Photosynthetic Bioenergetics

Light Reactions, Photophosphorylation & Energy Balance

From photon capture → electron flow → proton gradient → ATP + NADPH



Gulzhanay Kamshybayeva, PhD
Senior Lecturer

Same bioenergetic principle — a new energy source

BRIDGE FROM RESPIRATION

Mitochondria

Chemical energy from nutrients

$NADH/FADH_2$ → electron transport
→ proton gradient → ATP synthase

Chloroplasts

Light energy from photons

H_2O → electron transport
→ proton gradient → ATP synthase

What changes?

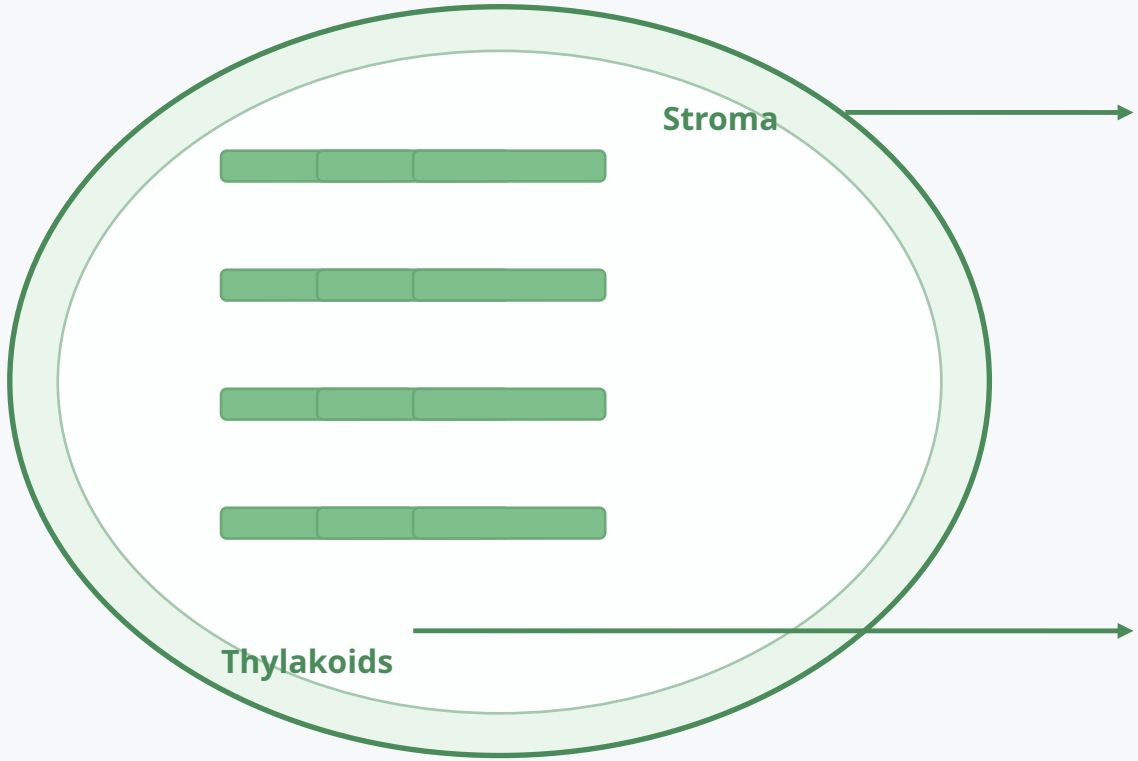
Energy source, electron donor, terminal acceptor, membrane orientation and products change.

The chemiosmotic logic remains.

Do not relearn ETC from the beginning: use the same energy-conversion logic in a new organelle.

Chloroplast architecture determines where energy conversion occurs

STRUCTURE → FUNCTION



Thylakoid membrane

Photosystems, electron carriers and ATP synthase are embedded here. Light-driven electron transport creates a proton gradient.

Thylakoid lumen

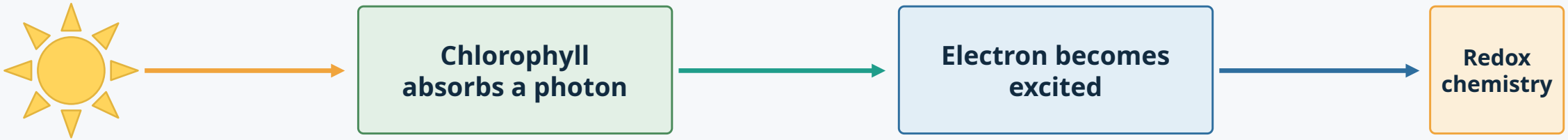
H^+ accumulates inside the thylakoid. This is the high-proton side during the light reactions.

