Light

Light is part of the electromagnetic spectrum

Light is a electromagnetic wave. This wave has a wavelength that can be measured in meters. Of course light waves are very small. Shown below is a chart showing the relationship between the length of the light wave in nanometers as a function of the color of light we humans are able to observe. It turns out that plants respond to these wavelengths (and more!).

Light is the driving force, the energy for photosynthesis. Light is just one part of the electromagnetic spectrum. A wide range of of the spectrum is shown below. You will notice that wavelengths shorter than visible light include gamma rays, x-rays, and ultraviolet light. Waves longer than visible light include infrared, microwaves and radio waves. You should also notice that shorter waves have higher energy than longer waves. This is why waves shorter than we can see are damaging to our cells and our DNA. We can live with essentially no ill effects from waves longer than visible light.
Starlight is the solar power of the earth

All biological energy comes from sunlight and this energy encompasses the range of the electromagnetic spectrum known as light. The solar spectrum is shown below.
If you remember that visible light covers the range of wavelengths from 400 to 700 nm, then you can see here that sunlight includes waves that are ultraviolet (280 to 400 nm) and waves that are infrared (greater than 700 nm). Fortunately you can see that the difference between curve A and B is maximized in the ultraviolet; we can thank ozone for the sunscreen! The infrared wavelengths are abundant and represent the bulk of solar energy; these provide the heat that keeps us warm and gives us summers. Also shown is the absorption spectrum for chlorophyll. This curve indicates the wavelengths that efficiently drive the photosynthetic reactions.

**Chlorophyll absorbs blue and red light**

The green pigment, chlorophyll, plays a central role in photosynthesis. The fact that it is green means that it absorbs blue and red light and reflects green when it is illuminated by white (all wavelengths) light. The absorption spectrum you saw before for chlorophyll, is turned sideways below.
It shows two absorption maxima in the blue and red portions in the spectrum. Next to this, is an energy diagram that shows how an electron can be elevated to a higher energy level in the electron cloud of chlorophyll by absorbing a high energy photon. Blue is at the high-energy end of the spectrum, so light of this wavelength is responsible for this much excitation and explains the absorption peak in the blue. Red wavelengths are lower in energy and only boost the electron to a lower energy level than can blue light. This stable excitation state is responsible for the red absorption peak.

**Excited electrons can fluoresce**

You can also see in the figure above, that when an electron is in the lower excited state, it can drop back to the ground state and the energy lost can be re-emitted as a photon of light in a process known as fluorescence. This light is, of course at a lower energy level, thanks to the second law of thermodynamics. That means of course that the re-emitted photon is of a longer wavelength. Chlorophyll fluoresces at a deep-wine-red color at the limit of human vision. Please note, of course, that in an intact chloroplast the energy is seldom re-emitted; instead the energy and the excited electron are stripped from chlorophyll. They are taken from chlorophyll and sent through an electron transfer system. The energy is ultimately trapped in a phosphate bond in ATP (photophosphorylation) and in an energy rich molecule known as NADPH. We shall see more of that below.
Chlorophyll structure explains its functions

Chlorophyll structure reveals the mechanism of its absorption of light, the excitation of its electrons, and its ability to give electrons off to an electron transfer system:

The tetrapyrrole ring system is a hydrophilic portion. It chelates a magnesium ion which, like most metal ions, has a large cloud of electrons to which it can add to or lose electrons without much problem...just a charge change. The tetrapyrrole ring system that chelates this magnesium shows a system of conjugated double bonds that expands the electron cloud by resonance of the conjugated bonds. These bonds also provide the light absorption features of the chlorophyll molecule that give it the green color. The difference in one ring distinguishes chlorophyll a (a reaction center pigment) from chlorophyll b (an antenna pigment). The structural similarity of these molecules to bacteriochlorophyll indicates the prokaryotic origin of chlorophyll and is further evidence for the endosymbiont theory for the origin of chloroplasts.

