PLANT PHYSIOLOGY
Light Reaction: Basic Process

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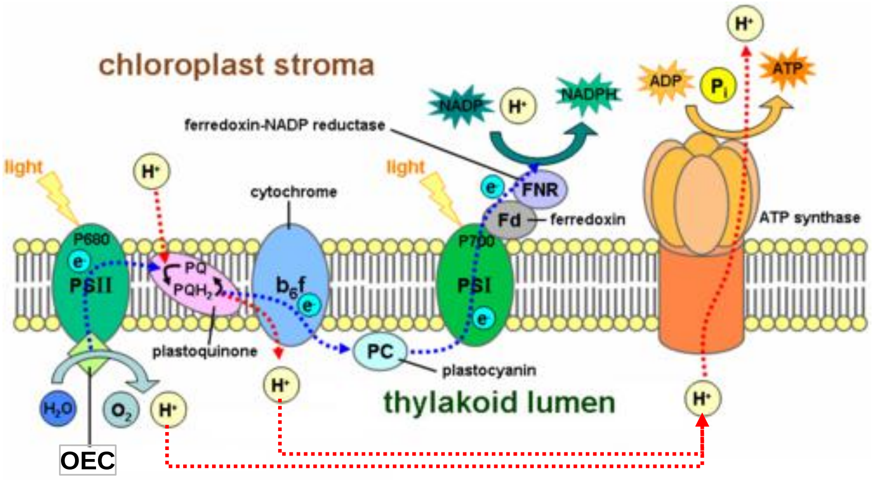


Reaksi cahaya fotosintesis adalah proses konversi energy radiasi cahaya atau radiasi matahari pada kondisi alami menjado energy kimia (NADPH dan ATP). Ini melibatkan sejumlah komponen dan rangkaian reaksi pada membrane thylakoid yang terjadi dalam khloroplast.

LECTURE OUTCOMES

After the completion of this lecture and mastering the lecture materials, students should be able to

1. Explain the characteristics of light as a source of energy in the process of photosynthesis
2. Calculate the quantity of solar radiation at the top of earth's atmosphere
3. Explain the process of NADPH formation in the conversion of radiation energy to be chemical energy
4. Explain the process of ATP formation in the conversion of radiation energy to be chemical energy

LECTURE OUTLINE

1. INTRODUCTION
1.1 Importance of Photosynthesis
1.2 Definition

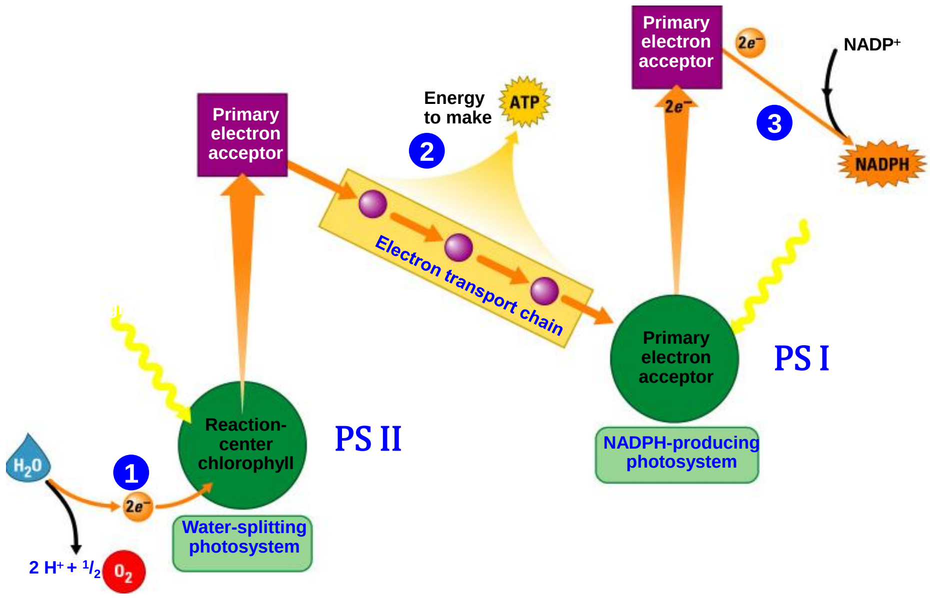
2. SOLAR RADIATION
2.1 Sun Temperature
2.2 Electromagnetic Radiation
2.3 Stefan-Boltzmann Law
2.4 Inverse Square Law
2.5 Wave Theory of Light
2.6 Quantum Theory of Light
2.7 Plank's Theory

3. PHOTOSYNTHESIS
3.1 Introduction
3.2 Photosynthesis Site
3.3 Photosyntheic Pigments
3.4 Light Absorption by Pigments

1. INTRODUCTION

- **Importance of Photosynthesis**
  1. Photosynthesis is central to all life on earth, providing not only oxygen but also organic compounds that are synthesized from atmospheric CO_2 and water using light energy as the driving force (Flügge et al., 2016).
  2. Almost all forms of life today depend on the ability of photosynthetic oxygenic organisms to convert light energy into chemical energy and to produce molecular oxygen (Caffarri *et al*., 2014).
  3. Photosynthetic organisms convert more than 10^9 metric tons of atmospheric CO_2 into biomass per year (Flügge *et al*., 2016).

