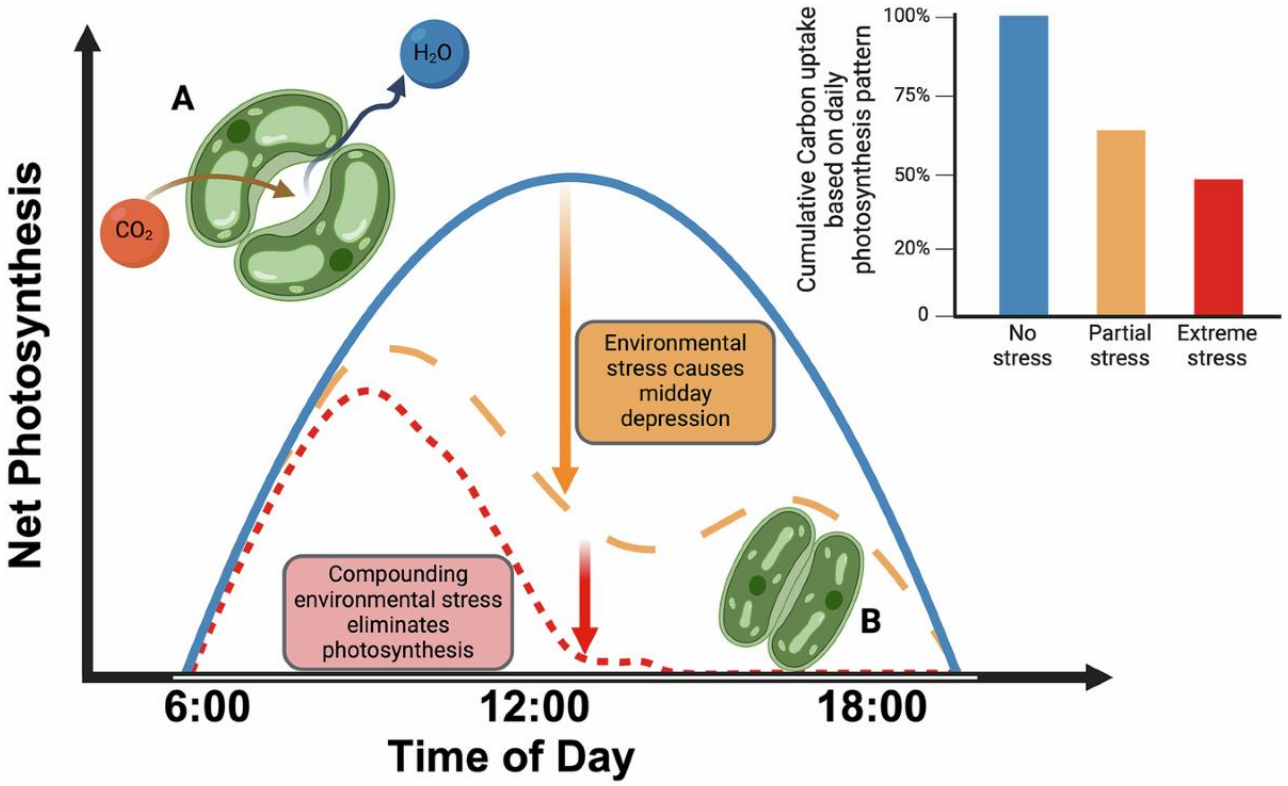
Water stress

Only a very small fraction of water is used directly in photosynthesis ~1% (for photolysis in PSII). Therefore, water affects photosynthesis mainly **indirectly.**

- **Stomatal Closure**
- **Reduced Assimilate Transport**
- **Damage to Photosynthetic Apparatus**
- **Reduced Leaf Area**