The long phytol tail of chlorophyll is hydrophobic and the resulting amphipathic nature of the complete molecule allows it to integrate into membranes and hydrophobic domains of membrane proteins.
**Chlorophyll is not the only photosynthetic pigment**

While chlorophyll a plays a very important role in photosynthesis, plants have additional pigments that participate in photosynthesis. These are indeed called **antenna pigments**. For true plants, which taxonomists are generally defining as green algae, bryophytes, ferns, and seed plants, the pigments for photosynthesis are chlorophylls a and b, carotenoids, and xanthophylls. In the figure above you can see that the structures of β-carotene, zeaxanthin, and lutein are also hydrophobic and thus integrate into chloroplast photosystems. These pigments are apomorphies...cyanobacteria used phycobilin pigments instead.

**Antenna pigments enhance photosynthetic efficiency**

As you can see above, β-carotene and the two xanthophylls also have conjugated double bonds and rings at either end, this gives the molecules the ability to absorb light. These are yellow-orange pigments and they absorb light in the blue and green areas of the visible spectrum.

![The photosynthetic pigments absorb much of the spectrum](image)

What is worth noting here is how these pigments complement the absorption of light by chlorophyll. This means that plants with these antenna pigments can use light of wavelengths that do not excite chlorophyll. The energy absorbed by those pigments is passed to chlorophyll and used in photosynthesis:
You can see how light energy absorbed by antenna pigment molecules (chlorophyll b, β-carotene, etc.) is transferred ultimately to a chlorophyll a reaction center pigment to drive photosynthesis. This fact is verified by the quantum efficiency of photosynthesis...
Light waves have amplitude

Light waves have crests and valleys of a particular height or amplitude. This parameter of waves is perceived as brightness or intensity. There are a range of units for this parameter, both English and Metric...depending on the source, the surface, or the passage. But below is a comparison of amplitudes based on the English unit, the foot-candle. It is the light produced by a candle as measured one-foot from the flame...not too "scientific" but it does have some fun powers-of-ten relationships that make it memorable.
In laboratory, we will use metric units for measuring light intensity. But before we leave English units, I'd like you to understand the relationship between light intensity and photosynthesis and respiration (see below). Obviously respiration does not respond to light so its curve is completely flat. Photosynthesis increases as you increase the light intensity from darkness. Where these two curves intersect, the rate of photosynthesis, measured as oxygen produced, matches the rate of respiration, measured as oxygen consumed. (Obviously one could measure the reactions by carbon dioxide or sugar, etc.)

**Light: An Energy Waveform With Particle Properties Too**

Many metric units for different purposes  
We will use an easy-to-remember English unit: foot-candle

- 0 fc = darkness
- 100 fc = living room
- 1,000 fc = CT winter day
- 10,000 fc = June 21, noon, equator, 0 humidity
The light intensity (in whatever units used) where these curves intersect is called the **compensation point**. When plants are kept at intensities above the compensation point, they are doing photosynthesis faster than they are using up the products in respiration. So at these higher intensities, the plant can add to its reserves, can grow, or can reproduce. However, whenever a plant is at intensities below the compensation point, it is burning up photosynthate faster than it is being produced. Kept here for any length of time it will be using up its reserves, and may even die. In the graph above, the plant has a compensation point that is below that found in most rooms of a house; such a plant is likely a potential houseplant. Ferns and African violets may be among these.

Not every plant has the same compensation point, as you might expect! Indeed in the figure below, two plant responses to light intensity are shown. The assumption made in the figure is that the rate of respiration in both plant A and plant B are the same (this may not be a valid assumption!). You will notice that plant B is far less efficient in photosynthesis; it takes much more light to reach its compensation point. Plant B is likely a crop plant such as corn or soybeans; they would never make it as houseplants. You might also notice how houseplants "burn up" (their photosystems bleach out!) when exposed to extremely high light intensity.
Light also has particle properties: photons

The light wave passes a point much like a particle. These "packets" of light are called photons. In fact in plant physiology we usually measure light intensity as photon flux density (PFD) measured in units of photons m$^{-2}$ s$^{-1}$.