Stroma

ATP and NADPH are produced on the stromal side and then support carbon fixation.

Photons excite pigments — light becomes redox potential

ENERGY CAPTURE



Pigments are not ATP

Chlorophyll captures light energy; it does not “make ATP” by itself.

Excitation is temporary

The excited electron must be transferred into a reaction-center redox pathway before the energy is lost.

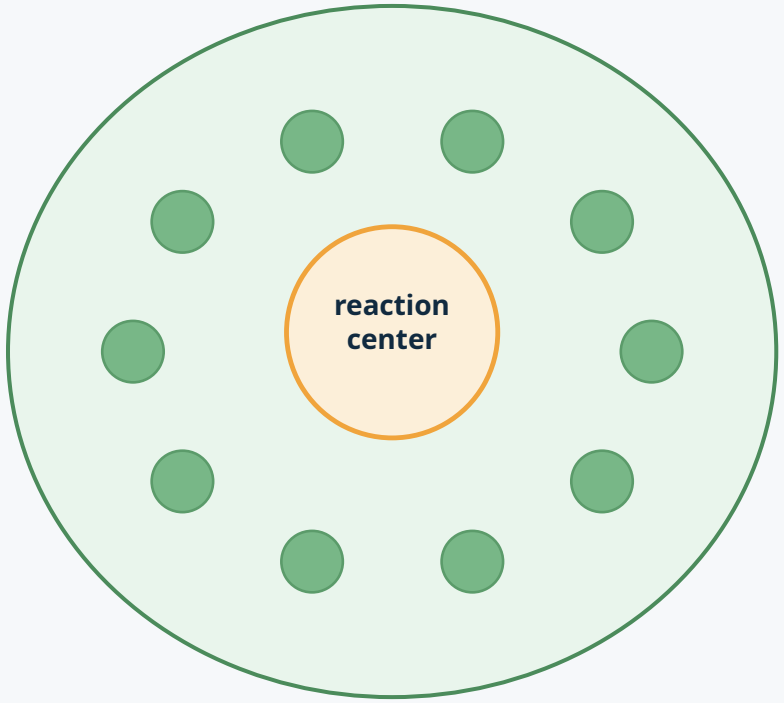
Energy is transferred stepwise

Photosystems convert photon energy into directional electron flow.

The first conversion is: photon energy → excited electron → redox energy.

A photosystem combines an antenna with a reaction center

PHOTOSYSTEM DESIGN



1. Antenna pigments

Collect photons and transfer excitation energy toward the reaction center.

2. Reaction center

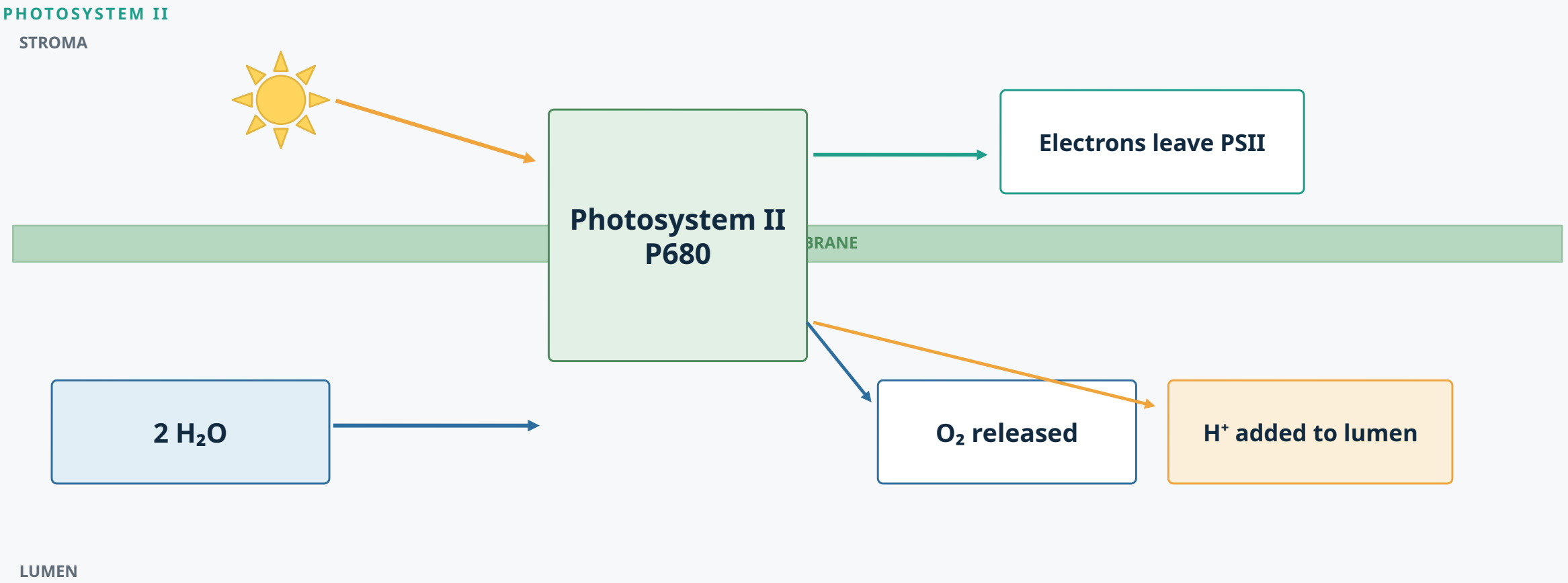
Performs charge separation: an excited electron is transferred to an acceptor.

