Just Like the Guy From Krypton…
Photosynthesis

An Overview of Photosynthesis

- Most of the energy used by almost all living cells ultimately comes from the sun
  - plants, algae, and some bacteria capture the sunlight energy by a process called **photosynthesis**
  - only about 1% of the available energy in sunlight is captured

- Photosynthesis takes places in three stages

  1. capturing energy from sunlight
  2. using the captured energy to produce ATP and NADPH
  3. using the ATP and NADPH to make carbohydrates from CO_2 in the atmosphere

- The overall reaction for photosynthesis may be summarized by this equation

$$6\ CO_2 + 12\ H_2O + light \rightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$$

- The process of photosynthesis is divided into two types of reactions

  - **light-dependent** reactions
    - take place only in the presence of light and produce ATP and NADPH

  - **light-independent** reactions
    - do not need light to occur and result in the formation of organic molecules
    - more commonly known as the **Calvin cycle**

- All stages of photosynthesis take place in the chloroplast
  - the chloroplast contains internal membranes called **thylakoids**
  - the thylakoids are stacked together in columns called **grana**
  - the **stroma** is a semiliquid substance that surrounds the thylakloids

- The **photosystem** is the starting point of photosynthesis
  - it is a network of pigments in the membrane of the thylakoid
    - the primary pigment of a photosystem is **chlorophyll**
    - the pigments act as an antenna to capture energy from sunlight
    - individual chlorophyll pigments pass the captured energy between them

Journey into a leaf

Journey into a leaf

How Plants Capture Energy from Sunlight

- Light is comprised of packets of energy called **photons**
  - sunlight has photons of varying energy levels
    - the possible range of energy levels is represented by an **electromagnetic spectrum**
  - human eyes only perceive photons of intermediate energy levels
    - this range of the spectrum is known as **visible light**

Photons of different energy: the electromagnetic spectrum

- **Pigments** are molecules that absorb light energy
  - the main pigment in plants is chlorophyll
    - chlorophyll absorbs light at the end of the visible spectrum, mainly blue and red light
  - plants also contain other pigments, called **accessory pigments**, that absorb light levels that chlorophyll does not
    - these pigments give color to flowers, fruits, and vegetables
    - they are present in leaves too but masked by chlorophyll until the fall when the chlorophyll is broken down

Absorption spectra of chlorophylls and carotenoids

Organizing Pigments into Photosystems

- In plants, the light-dependent reactions occur within a complex of proteins and pigments called **photosystems**
  - light energy is first captured by any one of the chlorophyll pigments
  - the energy is passed along to other pigments until it reaches the **reaction center** chlorophyll molecule
  - the reaction center then releases an excited electron, which is then transferred to an electron acceptor
  - the excited electron that is lost is then replaced by an electron donor

How a photosystem works

- The light-dependent reactions in plants and algae use two photosystems
  - Photosystem II
    - captures a photon of light and releases an excited electron to the electron transport system (ETS)
      - the ETS then produces ATP
      - a molecule of water is split to replace the excited electron from the reaction center
  - Photosystem I
    - absorbs another photon of light and releases an excited electron to another ETS
      - the ETS produces NADPH
      - the electron from photosystem II replaces the electron from the reaction center

Plants use two photosystems

How Photosystems Convert Light to Chemical Energy

- Plants produce both ATP and NADPH by **non-cyclic photophosphorylation**
  - the excited electrons flow through both photosystems and end up in NADPH
  - high energy electrons generated by photosystem II are used to make ATP and then passed along to photosystem I to drive the production of NADPH

- Photosystem II
  - its reaction center consists of more than ten transmembrane proteins
  - this is surrounded by an **antenna complex** of pigments that funnel captured photons to the reaction center
  - the reaction center yields an excited electron to the primary electron acceptor
  - water is split to provide replacement electrons to the reaction center, resulting in the production of O_2

- The electron transport system (ETS) receives the excited electron from the electron acceptor
  - the ETS is comprised of proteins that are embedded in the thylakoid membrane
  - one of these proteins acts as a proton pump to move a proton from the stroma into the thylakoid space
  - at the end of the ETS, the electron is passed to the reaction center of photosystem I

- As a result of the proton pump of the ETS, a large concentration of protons builds up in the thylakoid space
  - the thylakoid membrane is impermeable to protons
  - protons can only re-enter the stroma by traveling through a protein channel called **ATP synthase**
    - the protons follow their concentration gradient in a process called **chemiosmosis**
    - as protons cross the ATP synthase, ADP is phosphorylated into ATP

Chemiosmosis in a chloroplast

- Photosystem I
  - its reaction center is comprised of a membrane complex of at least 13 protein subunits
  - this is surrounded by an **antenna complex** of pigments that funnel captured photons to the reaction center
  - the reaction center yields an excited electron to an electron to an ETS that in turn reduces $NADP^+$ into NADPH
    - because this removes a proton from the stroma, the production of NADP also aids in establishing the proton gradient for chemiosmosis to occur

The photosynthetic electron transport system

Building New Molecules

- Cells use the products of the light-dependent reactions to build organic molecules
  - ATP is needed to drive endergonic reactions
  - NADPH is needed to provide reducing power in the form of hydrogens

- The synthesis of new molecules employs the light-independent, or Calvin cycle, reactions
  - these reactions are also known as C_3 photosynthesis

- The Calvin cycle reactions occur in three stages

  1. Carbon fixation
     - carbon from CO2 in the air is attached to an organic molecule, RUBP

  2. Making sugars
     - the carbons are shuffled about through a series of reactions to make sugars

  3. Reforming RUBP
     - the remaining molecules are used to reform RUBP

How the Calvin cycle works

- The Calvin cycle must "turn" 6 times in order to form a new glucose molecule
  - only one carbon is added from CO_2 per turn

- The Calvin cycle also recycles reactants needed for the light-dependent reactions
  - it returns ADP so that it is available for chemiosmosis in photosystem II
  - it returns NADP+ back to the ETS of photosystem I

Reactions of the Calvin cycle

Photorespiration: Putting the Brakes on Photosynthesis

- Many plants have trouble carrying out C_3 photosynthesis when it is hot
  - plants close openings in their leaves, called **stomata** (singular, **stoma**), in order to prevent water loss
  - the closed stoma also prevent gas exchange
  - O_2 levels build up inside the leaves while the concentrations of CO_2 fall
    - the enzyme rubisco in the Calvin cycle fixes oxygen to RUBP instead of carbon
    - this process is called **photorespiration** and short-circuits photosynthesis

Plant response to hot weather

- Some plants have adapted to hot climates by performing **C_4 photosynthesis**
  - these C_4 plants include plants, such as sugarcane, corn, and many grasses
  - they fix carbon using different types of cells and reactions than C_3 plants and do

not run out of CO_2 even in hot weather

- CO_2 becomes trapped in cells called **bundle-sheath cells**

Carbon fixation in C_4 plants

- Another strategy to avoid a reduction in photosynthesis in hot weather occurs in many succulent (water-storing) plants, such as cacti and pineapples
  - these plants undergo **crassulacean acid metabolism (CAM)**
    - photosynthesis occurs via the C_4 pathway at night and the C_3 pathway during the day

Comparing carbon fixation in C_4 and CAM plants