- **Definition**
  1. The process of converting **solar energy** into **chemical energy**.
  2. The process of CO_2 reduction into carbohydrates (sugars) at the expense of **NADPH & ATP**.



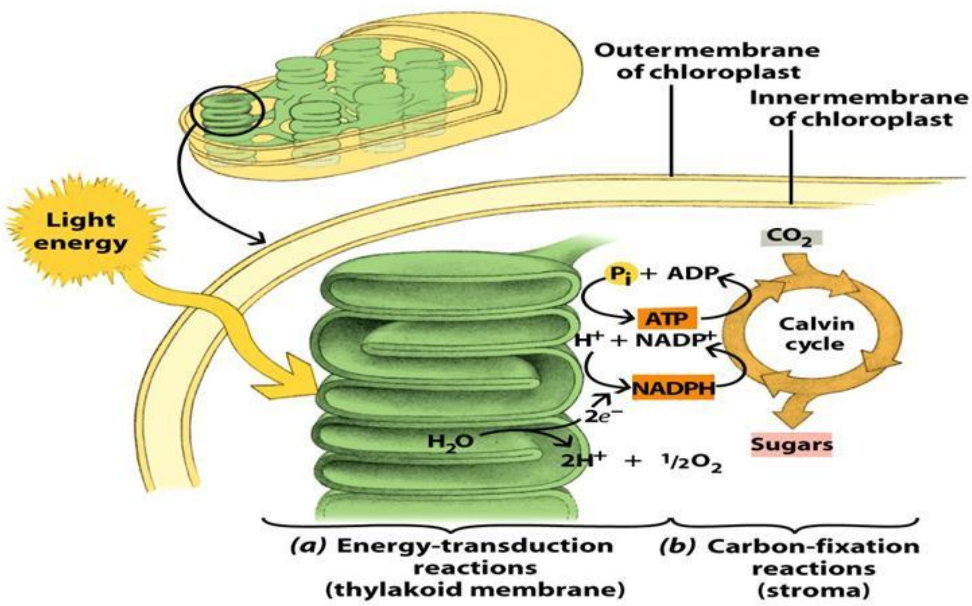


Figure 7-9
Biology of Plants, Seventh Edition
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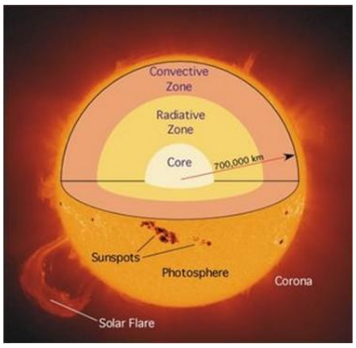
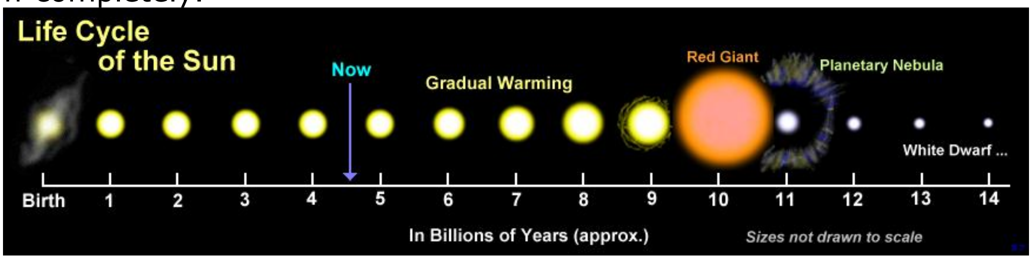
2. SOLAR RADIATION