Photosynthesis in plant physiology

Diurnal Patterns



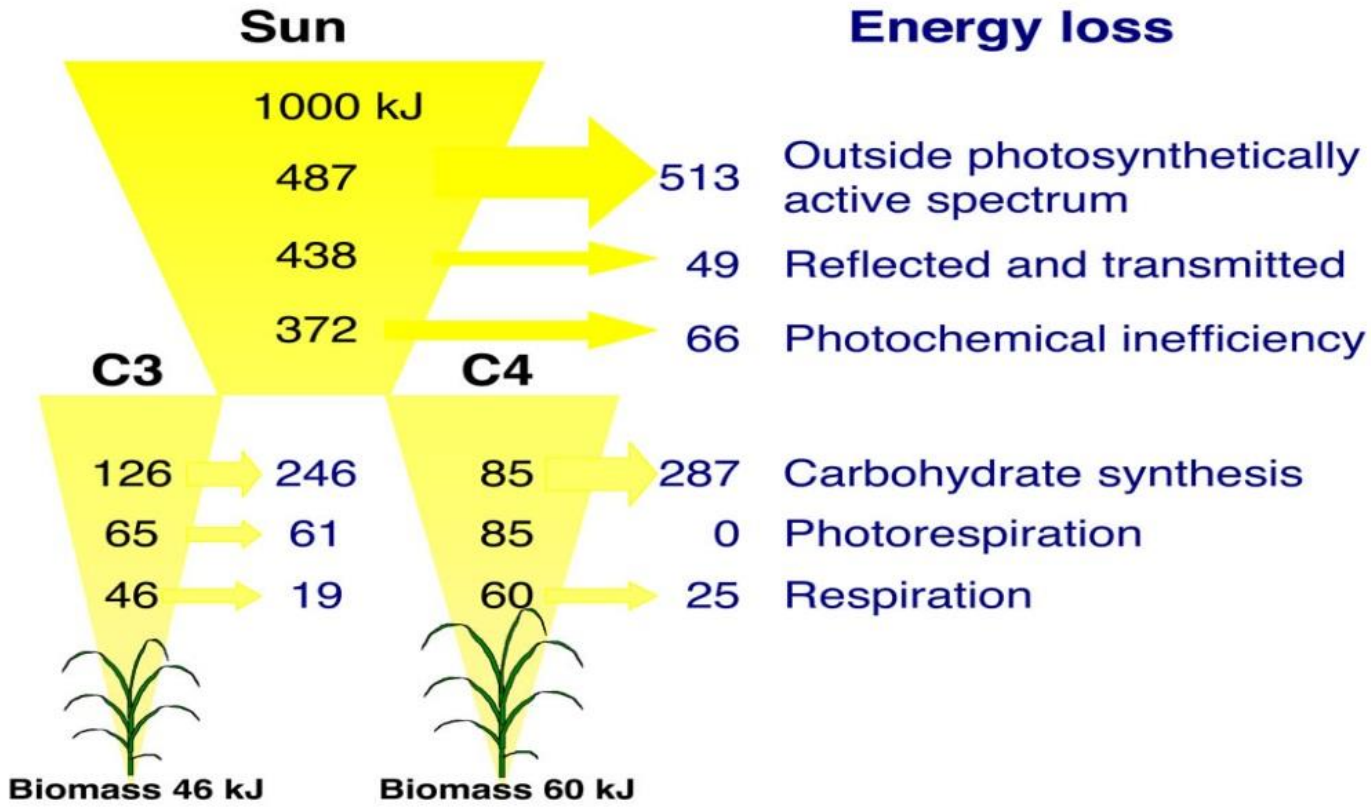
Normal Conditions — Single Peak Curve

Stress Conditions — Double Peak Curve (Midday Depression)

A temporary decline in photosynthetic rates around noon, despite high light intensity.

Photosynthesis on crop yield improvement

Light Use Efficiency (LUE)/ 光能利用效率 is the percentage of incident solar energy that is converted into chemical energy stored in plant biomass over a given time and land area.



Photosynthesis on crop yield improvement

Why Is Light Use Efficiency Low?

