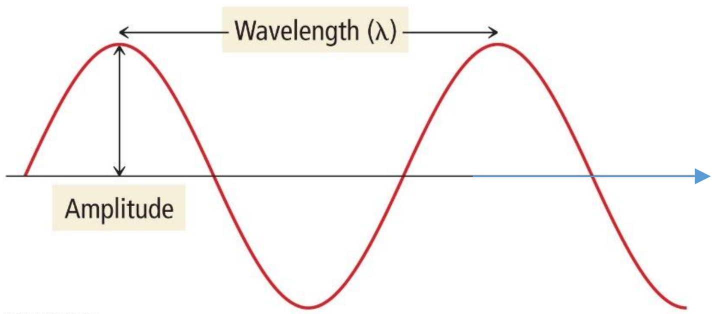
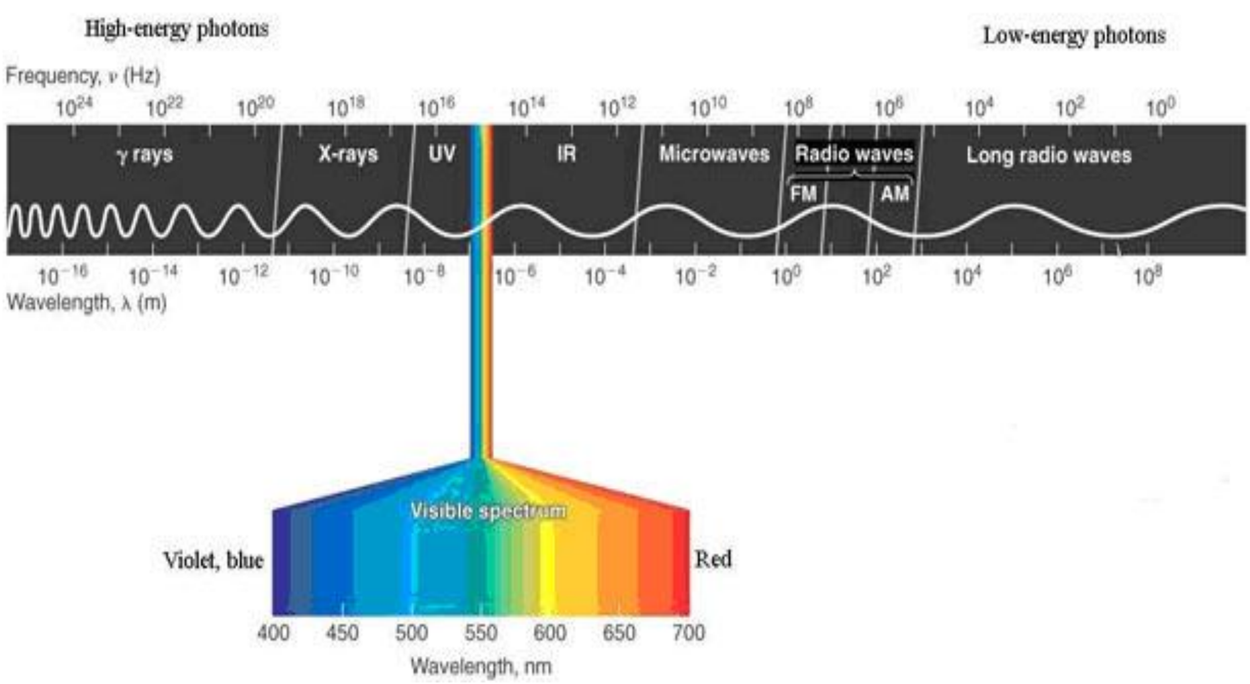
Unit 4: Light and Solar Energy

4.1. The Nature of Light

During our study of atomic structure in chemistry, we learn that light is yet another form of energy. As a model, we think of light as a wave of *electromagnetic radiation* (composed of both an electric field and a magnetic field) traveling through space at a velocity, *c* (the "speed of light"**)** of approximately 3.00 x 10^8 m/s. As shown in the figure below, a light wave may be characterized by its *amplitude*, which corresponds to the intensity of the light – how bright it is.