- ## Sun Temperature

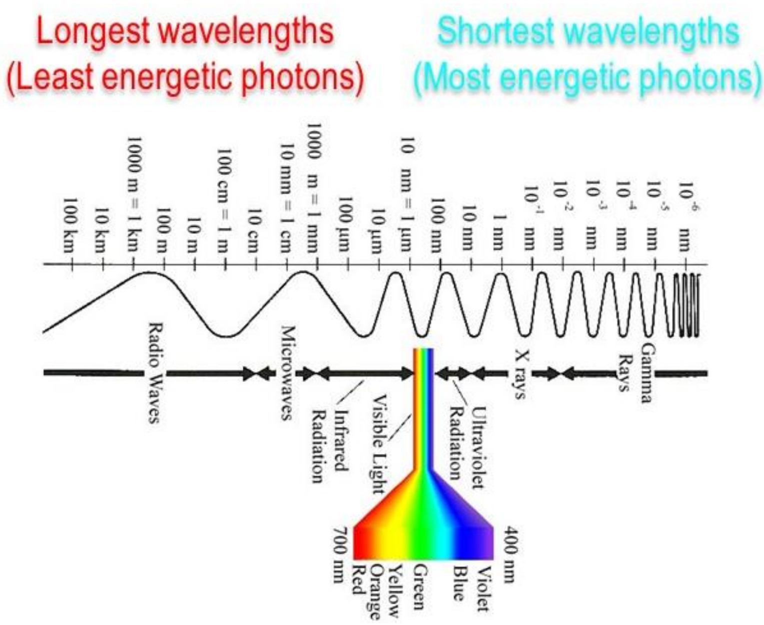


1. Solar energy is the ultimate source of energy for life on earth.
2. Solar energy is created at the core of the sun when hydrogen atoms are fused into helium by nuclear fusion.
3. Temperatures of the sun are
   - about 15,000,000^{0}K at the core, and
   - about 5,800^{0}K at the photosphere (radiative surface of the sun)
4. The Sun appears to have been active for 4.6 billion years and has enough fuel to go on for another five billion years (5.10^9 years) or so.
5. At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up, ultimately growing so large that it will swallow the Earth.
6. After a billion years as a red giant, it will suddenly collapse into a white dwarf -- the final end product of a star like ours. It may take a trillion years to cool off completely.



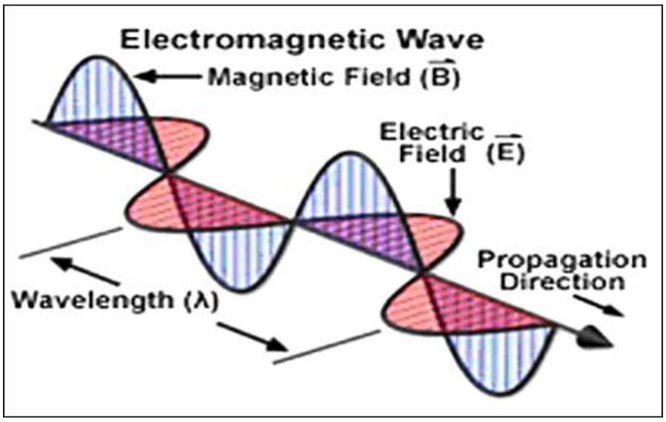
- ## Electromagnetic Radiation

1. The solar energy is transmitted in the form of **electromagnetic radiation**.
   - **Electromagnetic radiation** is a kind of radiation including visible light, radio waves, gamma rays, and X-rays, in which electric and magnetic fields vary simultaneously.



Gambar 1. The Electromagnetic Spectrum

2. **Radiation** is the transfer of energy through some material or through space in the form of *electromagnetic waves*.
3. **Electromagnetic waves** are the self-propagating, mutual oscillation of electric and magnetic fields.
4. Electromagnetic waves move electromagnetic energy through space (either empty or filled with transparent matter).
5. Most of the electromagnetic radiation emitted from the sun's surface lies in the visible band centered at 500 nm.



- **Stefan–Boltzmann Law**
1. This law states that the power emitted per unit area of the surface of a black body is directly proportional to the fourth power of its absolute temperature. That is

$$R=\varepsilon\sigma T^4$$

Where
R = radiation flux ($W.m^{-2} = J.m^{-2}.s^{-1}$)
ε = emissivity ($0 \le \varepsilon \le 1$)
σ = Stefan-Boltzmann constant (5,67032 x 10^{-8} $W.m^{-2}.K^{-4}$)
T = absolute temperture (273 + ^{0}C).

2. Apply Stefan-Boltzmann Law To Sun and Earth
$R=\varepsilon\sigma T^4$

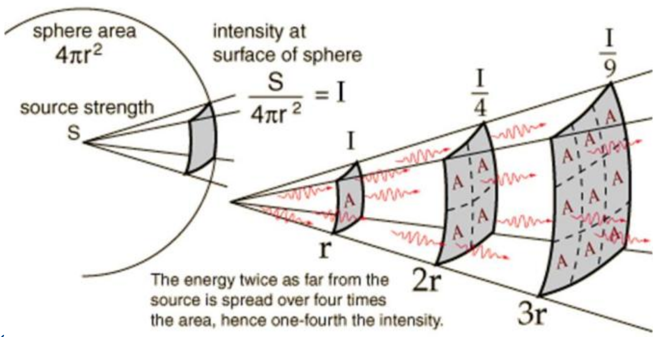
Sun (5800 ^{0}K)
R_S = (5.67 x 10^{-8} W/m^2 K^4) * (5800 ^{0}K)^4
= **64,164,532** W/m^2

Earth (300 ^{0}K)
R_E = (5.67 x 10^{-8} W/m^2 K^4) * (300 ^{0}K)^4
= 459 W/m^2

Sun emits about 160,000 times more radiation per unit area than the Earth because Sun's temperature is about 20 times higher than Earth's temperature→ 6000/300 = 20

- **Inverse Square Law**
1. The amount of radiation passing through a specific area is inversely proportional to the square of the distance of that area from the energy source.

$$I = E(4\pi R^2)/(4\pi r^2)$$



I = Irradiance at the surface of the outer sphere
E = Irradiance at the surface of the object (Sun)
R = 6.96×10^5 km (Radius of the Sun)
r = 1.5×10^8 km (Average Sun-Earth Distance)
I = 64,164,532 W/m^2 x$(6.96 \times 10^5)^2/(1.5 \times 10^8)^2$
I = 1382 W/m² (The generally accepted solar constant of **1368 W/m²** is a satellite measured yearly average)