Factor	Description	Impact on Photosynthesis
Light leakage (>50%)	Large fraction of solar radiation not absorbed by canopy	Reduced available energy
Light saturation & waste	Light exceeds photosynthetic capacity (PAR up to 1800–2000 μmol m^{-2} s^{-1} vs saturation ~540–900)	Excess energy dissipated (heat, NPQ)
Environmental constraints	Suboptimal temperature, water, nutrients	Limits biochemical processes
Respiration losses	Carbon lost via maintenance and growth respiration	Reduces net biomass accumulation

Photosynthesis on crop yield improvement

Radiation Use Efficiency (RUE) / 辐射利用效率

RUE is the ratio of biomass accumulation (dry matter) to absorbed photosynthetically active radiation (PAR) over a given period.

Plant Type	RUE Range ($g \cdot MJ^{-1}$)
C_3 plants	~0.85 – 3.0
C_4 plants	Up to ~4.8

Photosynthesis on crop yield improvement

Biomass = Photosynthetic production − Respiratory losses

Photosynthetic production = Photosynthetic capacity × Photosynthetic duration × Photosynthetic area

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Review

Perspectives of improving rice photosynthesis for higher grain yield

Dongliang Xiong

National Key Laboratory of Crop Genetic Improvement, Hubei Hongshan Laboratory, MARA Key Laboratory of Crop Ecophysiology and Farming System in the Middle Reaches of the Yangtze River, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, Hubei 430070, China

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Grain yield
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QTL
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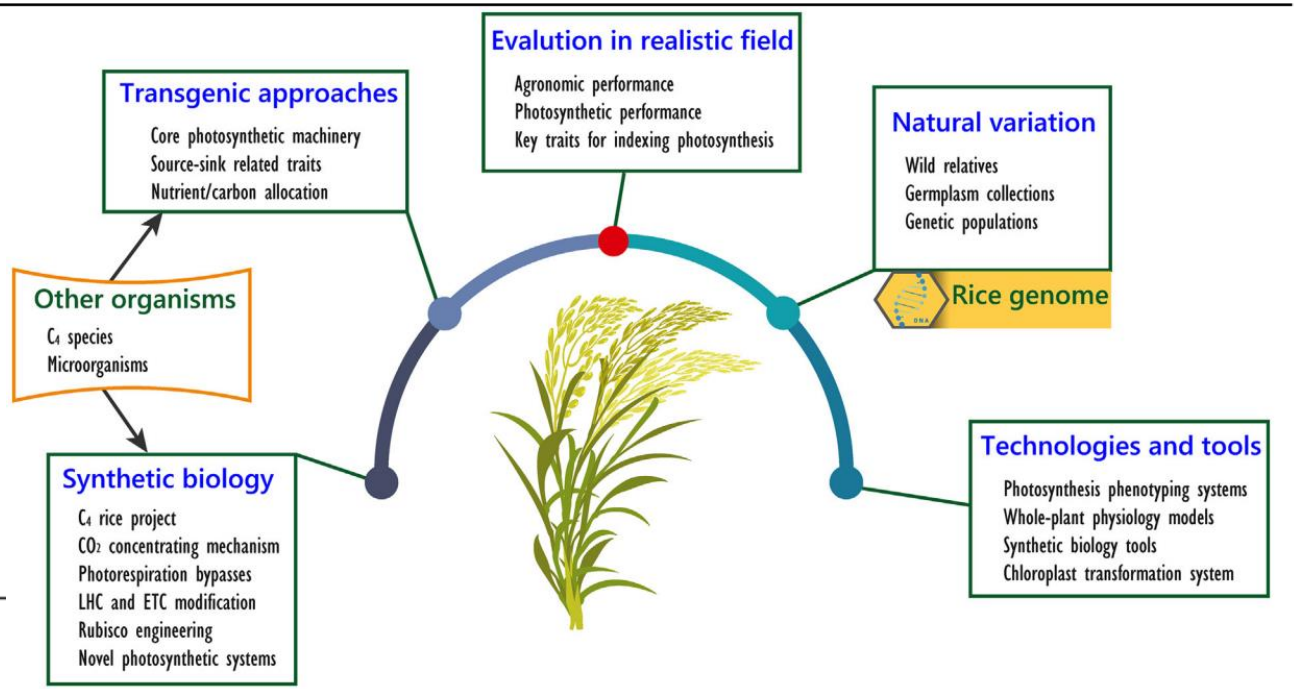
Sink-source relationships