Why this matters

The photosystem converts a fleeting photon event into a chemically useful electron-transfer event.

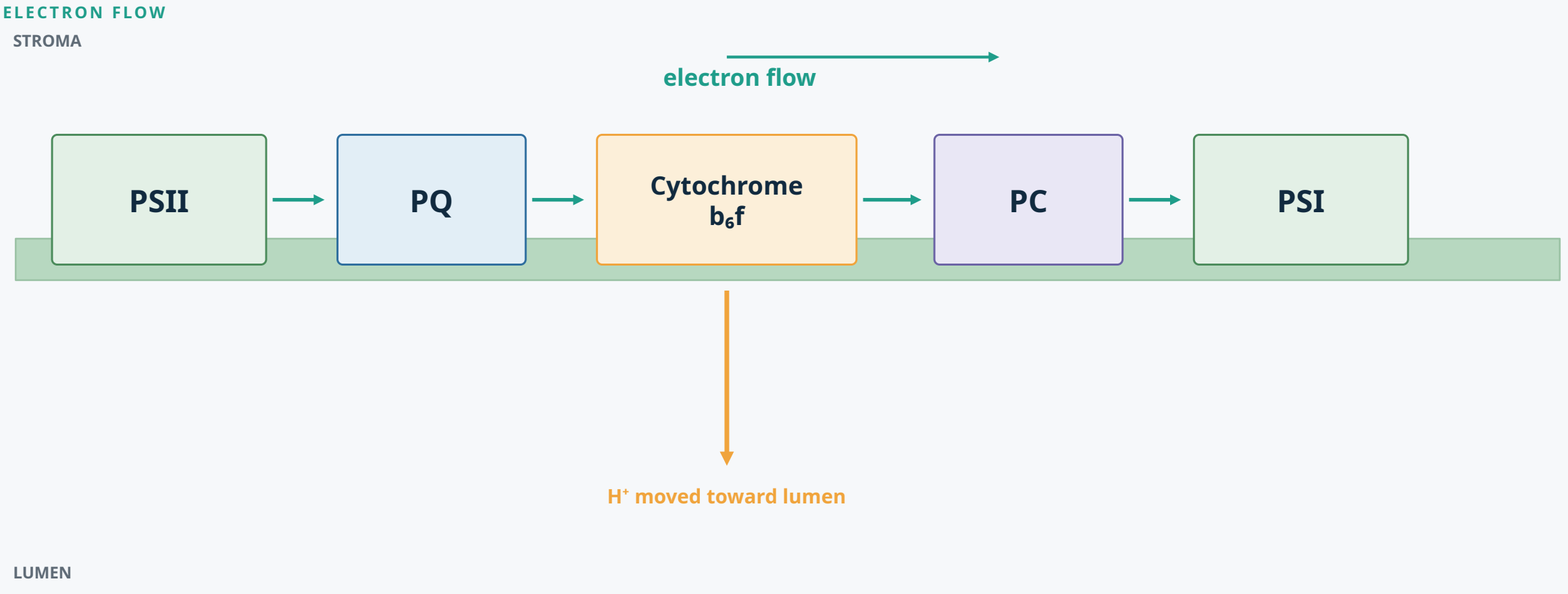
Photosystem II and Photosystem I use the same basic design but perform different steps of linear electron flow.

Photosystem II starts linear electron flow by oxidizing water



Water supplies replacement electrons; oxygen is a by-product of water oxidation, not of CO_2 fixation.

