The nature of light

This is a short description of what we know about light because there have been quite a few questions about that. The true nature of light is quite complex and I'm not completely certain we can claim to understand it. However, I want go into a bit more detail than what we can cover in class. Some of this will involve math that is well beyond the course itself, but hopefully a brief description of it can be given to it is understandable.

A classical definition of light is that it is a self-sustaining perpendicular electric and magnetic fields.[1] That's a lot of words that need to be picked apart. The fact that it is self-propagating means that light does not need a medium to go through, unlike sound moving through air or waves across a surface of water. Perpendicular means that the two things are at a 90 degree angle to one another. Describing electric and magnetic fields is a bit more difficult. We have already talked about one type of field in the class though we didn't use that terminology. The force of gravity can be viewed as a field that surrounds anything that has mass. Similarly, an electric field surrounds anything that has a charge. Electric fields affect charges is a similar manner to how gravity affects mass. Magnetics fields are a different type of field that arises any time charges are in motion or more generally, when there is a change in an electric field. The behavior of electric and magnetic fields is described classically by Maxwell's equations. Those equations in differential form are given here.

$$\nabla \cdot E = \frac{\rho}{\epsilon_0} \qquad 1$$

$$\nabla \cdot B = 0 \qquad 2$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad 3$$

$$\nabla \times B = J\mu_0 + \epsilon_0 \mu_0 \frac{\partial E}{\partial t} \qquad 4$$

The **E** and **B** are the electric and magnetic fields, ρ is a charge, ε_0 is the electric permittivity of free space, μ_0 is the magnetic permeability of free space, and J is a current (moving charge). The fields themselves are vector fields. That is to say that at every point in space they have a direction. Unfortunately for this class, these equations involve a fair bit of differential multi-variable calculus. I'll try to put it into words though. The first two equations tell us the divergence of the two fields (divergence is given by the del operator dotted with a vector field). The divergence of a function is a measure of how much a vector field is flowing out if a single point. So equation 1 tells us that the electric field flows away from a point by an amount proportional to the amount of charge at that point. The second one says that for every point in space, the amount of magnetic field flowing in is equal to that flowing out.

The 3rd and 4th equations are a bit more complex, but they are the ones that matter more

1 Classical physics here means physics prior to relativity and quantum mechanics. Physics that includes those theories is typically referred to as modern physics.

for understanding light. They both deal with the curls of the fields. That is to say that the describe how much a given field bends at a certain point. So equation 3 says that an electric field bends when there is a changing magnetic field (this is how generators work). For us this means that a changing magnetic field will induce a current loop. Equation 4 says that we induce magnetic field loops by either having a current (that's what an electromagnet is) or by changing the intensity of an electric field.

Notice that in these equations, a changing **E** field produces a **B** field and a changing **B** field produces an **E** field. This is how light propagates. These equations also tell us how fast light should travel and I'll leave looking up the details of that to anyone who is really interested. Given these equations, $c=1/\sqrt{\epsilon_0 \mu_0}$. This is why Einstein postulated that the speed of light is the same for all observers because there is no reason to believe that ε and μ should change just because you are moving relative to a light source. Instead, they are fundamental constants of the nature of a vacuum. If you want to know even more about Maxwell's equations, wikipedia is a decent place to start (http://en.wikipedia.org/wiki/Maxwell%27s_equations).

So that explains light in a classical sense as simply waves in the electric and magnetic fields that moves through space. This model is further complicated by the fact that quantum mechanics plays a role. That is where wave-particle duality and the quantization of photon energy levels comes in. It isn't clear that there is much value in trying to describe a mental image of how light is both a particle and a wave though I did that a bit in class. This is a general issue with quantum mechanics. Because quantum mechanics only really matters when things are incredibly small, the behaviors that you get from those things often don't fit our macroscopic intuitions. Instead, it is often best to just describe the way that we know that certain parts of quantum mechanics are true.

In the case of light, the foundations for the quantum theory of light were laid by Plank working on blackbody radiation and by Einstein in regards to the work function of atoms. Describing Plank's work is harder so we'll look at Einstein's work instead. As you know, normal matter is made of atoms and those atoms have a nucleus that has electrons around it. Under certain situations, the electrons can be knocked free of the atom. If you knock the electrons free, you can detect it as an electric current if you set things up properly. Einstein worked with metal surfaces and found that you only knock free electrons when you get to a certain wavelength/frequency. If you had a light source where the wavelength was too large, it doesn't matter how bright the light is, no electrons come off. Use a light source with a shorter wavelength though, and even if the bulb is less bright and you are using less total energy, the electrons will be knocked loose. The classical description of light can't explain this. You can only explain this if light has a particle nature to it and your bulb is emitting photons that have an energy that depends on the wavelength of the light. (For more info on this go here http://en.wikipedia.org/wiki/Photoelectric_effect.)