Of greater importance to us, though, is the *wavelength*, λ, which we may define as the distance in meter (m) of one full cycle of the wave. The wavelength corresponds to the color of the light, if we can see it at all. It turns out that visible light is only a very small portion of the *electromagnetic spectrum* and encompasses the range of about 400 nm – 750 nm (1 nm = $1\text{x}10^{-9}$m). We can also describe a light wave in terms of its *frequency, ν.*



The frequency is simply the number of full waves (wavelength, in meters) that pass a fixed point per second. Since light waves travel at a constant velocity, *c* the frequency may be expressed as:

$$\nu\left(s^{-1}\right) = \frac{c\left(\frac{m}{s}\right)}{\lambda(m)}$$

4.2. Light and Electron Behavior

One of the earliest major breakthroughs toward our current understanding of the behavior of electrons and where they may be found within the atom was the observation that many metals will emit electrons when light shines on their surface. This phenomenon was termed the *photoelectric effect*. Classical wave theory suggested that this was the result of the light energy being absorbed by the electron, providing it with enough kinetic energy to escape from the atoms on the surface. Furthermore, it was demonstrated that the light must be of a minimum frequency, the *threshold frequency*, in order for electrons to be emitted. It was nonother than Albert Einstein who put it all together and proposed that the light energy was delivered to the atoms in discreet packets which he called *photons*. Einstein proposed that the energy contained within one photon of light was directly proportional to its frequency, or inversely proportional to its wavelength. In mathematics, we learn that we can turn a proportionality into an equality / equation by adding a constant. In this case, Einstein incorporated *Planck's Constant, h*, to arrive at his now famous equation:

$$E = h\nu = \frac{h \bullet c}{\lambda}$$

For this equation, ν must have units of 1/s (also written as s^{-1}), *c* has units of m/s, λ must have units of meters, and $h = 6.626 \times 10^{-34}$ J·s. Recall that 1 J = 1 kgm^2/s^2, so we must use SI units for all of our variables.

So… one photon of light with ν equal to the threshold frequency for a particular electron contains just enough energy to allow the electron to escape the atom once it has absorbed that energy. This is referred to as the *binding energy*, ϕ, of the electron. What happens if an electron is hit by a photon of light with ν that is greater than the threshold frequency? Such a photon would contain more than enough energy needed by the electron to escape. The answer is relatively simple. The excess energy is retained by the electron and converted into kinetic energy – energy of motion. In such a case, we can now say that the total amount of energy of the photon will be equal to the sum of the binding energy and the kinetic energy of the electron after it has escaped the atom.

$$E_{photon} = h\nu = \phi + KE$$

How is it that we are able to observe such behavior of electrons in the presence of light? It is because electrons are very small. It has been established that the electron is a particle of matter, with a mass of 9.11×10^{-31} kg. *Very* small indeed! To put it into perspective, a single speck of dust, which is barely visible to the naked eye, contains more electrons than the number of people who have *ever* lived on Earth. Just recently, the United Nations reported that the *current* population of the world had reached an excess of 8 billion, or 8 x 10^9 living people. That is just right now. Imagine how many people have lived on Earth since the Creation of Man?

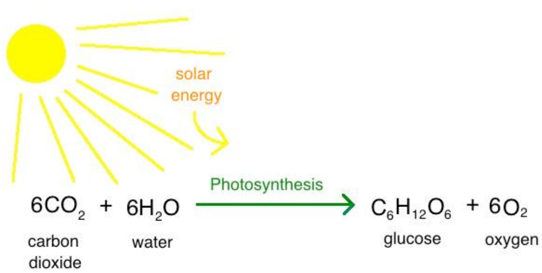
In short, 1 Joule of energy would have a greater effect on an electron with a mass of 9.11 x 10^{-31} kg than it would on a baseball with a mass of 0.145 kg. The French physicist, Louis De Broglie (1892 – 1987) postulated that any particle of matter in motion will have wave-like behavior – it will move, like light, with a wavelength that is inversely proportional to its momentum. The momentum of a moving object is defined as its mass (kg) multiplied by its velocity (m/s). Once again, the constant that converts this proportionality into an equality is Planck's constant, *h*. This gives an equation for what is referred to as the "De Broglie wavelength" of:

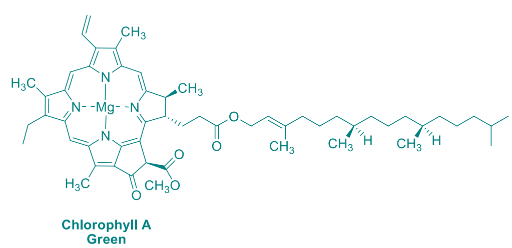
$$\lambda = h/mv$$

Even for what we would consider to be a very small object, if we can see it, then the mass is going to be large enough that the De Broglie wavelength becomes insignificantly small. But for an electron, with a mass of 9.11 x 10^{-31} kg, it does become significant. Electrons, like light, travel with a wave motion!

4.3. Photosynthesis

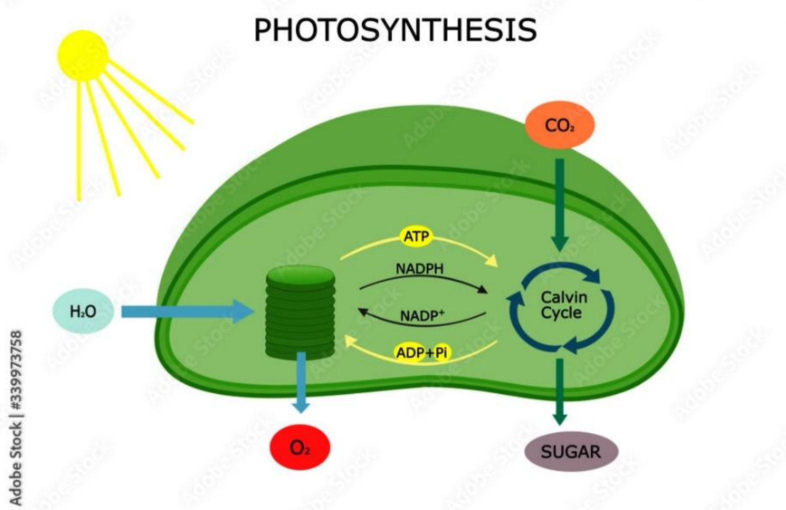
In a way, nature has been using the photoelectric effect to sustain life on Earth since long before people knew anything about physics or chemistry. Green plants, algae, and some bacteria have the ability to harness light energy from the sun and convert it into the chemical energy that is used to chemically convert carbon dioxide and water into glucose, the "energy source of life" by the process of *photosynthesis*. The biggest difference, of course, is that it is not a metal that is absorbing light and giving up electrons. Rather, it is an organic compound – chlorophyll.





The synthesis of glucose is essential for sustaining life as we know it, but another benefit is that the process of photosynthesis also removes large quantities of carbon dioxide from the atmosphere. Without Earth's abundance of plants and algae to continually suck up carbon dioxide, the gas would build up unchecked in the atmosphere. Although photosynthetic organisms remove some of the carbon dioxide produced by human activities, rising atmospheric levels are trapping heat and causing climate to change. Many scientists believe that preserving forests and other expanses of vegetation is increasingly important to combat this rise in carbon dioxide levels.