2. Radiation emitted by a human body
- The net power radiated is the difference between the power emitted (P_{emit}) and the power absorbed (P_{abs}):

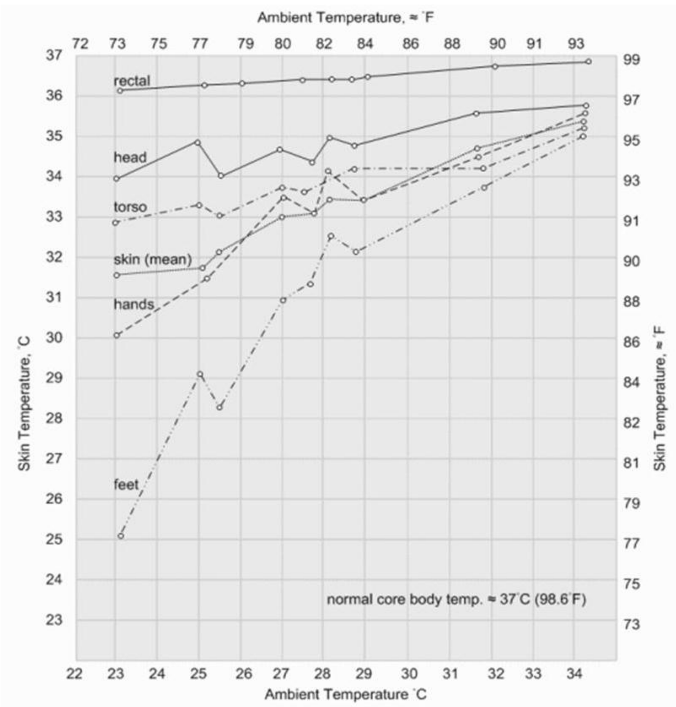
$$P_{net} = P_{emit} - P_{abs}$$

- Applying the Stefan–Boltzmann law,

$$R = \varepsilon\sigma A(T^4 - T_0^4)$$

A = the total surface area of an adult is about 2 m²,
ε = the mid- and far-infrared emissivity of skin and most clothing is near unity, as it is for most nonmetallic surfaces.
T = skin temperature is about 33°C, but clothing reduces the surface temperature to about 28 °C when the ambient temperature is 20 °C (T_0)
- Hence, the net radiative heat loss with $\varepsilon = 0.97$ and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is about

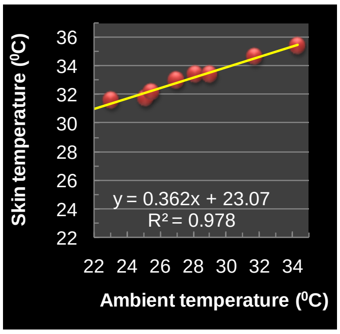
- $P_{emit} = \varepsilon\sigma A(T^4 - T_0^4) = 0.97 * 5.67 \times 10^{-8}$ W m^{-2} K^{-4} $*2$ m$^2(273^4 + 28^4)$
  = **902.92 W.m^{-2} or J.s^{-1}**
- $P_{abs} = \varepsilon\sigma A(T^4 - T_0^4) = 0.97 * 5.67 \times 10^{-8}$ W m^{-2} K^{-4} $*2$ m$^2(273^4 + 20^4)$
  = **810.69 W.m^{-2} or J.s^{-1}**
- **P_{net} = 902.92-810.69 = 92.23** J.s^{-1}
  = 92.23 x 24 hours x 60 minutes x 60 seconds = 7,968,672 J/day = **7.97 MJ/day**