Electrons move from PSII to PSI through a thylakoid electron-transfer chain



Cytochrome b_6f links electron transfer to proton translocation — the key step that builds the proton-motive force.

Three processes make the thylakoid lumen proton-rich

PROTON-MOTIVE FORCE

1. Water oxidation

PSII releases H^+ into the lumen when water is oxidized.

2. Cytochrome b_6f

Electron transfer through the PQ/b_6f system moves additional protons toward the lumen.

3. $NADP^+$ reduction

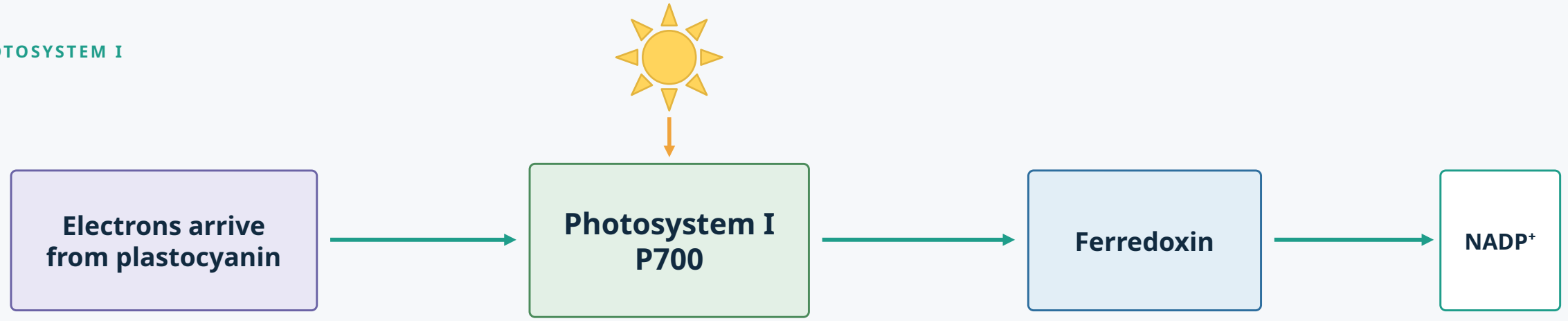
On the stromal side, formation of NADPH consumes reducing equivalents and contributes to the transmembrane proton imbalance.

LOWER [H^+] STROMA → HIGHER [H^+] LUMEN

The proton gradient stores light-derived energy before ATP is synthesized.

Photosystem I re-energizes electrons for strong reducing power

PHOTOSYSTEM I



Why a second photon?

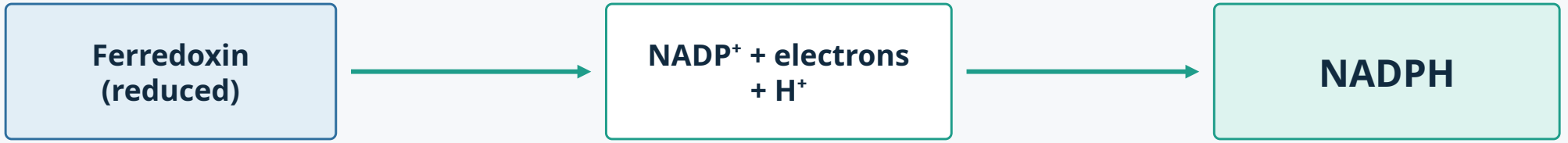
The electron lost energy while moving from PSII to PSI. PSI raises its energy again.

Bioenergetic outcome

The re-excited electron becomes strong enough to support reduction of $NADP^+$ to NADPH.

NADPH stores reducing power on the stromal side

REDUCING POWER



NADPH is not ATP

It is a reduced electron carrier used mainly for reductive biosynthesis.

Produced by light reactions

NADPH captures electron energy at the end of linear electron flow.

Consumed in carbon fixation

The Calvin cycle uses NADPH to reduce carbon intermediates while building carbohydrates.

Light reactions produce two currencies with different jobs: ATP for energy coupling and NADPH for reducing power.