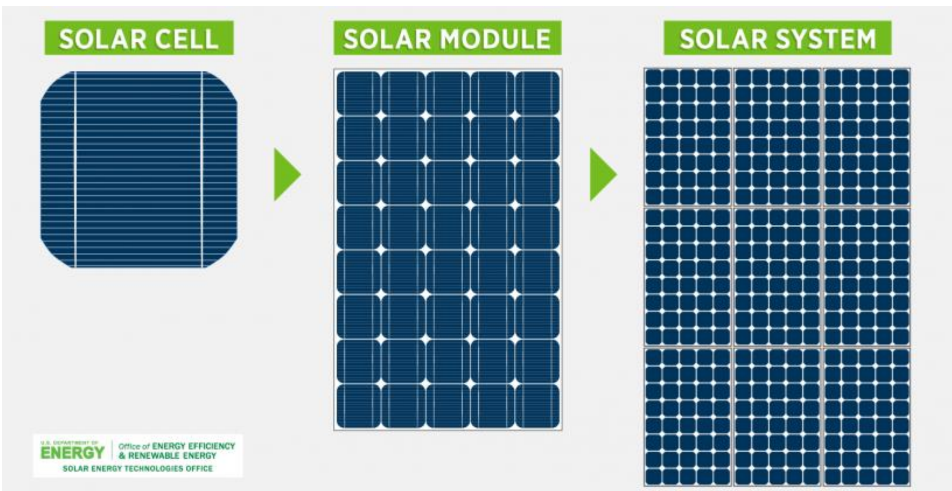
On land, green plants are by far the most common organisms that use photosynthesis for the chemical production of glucose. All green plant tissues can photosynthesize, but in most plants, the majority of photosynthesis takes place in the leaves. Green plant cells contain organelles called chloroplasts, which are specialized to carry out the reactions of photosynthesis. The entirety of photosynthesis is a combination of two separate processes – a series of *light-dependent reactions*, which take place within membrane-bound structures called *thylakoids*, and the light-independent *Calvin Cycle*. During the light-dependent process, light is absorbed by chlorophyll within the thylakoids, and the chlorophyll gives up electrons, much like the photoelectric effect. These electrons are used to convert ADP into ATP, a compound that stores energy, and also to reduce $NADP^+$ to NADPH, a natural reducing agent. The process requires water as a reactant and releases oxygen. The ATP and NADPH then become a part of the Calvin Cycle which ultimately produces glucose from carbon dioxide, and releases ADP and $NADP^+$ back to the light-dependent process. And the cycle continues… for as long as there is available light!



4.4. Solar Panels

Solar panels use the photoelectric effect, also called the *photovoltaic effect*, to generate electricity from sunlight. When photons of light hit the solar panel, they knock electrons loose from the atoms in the solar panel. These electrons flow through the material to create an electric current. The more photons that hit the solar panel, the more electricity is produced.

A typical rooftop solar panel is composed of about 30 individual *modules*, and each module is composed of numerous individual *photovoltaic cells* all linked together. These cells are composed of a semi-conducting material that conducts electricity only when energy is provided—by sunlight, in this case. When the semiconductor is exposed to sunlight, the electrons on the surface absorb the light, and are released – the photoelectric effect. These electrons then flow through the semiconductor as electrical current, because other layers of the photovoltaic cell are designed to extract the current from the semiconductor. Then the current flows through metal contacts—the grid-like lines on a solar cell—before it travels to an inverter. The inverter converts the direct current (DC) to an alternating current (AC), which flows into the electric grid and, eventually, connects to the circuit that is your home's electrical system. As long as sunlight continues to reach the module and the circuit is connected, electricity will continue to be generated.



A module's ability to convert sunlight into electricity depends on the semiconductor. The main semiconductor used in solar cells, not to mention most electronics, is silicon. In fact, it's found in sand, so it's inexpensive, but it needs to be refined in a chemical process before it can be turned into the crystalline silicon that is used to make the photovoltaic cell. Silicon is an ideal material for photovoltaic cells, as it has a threshold frequency of about 2.73×10^{14} Hz, which corresponds to a wavelength of 1.1×10^{-6} m, which falls into the infrared region of the electromagnetic spectrum. This is also at the lower end of wavelengths of light that reach us from the sun, so silicon is capable of absorbing and using most wavelengths of light that reach the Earth. However, higher energy portions of sunlight are not usable by silicon photovoltaic cells, which is significant. Because of this, the U.S. Department of Energy estimates that the maximum theoretical efficiency for a silicon cell is only about 32%.