Photosystems

**Photosystem** (fig 10.12) = rxn center surrounded by several light-harvesting complexes

**Light-harvesting complex** = pigment molecules bound to proteins (act as antenna for rxn center)

**Rxn center** = protein complex that includes 2 special chlorophyll a molecules + primary e-acceptor molecule

**First step of light rxns:** special chlorophyll a molecule transfers its excited e- to the primary e-acceptor

A Photosystem: A Reaction Center Associated with Light-Harvesting Complexes

- A photosystem
  - Is composed of a reaction center surrounded by a number of light-harvesting complexes

Light-harvesting Complexes and Reaction Centers

- The light-harvesting complexes consist of pigment molecules bound to particular protein
- They funnel the energy from photons of light to the reaction center
- When a reaction-center chlorophyll a molecule absorbs energy, one of its electrons gets bumped up to a primary electron acceptor
Photosystems

Two types of photosystems embedded in the thylakoid membranes of land plants (Fig 10.13)

1. Photosystem I (PS I)
   - Reaction center chlorophyll a = P700
   - Cyclic and noncyclic e- flow

2. Photosystem II (PS II)
   - Reaction center chlorophyll a = P680
   - Noncyclic e- flow

Noncyclic e- flow (Fig 10.13)
- Uses PS II & PS I
- Excited e- from PS II → ETC → produces ATP
- Excited e- from PS I → ETC → used to reduce NADP+
- Electrons ultimately supplied from splitting water → releases O2 and H+

Cyclic e- flow (Fig 10.15)
- Uses only PS I
- Only generates ATP
- Excited e- from PS I cycle back from 1st ETC
- No O2 release & no NADPH made

Two Photosystems

- The thylakoid membrane
  - Is populated by two types of photosystems, I and II

Noncyclic Electron Flow — Involves both Photosystems

- Produces NADPH, ATP, and oxygen, and is the primary pathway of energy transformation in the light reactions.

Figure 10.13
A mechanical analogy for the light reactions

Cyclic Electron Flow
- Under certain conditions
  - Photoexcited electrons take an alternative path
  - Uses Photosystem I only

In cyclic electron flow
- Electrons cycle back to the first ETC
  - Only ATP is produced
**Light Reactions and Chemiosmosis**

**The light reactions and chemiosmosis**: (fig 10.17)

As e- are brought down their E gradient through the ETCs embedded in the thylakoid membranes → E is being used to pump H+ into the thylakoid space

**ATP synthase** is the only place H+ can flow along its concentration gradient → E from this flow is used to join ADP + Pi → ATP

NADPH is made by NADP+ reductase

ATP and NADPH → used to power Calvin cycle

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**Comparison of chemiosmosis in mitochondria & chloroplasts** (fig 10.16):  

ATP generation basically the same (ETC + ATP synthase)

**Mitochondria** use high-E e- extracted from organic molecules (glucose)

**Chloroplasts** use light E to drive e- to top of the ETC
Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria
  - Generate ATP by the same basic mechanism: chemiosmosis
  - But use different sources of energy to accomplish this. Chloroplasts use light energy and mitochondria use the chemical energy in organic molecules.

The spatial organization of chemiosmosis

- Differs in chloroplasts and mitochondria

Chemiosmosis: Chloroplasts vs. Mitochondria

- In both organelles
  - Redox reactions of electron transport chains generate a H+ gradient across a membrane
- ATP synthase
  - Uses this proton-motive force to make ATP
The Calvin Cycle

Calvin cycle uses ATP & NADPH to convert CO₂ to sugar

- **The Calvin cycle**
  - Is similar to the citric acid cycle
  - Occurs in the stroma

---

Calvin cycle (fig 10.18) = anabolic process that builds carbohydrates from smaller molecules (CO₂ and H₂O)

Consumes E (ATP) from the light reactions

Uses NADPH (from the light reactions) as the reducing agent for adding high energy e- to make sugar

---

Phase 1: Carbon fixation

CO₂ incorporated by attaching to 5-C sugar (ribulose bisphosphate = RuBP)

Catalyzed by Rubisco (ribulose bisphosphate carboxylase/oxygenase) = most abundant protein on Earth!

Unstable 6-C intermediate $\rightarrow$ 2 molecules of 3-phosphoglycerate (3-C sugar)

Phase 2: Reduction

3-phosphoglycerate has phosphate added $\rightarrow$ NADPH reduces intermediate $\rightarrow$ G3P (glyceraldehyde-3-phosphate)

One G3P exits the cycle to be used by the plant cell

Other 5 recycled to regenerate RuBP

Phase 3: Regeneration of CO₂ acceptor (RuBP)

Requires ATP

Five G3P (3-C) $\rightarrow$ Three 5-C molecules of RuBP

---

Calvin cycle (fig 10.18) = anabolic process that builds carbohydrates from smaller molecules

Consumes E (ATP)

Uses NADPH as reducing agent for adding high E e- to make sugar
The Calvin cycle

- The Calvin cycle

![Diagram of the Calvin cycle]