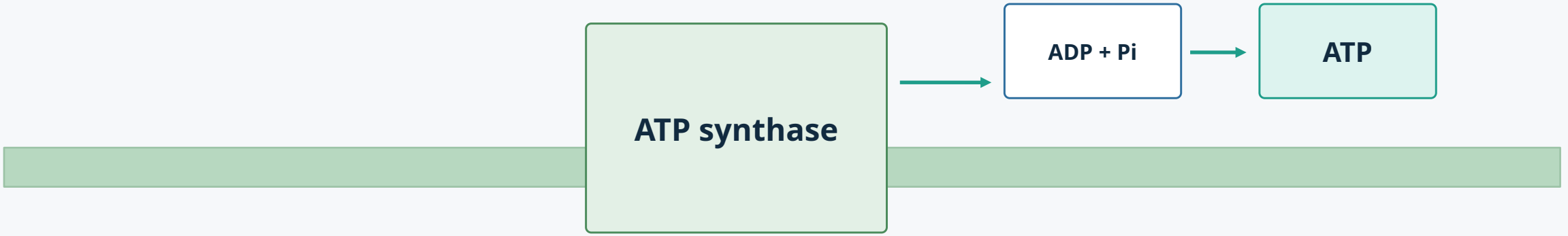
The Z-scheme links two photon inputs to directional electron flow



Linear flow: H_2O → PSII → carriers → PSI → $NADP^+$. Two light-driven boosts make the pathway possible.

Photophosphorylation converts the proton gradient into ATP

ATP SYNTHESIS
STROMA



Direction matters

H^+ flows from lumen → stroma through chloroplast ATP synthase.

Product location

ATP is released on the stromal side, where carbon fixation occurs.

LUMEN — high H^+

Same chemiosmotic principle as mitochondria — opposite compartment orientation.

What do the light reactions produce?

BALANCE SHEET

ATP

Produced by photophosphorylation.

Provides free energy for carbon fixation and other chloroplast processes.

NADPH

Produced at the end of linear electron flow.

Provides reducing power for carbon fixation.

O_2

Released when water is oxidized at PSII.

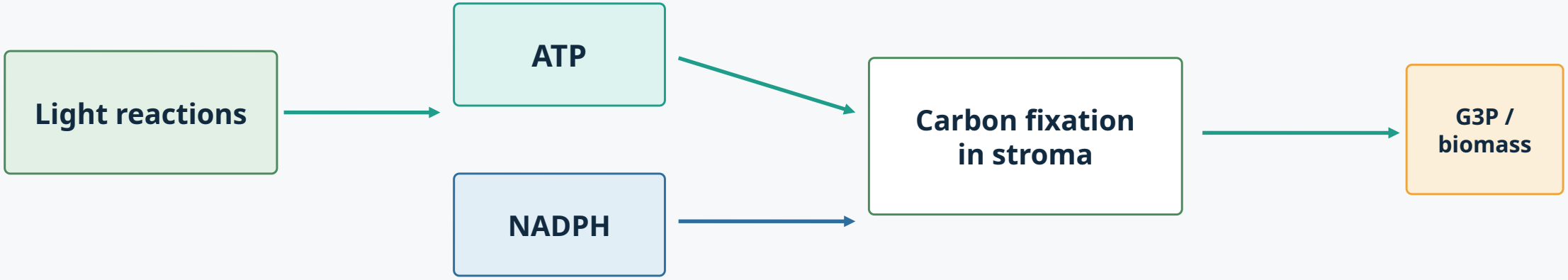
It is a by-product of electron donation from water.

Inputs light + H_2O + ADP + Pi + $NADP^+$ → **Outputs** **ATP + NADPH + O_2**

ATP and NADPH are intermediate energy currencies; the long-term carbon product is made later during carbon fixation.

ATP and NADPH must be supplied in the right balance

ENERGY BALANCE



ATP answers “how much work?”

ATP drives endergonic steps and regeneration reactions.

NADPH answers “where do electrons come from?”

NADPH reduces carbon intermediates.

Why balance matters

Too much of one currency cannot fully replace the other.