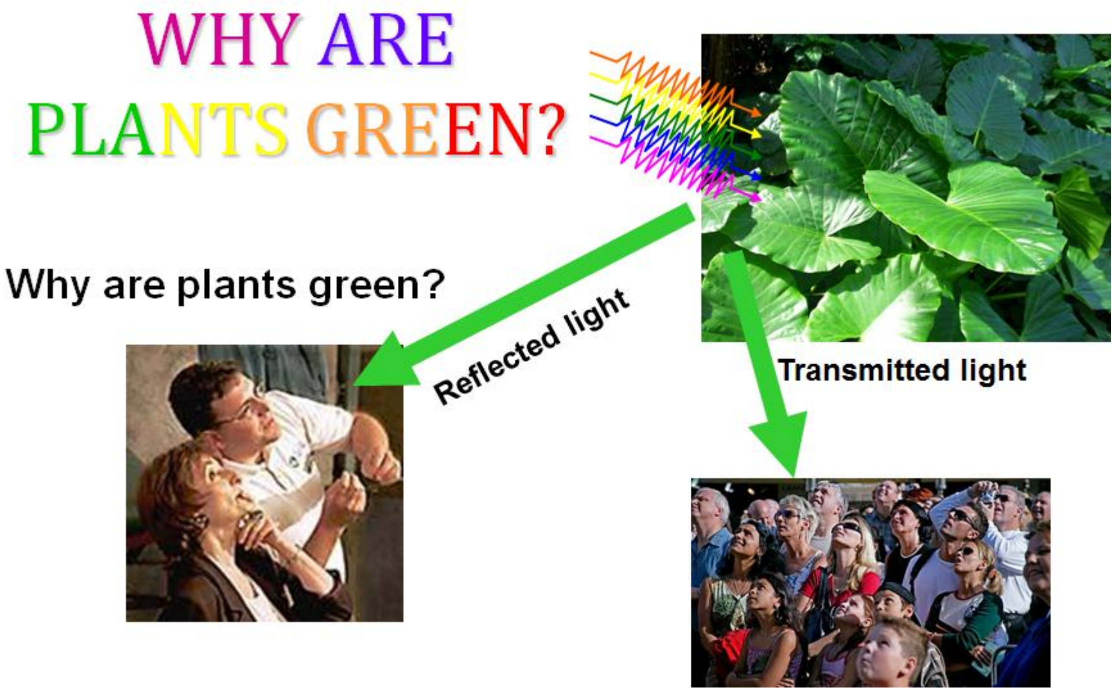


Skin temperatures on different parts of a nude person measured at different ambient temperatures
Adapted from: Olesen, B.W., 1982, Thermal Comfort, Technical Review, Bruel & Kjaer

Skin temperature and ambient temperature

- The air temperature in Malang, on average, is 27^{0}C
- What is the temperature of the skin?
- How much is the net radiative heat loss?

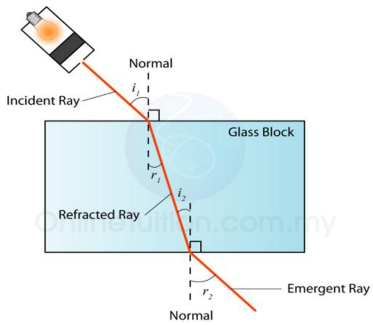




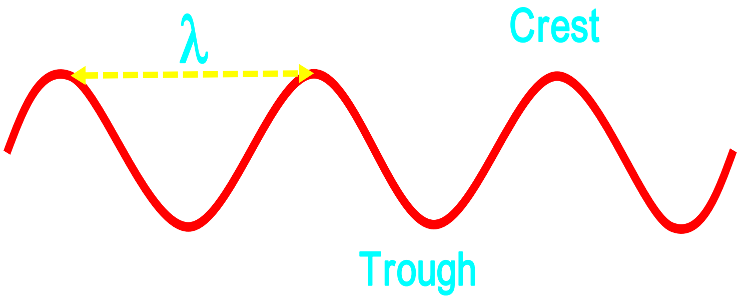
- **Wave Theory of Light**

  What is light?

  1. A simple way to answer is to say that light is a type of wave that causes objects to be visible to human eyes.
  2. The **wave theory of light** was the way we first understood light. The theory was spread most significantly by Robert Hooke and Christiaan Huygens in the 17th Century.
  3. If light was a wave, we would see
     - certain things
     - that light could reflect off shiny surfaces
     - **refract** (or bend) when moving from one material into another, and
     - **diffract** (or spread) around objects or when moving through slits.



  4. Light as a wave is characterized by
     - **Wavelength** (λ) – the distance between crests (or troughs) of a wave
     - **Frequency** (**v**) – the number of crests (or troughs) that pass by each second.
     - **Speed** (**c**) – the rate at which a crest (or trough) moves (3.10^5 km/s).



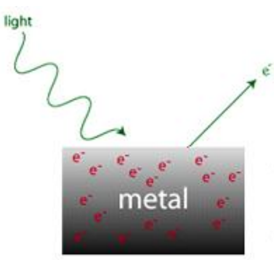
5. Maxwell calculated the speed of propagation of electromagnetic waves and found:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = \frac{1}{\sqrt{(8.85 \times 10^{-12}\,\mathrm{C^2/N\cdot m^2})(4\pi \times 10^{-7}\,\mathrm{N\cdot s^2/C^2})}}$$
$$= 3.00 \times 10^8\ \mathrm{m/s}$$

This is the speed of light in a vacuum.

- **Quantum Theory**
  1. By the 1900's **the wave model** was accepted by scientist as how light moved.
  2. The wave theory, however, could not explain several physical phenomena observed in beginning of the 20th century that led to the development of **Quantum theory of light**.
     - The wave theory was unable to explain *light until further heating, then it will glow red, yellow then "white" hot.*
     - *It also did not explain colors given off by various elements as they burn*.

  3. **Light as particles**
     - Light comes in quanta of energy called **photons** – **little bullets** of energy.
     - **A photon** is a type of elementary particle, the quantum of the electromagnetic field including electromagnetic radiation such as light.
  4. This idea of **light as particles** is supported by the well-known experiment – **Photoelectric effect**.
     - The **photoelectric effect** is the emission of electrons when light is shone onto a material. Electrons emitted in this manner can be called photo electrons.



Light is shown on a metal and after a certain binding energy is overcome, an electron is emitted from the metal.

- **Planck's Theory**
  1. Energy cannot be absorbed or emitted unless it is a complete packet.
  2. Planck's theory states that atoms can only absorb or release energy in fixed quantum units.