Trends in Plant Science

CellPress
REVIEWS

Opinion

Increasing Photosynthesis: Unlikely Solution For World Food Problem

Thomas R. Sinclair,[1,*] Thomas W. Rufty,[1] and Ramsey S. Lewis[1]

Increasing the photosynthesis rate of plants has been recently revitalized as an approach for increasing grain crop yields and solving world food crises. The idea that photosynthesis is the key to increasing grain crop yields is not new. Considerable research in the 1970s and 1980s showed that carbon input was not limiting for crop growth and yield. Instead, the availability and uptake of water and nutrients were found to be critical for increasing grain yield, and that conclusion still applies today. In this Opinion article, nitrogen limitation is given particular attention because of its quantitative linkage with vegetative and reproductive growth and its essential role as a quantitative component of seeds.

Photosynthesis Rate and Grain Yield

Recent publications [1–3] and a steady stream of articles in the popular press [4–12] suggest that new discoveries in photosynthesis research will lead to increased crop yields and provide the solution to global food shortages. The logic for this conclusion has been enunciated for decades and often stated as a 'truism':

Thomas Sinclair



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Crop Physiology & Ecology
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Carbon accumulation in the absence of additional nitrogen does not increase yield.

Yield increase requires greater nitrogen accumulation, plant nitro-

Homework Assignments

Energy Transformation in Artificial Plant Cells

A plant physiologist grows two groups of artificial plant cells. Both contain chloroplasts, mitochondria, enzymes, carbohydrates, lipids, proteins and nucleic acids, and get the same light, water and CO_2. Only their energy-processing systems differ.

Model 1

Strong producer, weak user

STRENGTH Chloroplasts: very active, make lots of glucose and O_2

WEAKNESS Mitochondria: inefficient, make ATP slowly

Model 2

Weak producer, strong user

WEAKNESS Chloroplasts: capture light poorly, make glucose slowly

STRENGTH Mitochondria: efficient, make ATP quickly

Results after 12 h light + 12 h dark	Normal	Model 1	Model 2
Light energy captured	100	160	35
Glucose made (light period)	100	150	30
O_2 released (light period)	100	155	30
Starch stored after light period	100	190	10
ATP made per glucose	100	40	120
Total ATP made (24 h)	100	55	40
Glucose left unused after 24 h	100	210	0
Cell growth over 24 h	100	70	45

Relative units (normal cell = 100). Green = above normal; orange = 60 or less. Invented data for this exercise.

Homework Assignments

Task 1 • Analyze

Trace the energy

- Draw a labeled diagram linking chloroplast and mitochondrion: light, CO_2, water, glucose, O_2 and ATP, with both equations.
- Explain the role of each part in Model 1 and Model 2.
- Use the data: why is Model 1 left with 210 units of glucose, and why is Model 2’ s total ATP only 40?

Task 2 • Evaluate

Which cell is more successful?

- Define “successful” first: growth, surviving darkness, energy for work now, or support for the whole plant.
- Make a claim and back it with at least two values from the table.
- Describe one situation where the other model would do better.

Task 3 • Create

Redesign the cells

- Change one factor per model: light, chlorophyll activity, mitochondrial efficiency, enzyme activity or glucose storage.
- Predict how the data would change.
- Name a new limitation the change could cause, and how you would test it.