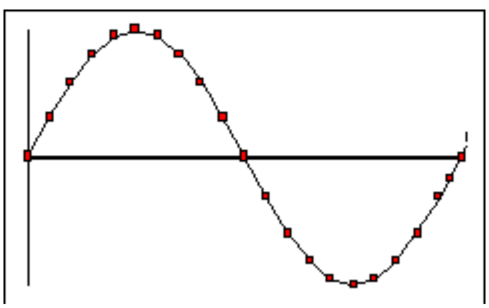
LIGHT AND ELECTROMAGNETIC RADIATION

Light is a Wave

Light is a wave motion of radiation energy in space. We can characterize a wave by three numbers:
- wavelength
- frequency
- speed



Shown here is precisely one ***wavelength*** of a wave on a string. (Several points are marked on it, but look at the smooth curve running through all the points. That's the wave.)

In other words, the ***wavelength*** is the distance needed for the wave to go up, back down again, and back to its starting point.

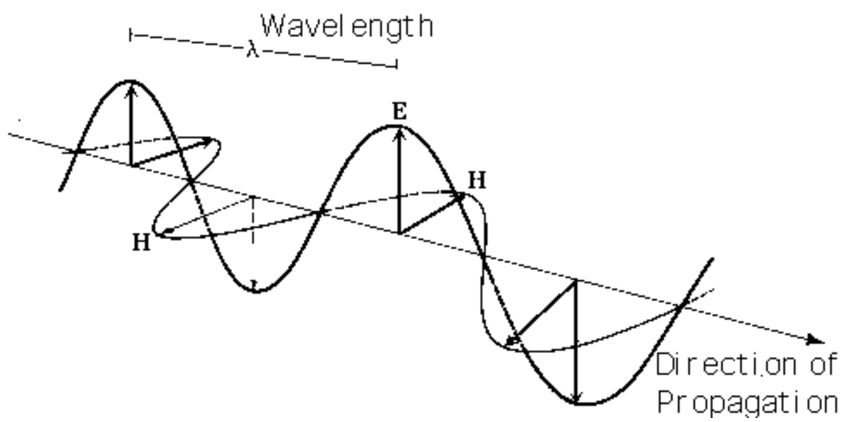
The ***frequency*** is the rate at which the wave oscillates. Think of a chip of wood floating in water at the beach. As a wave comes in to the shore, the chip bobs up and down. It will bob quickly if the wave has a high frequency, but slowly if the wave has a low frequency.

Finally, the ***wave speed*** is the speed at which (e.g.) the crest of the wave moves along past a particular point in space. The speed is related to the frequency and wavelength by a simple relation,

$$\text{Speed} = \text{Frequency} \times \text{Wavelength}$$

For example, a wave with a wavelength of 1 meter and a frequency of 10 oscillations per second will have a speed of 10 meters per second.

"Light" is a single word meaning "Electromagnetic Radiation" or sometimes just "Radiation". A light wave is actually made up of a little electric field (E) and a little magnetic field (H) which are running along together in space, like this: (the electric and magnetic fields are at right angles to each other – you have to visualize them in three dimensions)



What this diagram shows is just one ***light ray*** moving through space. But a source of light (e.g. a star) is actually sending light out in all directions at once.

Electromagnetic waves can have *any wavelength* (long or short), but all of them have exactly the same speed as they move through space: the famous ***speed of light***, 300,000 kilometers per second. This number is so important that it has the status of a fundamental physical constant of the universe. It is usually just called "c" (which appropriately enough stands for "constant"!)