3. The amounts of energy an object emits or absorbs are called *quantum* (*quanta* plural).
4. Related the Frequency of the radiation to the amount of energy.
   $E = hv = hc/\lambda$

   Frequency (v) = c/λ
   h = 6.6262×10^{-34} J-s (joule-seconds)
   c = speed of light (3×10^{8} m/s)

Visible radiation: visible to our eyes (wavelength :0.4×10^{-6} - 0.7×10^{-6} m)
Red = 0.65 mm, Orange = 0.60 mm, Yellow = 0.55 mm, Green = 0.50 mm, Blue = 0.45 mm & Violet = 0.40 mm

Cahaya dan PAR

- Tanaman dalam proses fotosintesis hanya dapat memanfaatkan pancaran radiasi matahari yang terletak pada batas panjang gelombang 400 - 700 nm
- Radiasi pada batas panjang gelombang 400 - 700 nm disebut PAR (photosynthetically active radiation) atau cahaya nampak (visible radiation)

Dengan memasukkan harga-harga konstanta, maka

$$E = \frac{6.626 10^{-34}\,Js\, 3.10^{17}\,nms^{-1}}{\lambda} \quad E = \frac{19{,}878.10^{-17}\,J}{\lambda}$$

dimana λ dalam satuan nano meter (nm)

- Sebagai contoh, kandungan energi 1 photon cahaya merah (λ = 680 nm) adalah

$$E = \frac{19{,}878.10^{-17}\,J}{680} = 29{,}232.10^{-20}\,J$$

- 1 J (Joule) = 10^{7} erg; 1 c (cal) = 4,2 J; 1 eV = $1{,}6.10^{-12}$ erg

$$E = \frac{N_A.h.c}{\lambda}$$

where

- **N_A** is Avogadro's number (= 6.02×10^{23} photons/mol)
- **h** is Planck's constant (= 6.62×10^{-34}J s per photon)
- **c** is the speed of light (= 3×10^{8} m.s^{-1}).

- For instance, the energy of "green light" (= 550 nm) is:

$$E = \frac{(N_A = 6.02.10^{23}\,photons/mol)(h = 6.02.10^{-34}\,J.s/photon)(c = 3.10^{8}\,m/s)}{\lambda = 550.10^{-9}\,m}$$

E = 217376.7 J = 0.2173767 MJ

a mol of blue light (l = 400 nm) = 298893.0 J
a mol of red light (l = 700 nm) = 170796.0 J

Summary of Photons

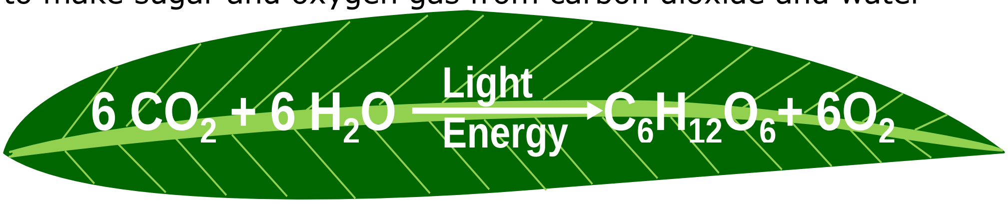
1. Photons can be treated as "*packets of light*" which behave as a particle.
2. To describe interactions of light with matter, one generally has to appeal to the particle (quantum) description of light
3. A single photon has an energy given by
   E = hc/λ

   where
   h = Planck's constant = 6.6×10^{-34} [J s]
   c = speed of light = 3×10^{8} [m/s]
   λ = wavelength of the light (in [m])

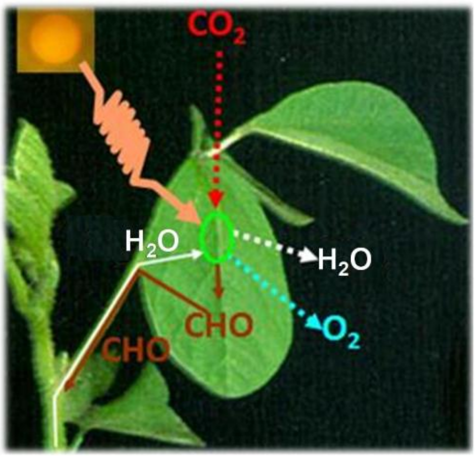
4. Photons also carry momentum. The momentum is related to the energy by:
   p = E/*c* = h/λ

3. PHOTOSYNTHESIS

- **Introduction**
  1. Photosynthesis is the process by which autotrophic organisms use light energy to make sugar and oxygen gas from carbon dioxide and water