If photosynthesis were to be completely efficient, the production of an oxygen molecule in photosynthesis theoretically requires just four protons and four electrons. However, in actual measurements, the quantum efficiency observed is about 10 photons per oxygen molecule. This is shown in the classic (1932) quantum efficiency plot of Emerson and Arnold:
This plot also shows that up to 2500 chlorophyll molecules can be involved in producing this oxygen molecule. At the time of Emerson, this seemed troubling but now we know that the light harvesting complex for the two photosystems each contain a few hundred chlorophylls, and they both must operate four times to make the oxygen molecule. A quick calculation reveals that Emerson's figures were very close to the mark (300 x 2 x 4 = 2400)! The quantum yield is the slope on this curve and this works out to 10 photons needed to make one molecule of oxygen.

**A wide range of wavelengths drive photosynthesis**

Emerson went on to study the effect of wavelength on photosynthesis. This kind of plot is sometimes called an "action spectrum", it shows how effectively various wavelengths drive photosynthesis. Superimposed on this plot we see the quantum yield as a function of wavelength of the photons. In both sets of curves, you can see that photons of green wavelength are less efficient than those in blue and red wavelengths. Photons with wavelength beyond 700 lack sufficient energy to drive photosynthesis! Recall that blue wavelengths have higher energy than red wavelengths. This fact tells us that whatever pigments are involved in photosynthesis, they apparently have a minimum energy required to excite an electron that is found in a red photon.
You can see that all but a few wavelengths between 500 and 575 nm are fairly effective for photosynthesis. The lower yield for the 500-575 nm (green) range of the spectrum explains the green color of plants. These wavelengths are reflected and transmitted rather than being as effective in driving the process. The absorption spectrum shown is for a chloroplast, obviously antenna pigments are at work here. What is critical to notice is the huge drop in efficiency at 700 nm; this is known as the "red drop" effect. Wavelengths beyond 700 nm are apparently of insufficient energy to drive any part of photosynthesis. Obviously some wavelengths cannot drive photosynthesis.

**Red and Far-Red Light are Synergistic**

Emerson also tried combining wavelengths and observed that red light (680 nm) could drive a certain amount of photosynthesis; far-red light (700 nm) could drive a similar amount. When the two colors of light were combined, the amount of photosynthesis yield was greater than the sum of the individual color yields:
This was called the Emerson enhancement effect and was the first good evidence that there were two photosystems, that one absorbed red light and the other absorbed far-red light, and that they both must operate to drive photosynthesis most effectively.

The Light Reactions are an Energy Transfer system

Using the information of Emerson, and further evidence since then, the basic photosystems for photosynthesis can be diagrammed. The need for two systems is explained when the system's energy is plotted on a vertical redox potential axis. Redox potentials that are oxidizing are at the bottom and those that are reducing are at the top. The light reactions of photosynthesis have often been sketched in the form of what is often called the Z scheme. I know it looks more like an N scheme...and here we emphasize the pigments and the light. In this particular sketch, the electron transfer system in the middle of the diagram has been omitted (more on that later!).
I really cannot tell you why we still call it a Z scheme when it looks like an N in most diagrams (as in the one above)...except that it was originally drawn sideways. What you should notice for now, is that the red-driven (680 nm) photosystem (PSII) and the far-red-driven (700 nm) photosystem (PSI) cooperate to transfer electrons from the photolysis of water to a B-vitamin known as NADP⁺.

Thinking of this system, you can see that an electron is excited by light energy absorption in a P680 chlorophyll, a reaction center pigment in PSII. This electron is passed through an electron transfer to PSI. The electron lost is replaced by the photolysis of water. This reaction is sometimes called the Hill reaction in honor of Robin Hill who studied it. Photolysis of water is the source of the oxygen produced in photosynthesis. The electron that left PSII and passed through the electron transfer system replaces an electron that is lost by PSI after it is excited by 700 nm light energy. This electron is ultimately trapped with an accompanying proton onto NADP⁺, a high-energy vitamin B molecule. You should also notice that PSI is not a strong enough oxidant to draw electrons from photolysis of water, and that the energized PSII is not a strong enough reductant to donate electrons to NADP⁺. Thus, **both** photosystems are needed to both oxidize water and to reduce NADP⁺...this explains why Emerson observed the (red/far-red) enhancement effect.