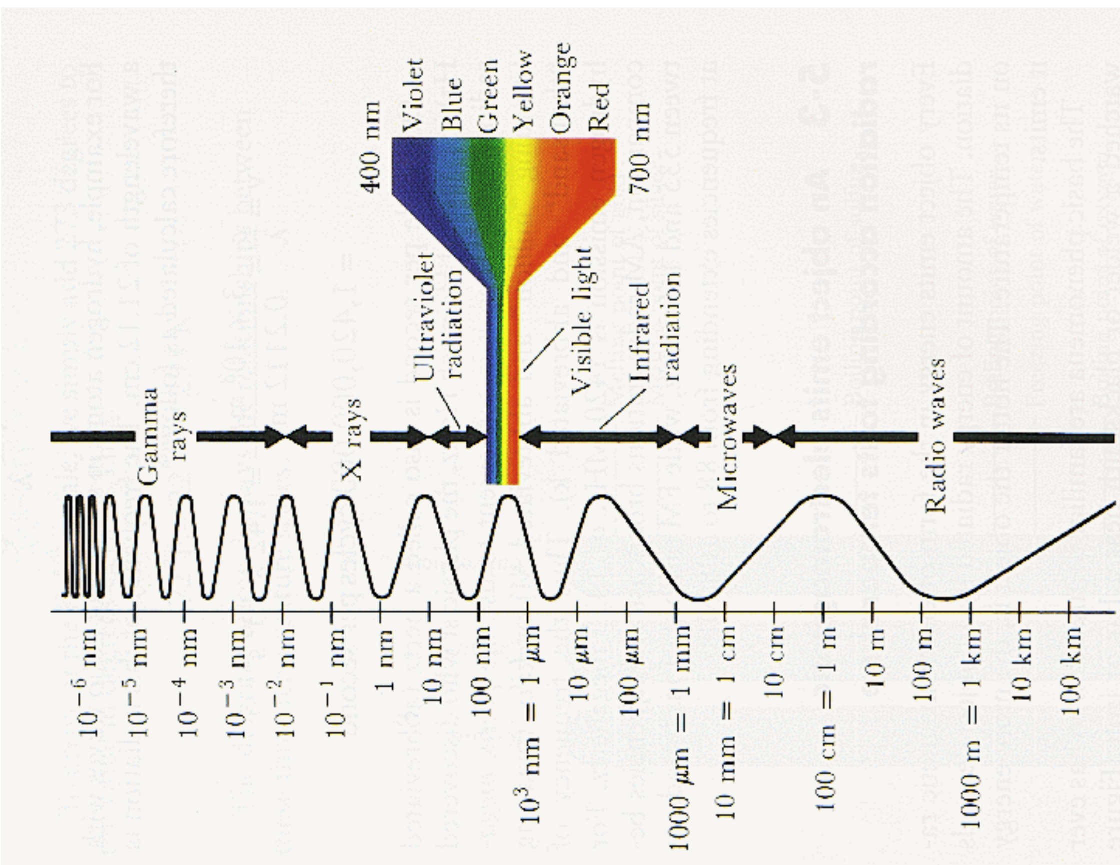
One thing which Einstein showed (and which has been verified experimentally over and over again) is that "c" is a kind of *ultimate* *speed limit* in the universe. No physical object with a finite mass can move as fast as the speed of light, and in fact the only thing that *can* move that fast is light itself.

Furthermore – and this is the really surprising thing – the speed of a light ray does not change with the observer's motion either: you can be standing still, running towards it, running away from it, and it makes no difference: you will always measure its speed as *c.* In fact, the constancy of "c" proved to be the basis for the theory of ***special relativity***, which Einstein worked out and published in 1905, and which involves the extreme and bizarre properties of moving objects and events when motion starts getting very fast.

One more thing about light as a wave motion: Electromagnetic waves are produced by a *moving electric charge:* specifically, what we mean is an electric charge which is "vibrating" or oscillating back and forth. For a cute interactive demonstration of an electric charge producing a wave, see:
https://phet.colorado.edu/en/simulation/radiating-charge
(You can use this demo also to see how the rate, or frequency, of vibration affects the wavelength of the light. Just change the "springiness" of the electron attached to the little spring.)

The nature of light as an electromagnetic wave was first worked out by the Scottish physicist James Clerk Maxwell, in the 1870's. Interestingly, Maxwell's work stands as the first great example of *unification of forces* in the history of physics. Before that, people thought that electricity and magnetism were two separate phenomena. But they are tied together: moving electric charges create magnetic fields, and moving magnets create electric fields. The two types of fields are inextricably locked together in a light wave like Siamese twins: each one creates and re-creates the other as they move along. Maxwell worked out the exact mathematical description of all this. He had, in fact, discovered the second of the ***four fundamental forces*** – electromagnetism. (The first one is gravity. The next two, the weak and strong forces, were only found a century later.)