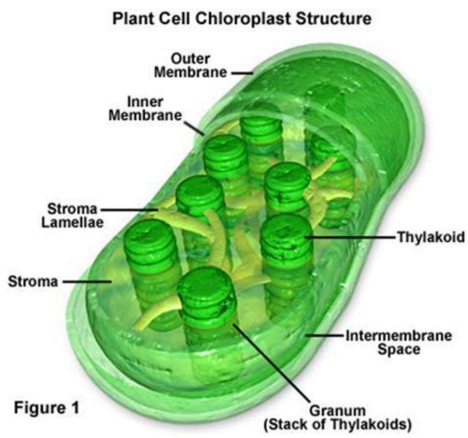


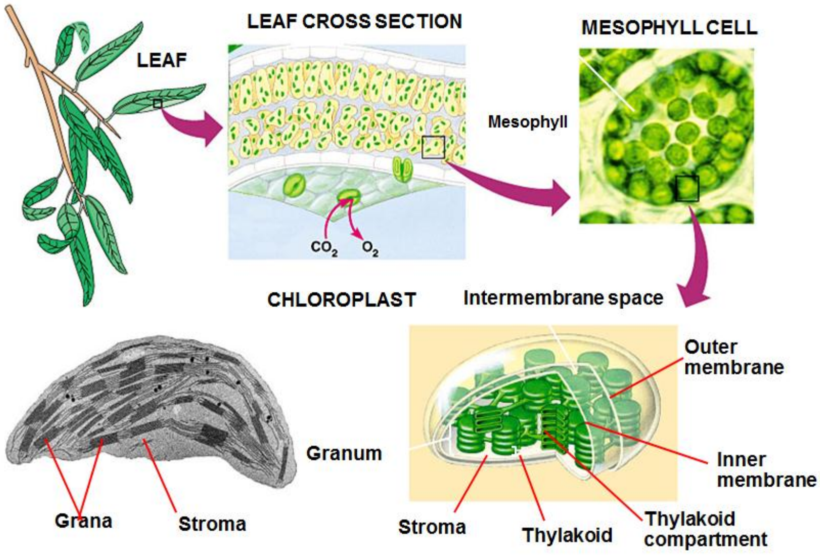
  2. This is an over simplification approach as H_2O never meets CO_2 directly in the photosynthesis.
  3. The reduction of CO_2 to be carbohydrate through photosynthesis requires energy (NADPH & ATP)
  4. Photosynthesis can be divided into two reactions
     - Light Reaction
       - Generation of $NADPH_2$
       - Generation of ATP
     - Dark Reaction
       - Diffusion of CO_2
       - Reduction of CO_2 (C3, C4 & CAM)
  5. Light Reaction Events
     a. Light Absorption
     b. Pigments
     c. Electron Excitation
        - **Fluorescence**
        - **Phosphorescence**
     d. Electron transfer & Synthesis NADPH
     e. Proton exchange & Synthesis ATP



- **Photosynthesis Site**
  1. Although all the green parts of a plant can carry out *photosynthesis*, it mainly occurs in the leaves due to the high abundance of chloroplasts.

2. In most plants, photosynthesis occurs primarily in the leaves, in the chloroplasts
   - The leaves have the most chloroplasts
   - The green color comes from chlorophyll in the chloroplasts
   - The pigments absorb light energy
3. A chloroplast contains:
   - Stroma (a fluid)
   - Grana (stacks of thylakoids)
4. The thylakoids contain chlorophyll
   - Chlorophyll is the green pigment that captures light for photosynthesis