Cyclic electron flow around PSI can increase ATP without making NADPH

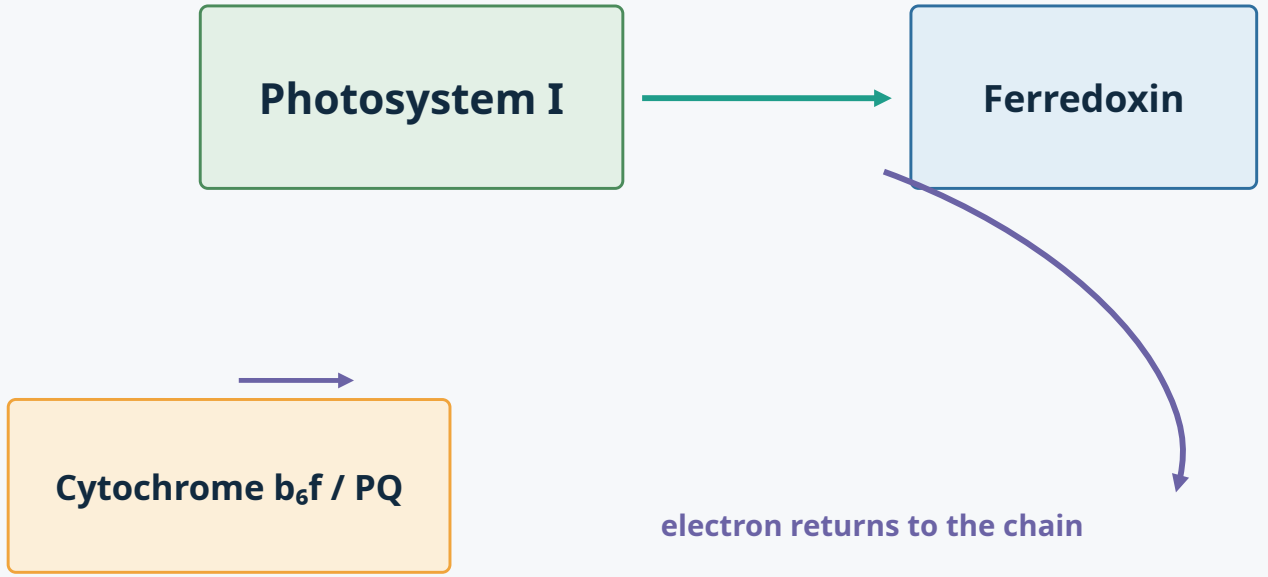
FLEXIBLE ENERGY BALANCE

What increases?

Proton-motive force and ATP production.

What does NOT increase?

No net NADPH formation and no additional water oxidation / O_2 evolution in the cyclic loop.



Cyclic flow is a regulatory option for adjusting ATP supply relative to NADPH.

Linear and cyclic electron flow solve different energetic needs

COMPARE MECHANISMS

Feature	Linear electron flow	Cyclic electron flow
Photosystems	PSII + PSI	PSI only
Electron source	H_2O	Electrons cycle back from PSI
O_2 evolution	Yes	No net O_2 from the cyclic loop
NADPH	Produced	Not produced
ATP	Produced	Produced / supplemented
Main purpose	ATP + NADPH supply	Adjust ATP/NADPH balance

Do not ask “which pathway is better?” Ask which ATP/NADPH balance the chloroplast needs.