Another term which is useful to introduce at this point is the ***electromagnetic spectrum***, which means the whole range of wavelengths that light is capable of having. Our human eyes can see what is called visible light, which has the familiar colors of the rainbow (red, orange, yellow, green, blue, violet). Red light has wavelengths around 0.8 micron (0.8 millionths of a meter) and violet light is around 0.4 micron. That is, in a literal sense, we see different wavelengths of light as different colors! But, the total range we can see with our eyes is not very big.



The diagram above shows schematically all the other kinds of light: *radio* waves have the longest wavelengths, *infrared* are a bit shorter, then *visible* light, then *ultraviolet*, then *X-rays*, and then *gamma rays* with the shortest wavelengths of all. However, these are just labels and there are no rigid boundaries between them. There is no basic difference between these except their wavelengths – they are all “light” or electromagnetic radiation.

One last important thing to mention – the shorter the wavelength, the higher the frequency (see again the little equation above). And, the higher the frequency, the more energy the wave carries. Gamma rays are quite energetic compared with visible light; radio waves are quite feeble by comparison.

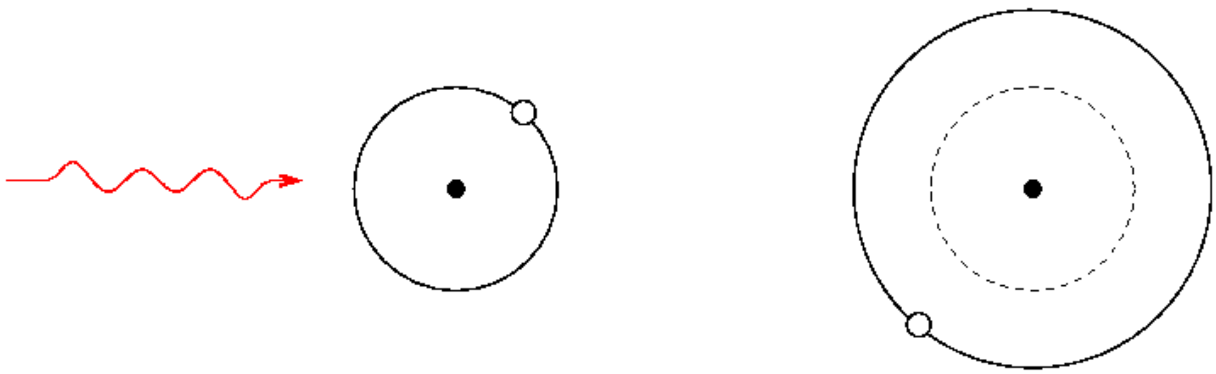
Light is a Particle

But we are not finished with the story. Now we have to introduce the other side of the dual nature of light: *photons.*

Just about a century ago (1900 – 1905) it became clear that light was able, in certain conditions, to behave in a very un-wavelike way. When light is absorbed by an atom (specifically, by an electron within the atom), the atom takes the energy of the light ray as if it is broken up into discrete chunks or *quanta*. It is as if the light is made up of little particles, now called ***photons***. These particles are quite different from the other subatomic particles (electrons, protons, neutrons) in that they have no electric charge, and no mass at all – they are just bundles of pure energy.

Historically, the concept of light as made up of photons is due (once again) to Albert Einstein. It marks one of the beginning points of the development of quantum mechanics, which dominated the progress of physics from about 1910 to 1930. Einstein’s work on this phenomenon, called the photoelectric effect, is what won him the Nobel Prize. Interestingly, however, he found the later developments in quantum mechanics (the uncertainty principle and all the rest of it) very hard to accept.

Here is how light interacts with an atom: a photon (indicated by the red wave on the left) comes in and is absorbed by the orbiting electron. As a result, the electron gains the energy that was in the photon, and it gets nudged "up" into a higher, more energetic orbit farther away from the nucleus.