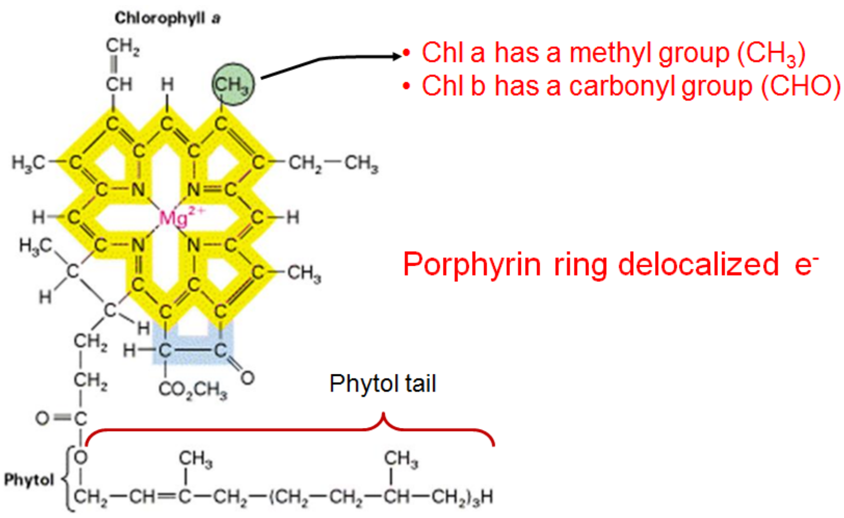


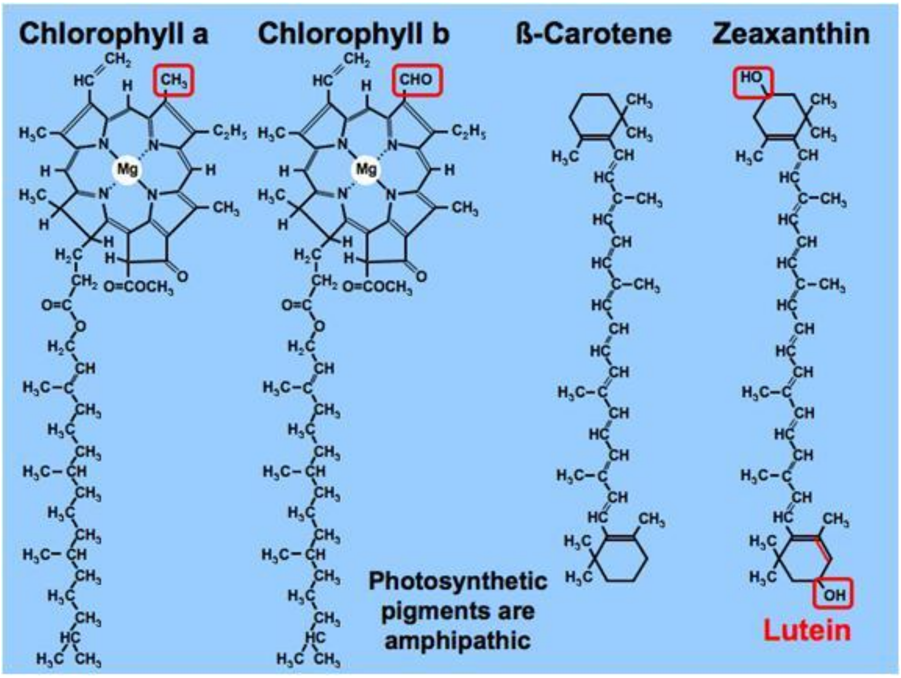


The location and structure of chloroplasts

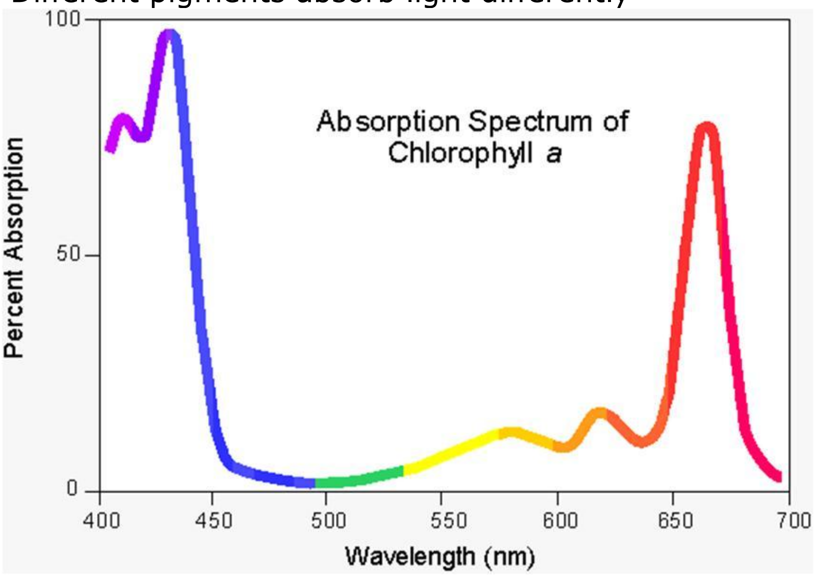
Photosynthetic Pigments

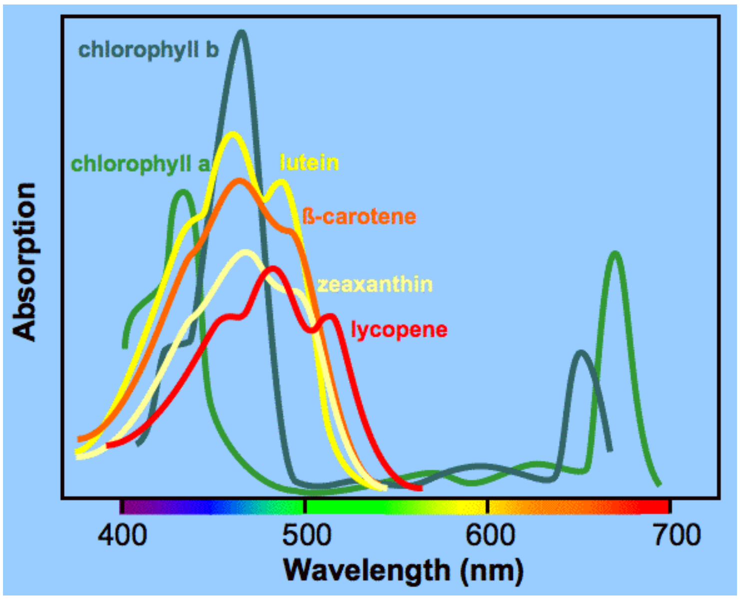
1. Pigments are "molecules that absorb specific wavelengths (energies) of light and reflect all others.
2. Photosynthetic pigments are associated with the thylakoid membranes.
3. Photosynthetic pigments (in order of increasing polarity):
   - Carotene - an orange pigment
   - Xanthophyll - a yellow pigment
   - Phaeophytin *a* - a gray-brown pigment
   - Phaeophytin *b* - a yellow-brown pigment
   - **Chlorophyll *a* - a blue-green pigment**
   - Chlorophyll *b* - a yellow-green pigment
   - Chlorophyll *c* (in some algae)
4. Chlorophyll *a* is the most common of the six, present in every plant that performs photosynthesis





- **Light Absorption of Pigments**
  1. Different pigments absorb light differently





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