Mitochondria and chloroplasts use related chemiosmotic logic

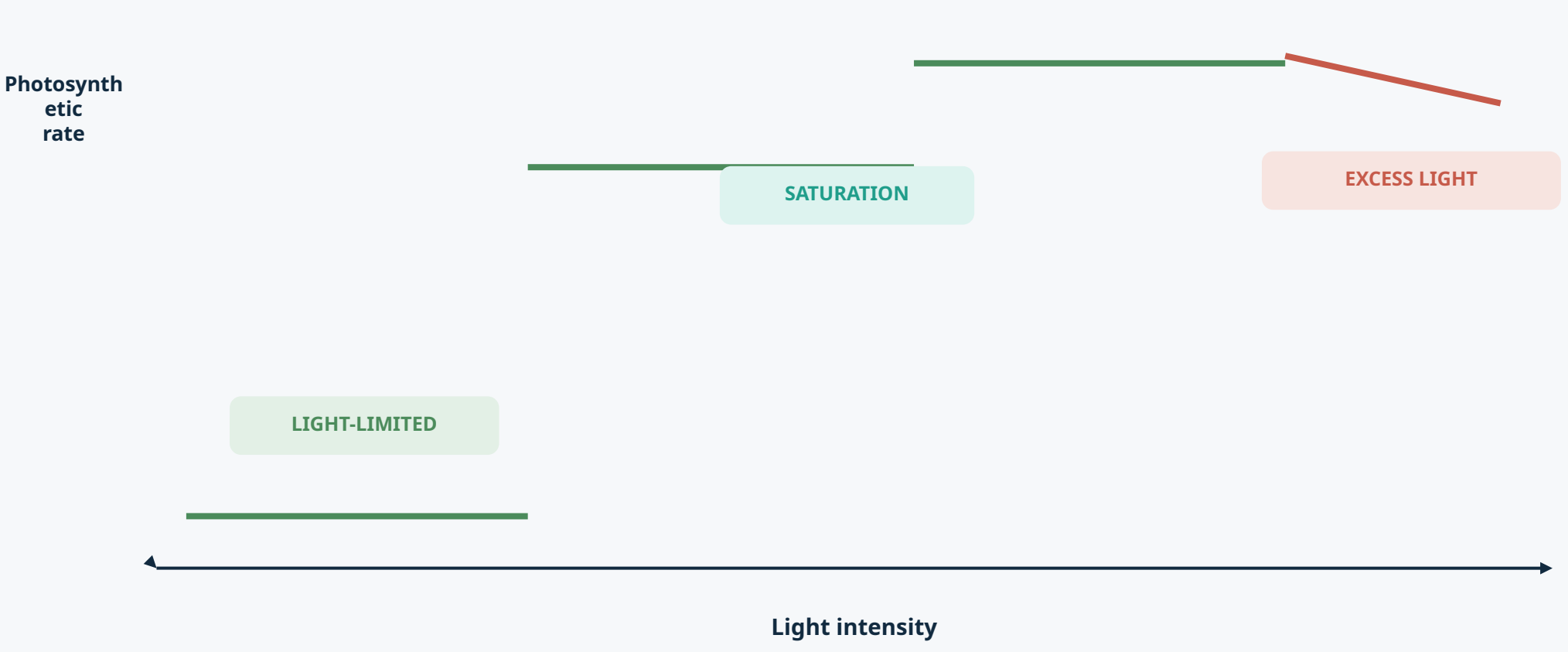
INTEGRATE THE COURSE

Question	Mitochondrion	Chloroplast
Primary energy input	Chemical energy from reduced fuels	Light energy
Main electron donor	NADH / FAD-linked carriers	H_2O for linear flow
Terminal acceptor	O_2	$NADP^+$
High-H^+ compartment	Intermembrane space	Thylakoid lumen
H^+ flows through ATP synthase	to matrix	to stroma
ATP formation	Oxidative phosphorylation	Photophosphorylation
Additional key product	H_2O from O_2 reduction	NADPH + O_2

Same principle: electron flow → ion gradient → ATP synthase. Different biology: source, direction and products.

Photosynthesis responds nonlinearly to light intensity

REGULATION BY ENVIRONMENT



At low light

More photons → more electron flow.

At saturation

Other processes become limiting.

At excess light

Protection and repair become important.

More light is useful only until the rest of the photosynthetic system can no longer process the extra excitation.

Non-photochemical quenching safely dissipates excess excitation as heat

PHOTOPROTECTION



What is protected?

Photosystem II reaction centers are less exposed to damaging over-excitation.

What is the trade-off?

Some absorbed light is deliberately not used for photochemistry.

Why this is useful

Short-term energy dissipation can prevent longer-term photodamage.

Photoprotection is regulated energy dissipation — not simply “wasted light.”

When excitation exceeds protective capacity, photoinhibition can occur

STRESS AND REPAIR

Excess excitation

High light can over-reduce electron carriers and increase the probability of reactive oxygen chemistry.

Reactive oxygen species

ROS can damage proteins, pigments and membranes when production exceeds antioxidant control.

PSII damage / repair

Photosystem II is particularly vulnerable and requires continuous repair under strong light stress.

Functional outcome

Electron transport and photosynthetic efficiency decrease until protection and repair restore function.

Bioenergetic control must balance energy capture with safe energy dissipation.

How can we measure photosynthetic bioenergetics?

EXPERIMENTAL LOGIC

Gas exchange

Measure CO_2 uptake and H_2O exchange at the leaf level.

Useful for net carbon assimilation and stomatal effects.

O_2 evolution

Track oxygen production as a direct consequence of water oxidation during oxygenic photosynthesis.