The Calvin cycle has three phases

- The Calvin cycle has three phases
  - Carbon fixation
  - Reduction
  - Regeneration of the CO₂ acceptor

The Calvin cycle

- Phase 1: Carbon fixation
  - CO₂ incorporated by attaching to 5-C sugar (ribulose bisphosphate = RuBP)
  - Catalyzed by Rubisco (ribulose bisphosphate carboxylase/oxygenase) = most abundant protein on Earth!
  - Unstable 6-C intermediate → 2 molecules of 3-phosphoglycerate (3-C sugar)

- Phase 2: Reduction

- Phase 3: Regeneration of the CO₂ acceptor (RuBP)
The Calvin cycle

- **Phase 2: Reduction**
  - 3-phosphoglycerate has phosphate added → NADPH reduces intermediate → G3P (glyceraldehyde-3-phosphate)
  - One G3P exits the cycle to be used by the plant cell
    - Other 5 recycled to regenerate RuBP

- **Phase 3: Regeneration of CO2 acceptor (RuBP)**
  - Requires ATP
  - Five G3P (3-C) → Three 5-C molecules of RuBP

Balancing gas exchange against water loss

Terrestrial plants have to balance gas exchange (CO₂ + O₂) w/ H₂O loss Happens at the stomata on leaves

If a plant closes its stomata during hottest part of day → accumulation of O₂ & no CO₂ uptake

**Photorespiration** = process that uses O₂ instead of CO₂ → only generates 1/2 the amount of 3-phosphoglycerate → decreases Ps output by siphoning organic material from Calvin cycle (up to 50%)

Rubisco can act on both CO₂ & O₂ (not discriminate)

C₃ plants
- Most plants
- Use only Calvin cycle to fix CO₂ in mesophyll
  - Limited by photorespiration
On hot, dry days, plants close their stomata
  • Conserving water but limiting access to CO₂
  • Causing oxygen to build up

Photorespiration: An Evolutionary Relic?
  • In photorespiration
    – O₂ substitutes for CO₂ in the active site of the enzyme rubisco
    – The process consumes oxygen and releases CO₂
    – The photosynthetic rate is reduced

Adaptations to Hot, Arid Climates
  • Alternative mechanisms of carbon fixation have evolved in hot, arid climates
    – C₄ plants separate initial carbon fixation from the Calvin cycle in space
    – CAM plants separate initial carbon fixation from the Calvin cycle in time
Adaptations to Hot, Arid Climates

- **C4 plants (fig 10.21a)** - exhibit a spatial separation of C-fixation
  - Preface Calvin cycle with alternate mode of C-fixation that forms a 4-C compound (occurs in mesophyll cells) - Ex. Corn and sugarcane
  - Associated with unique leaf anatomy (Kranz anatomy, fig 10.19)
  - PEP carboxylase adds CO2 to PEP (phosphoenolpyruvate) → 4-C oxaloacetate → converted to malate → transported to bundle sheath cells → broken down to CO2 (Calvin cycle) + pyruvate (3-C goes back to mesophyll to regenerate PEP)
  - PEP carboxylase has a much higher affinity for CO2 than rubisco does, and no affinity for O2
- **CAM plants (fig 10.21b)** Ex. Succulents, cacti, pineapples, etc.
  - Crassulacean Acid Metabolism plants adapted to arid environments
  - Temporal separation of C-fixation: open stomata at night and close during day
  - Take up CO2 at night → oxaloacetate → malate → malic acid stored in vacuole during the day
  - ATP + NADPH synthesized during day → malic acid transported out of vacuole → malate → CO2 + pyruvate at night

C4 Plants

- C4 plants minimize the cost of photorespiration
  - By incorporating CO2 into four carbon compounds in mesophyll cells
- These four carbon compounds
  - Are exported to bundle sheath cells, where they release CO2 used in the Calvin cycle
C₄ leaf anatomy and the C₄ pathway

- Separates initial carbon fixation from the Calvin cycle in space

Figure 10.10

CAM Plants

- CAM plants
  - Open their stomata at night, incorporating CO₂ into organic acids
  - During the day, the stomata close
    - And the CO₂ is released from the organic acids for use in the Calvin cycle
  - So they separate initial carbon fixation from the Calvin cycle in time.

CAM pathway is similar to the C₄ pathway

Figure 10.20
Importance of Photosynthesis

- About 50% of the organic material made by Ps is consumed as fuel for respiration in the plant body
- Not all plant cells make their own food → have to be supplied by Ps cells
- Two most important products we derive from plants come directly from Ps (what are they?)
- Fig 10.21 = nice overview of Ps

The Importance of Photosynthesis: A Review

- A review of photosynthesis

Two most important products of photosynthesis

- Organic compounds produced by photosynthesis
  - Provide the energy and building material for ecosystems
- Oxygen produced by photosynthesis
  - Provides an aerobic environment that allows for cellular respiration