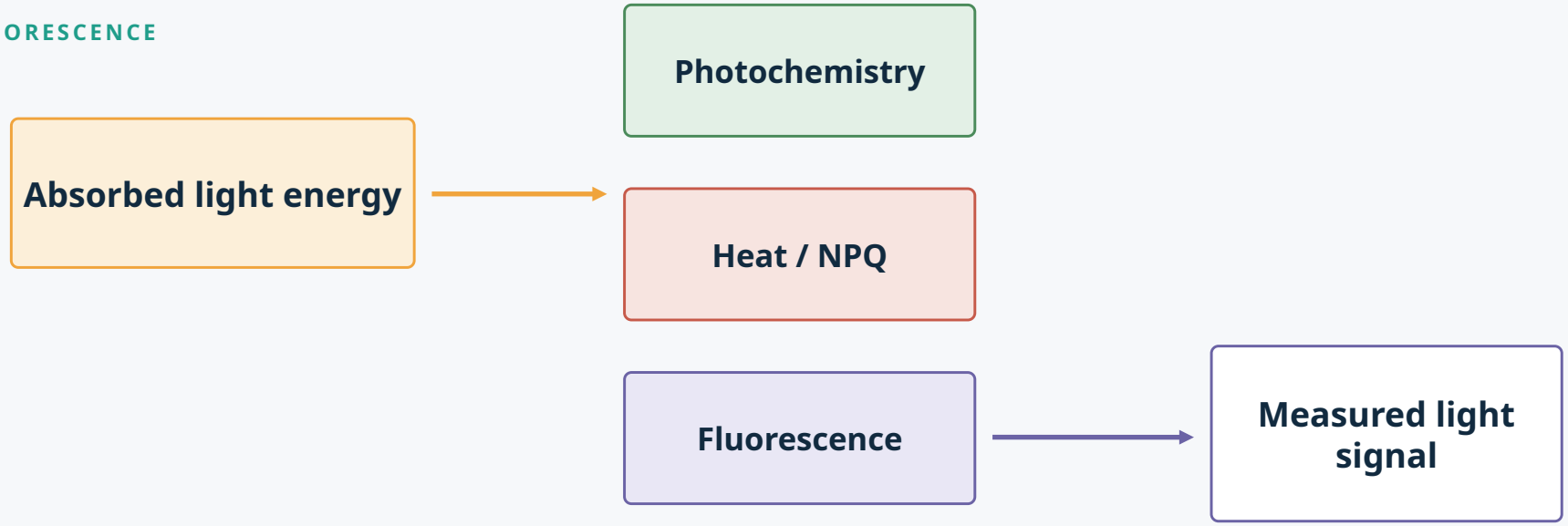
Chlorophyll fluorescence

Probe how absorbed excitation is partitioned between photochemistry, regulated heat dissipation and other losses.

As with mitochondrial bioenergetics, one measurement is rarely enough — combine readouts to identify mechanism.

Chlorophyll fluorescence reports the functional state of Photosystem II

FLUORESCENCE



Fv/Fm

A dark-adapted PSII efficiency indicator used to detect stress or photoinhibition.

NPQ

A fluorescence-based indicator of regulated non-photochemical energy dissipation.

Fluorescence does not measure ATP directly; it reports how excitation energy is being handled by the photosynthetic apparatus.

Mini-case: identify the most likely photosynthetic problem

INTERPRET DATA

Plant A — control

Moderate light
Normal CO_2 uptake
Normal Fv/Fm
Low NPQ after acclimation

Plant B — after excess light

CO_2 uptake ↓
Fv/Fm ↓
NPQ initially ↑
Recovery is slow

Reasoning

1. Carbon assimilation is impaired.
2. Lower Fv/Fm indicates reduced PSII photochemical efficiency.
3. High NPQ shows protective dissipation was engaged.
4. Slow recovery suggests photoinhibition / damage beyond short-term protection.

Interpret the pattern, not a single number: protection can increase first, while persistent stress can later reduce PSII function.

Biotechnology: photosynthetic efficiency is a systems problem

APPLIED BIOENERGETICS

Microalgae & photobioreactors

Productivity depends on photon delivery, mixing, CO_2 supply, temperature and the ability to avoid light saturation or shading.

Metabolic engineering

Changing carbon sinks or electron-flow regulation can alter the demand for ATP and NADPH.

Stress screening

Chlorophyll fluorescence and gas exchange can identify strains or conditions with better photosynthetic performance.

Engineering question: **How do we increase useful carbon conversion without simply increasing incident light?**

The best biological system is not the one that absorbs the most light — it is the one that converts and uses energy most effectively.

Take-home messages & open-access video supplements

- Light reactions convert photons into directional electron flow, a proton-motive force, ATP and NADPH.
- PSII oxidizes water; PSI re-energizes electrons and supports NADPH formation.
- Photophosphorylation uses the same chemiosmotic principle as oxidative phosphorylation, but in a different membrane orientation.
- Cyclic electron flow and photoprotection help match energy supply to cellular demand and environmental conditions.
- Gas exchange, O_2 evolution and chlorophyll fluorescence provide complementary experimental readouts.

Video supplements (open access)

1. HHMI BioInteractive — Light Reactions

youtu.be / Light Reactions

2. WALZ — Chlorophyll a Fluorescence Tutorial

walz.com / Tutorials

3. LI-COR — Basic Photosynthesis Measurements

licor.com / Basic Measurements

Use as optional reinforcement — the lecture itself does not depend on the videos.