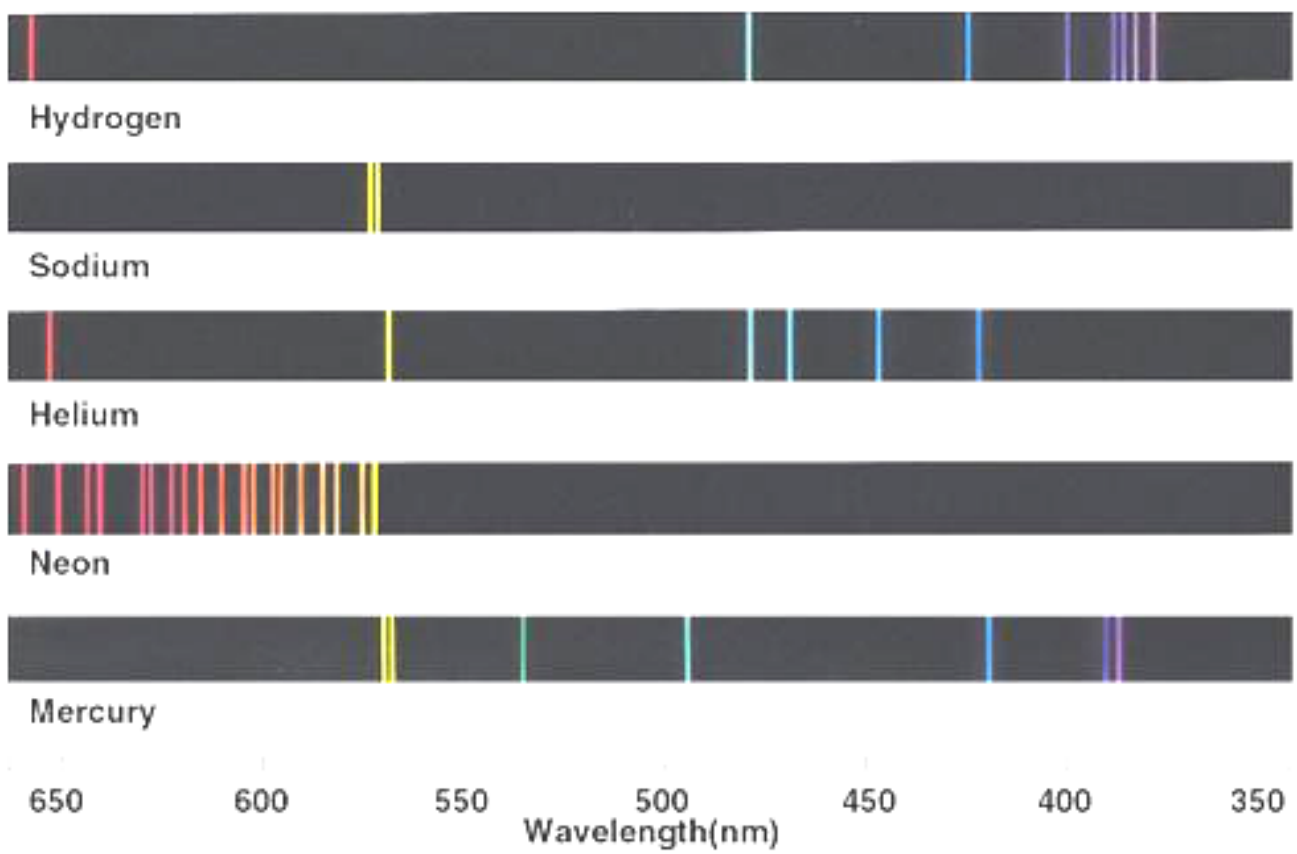


However (and here is the intriguing trick), not just any old photon passing by will do. *The electron can only be in certain specific orbits*, rather like steps on a stepladder (this is one of the basic principles of atomic structure, as seen through quantum mechanics). So, the photon must have exactly the right amount of energy to nudge the photon from its lower orbit to one of its higher possible ones. If a photon comes by with a different "in-between" value of energy, the electron can't do anything with it, and it just passes through the atom unaffected.

To describe this effect another way – most rays of light that pass by an atom will just slip right through it as if it were a ghost, because they have the "wrong" wavelengths. The atom can't do anything with them. However, the rare photons that happen to have just the right wavelength to boost the electron up to one of its higher orbits will be eagerly gobbled up by the atom.

The same process of absorption of light can happen in reverse: an electron in a "high" orbit can drop back down to a lower one, by emitting a photon of light with just the right amount of energy to account for the difference between the two orbits. Each element (hydrogen, oxygen, nitrogen, carbon, iron, ...) has its own characteristic set of electron orbits, and so has its own characteristic ***emission spectrum***. In a very real sense these are like "fingerprints" – each element is unique.

Here are some emission spectra for five of the elements. Notice the colored lines at certain wavelengths, which mark some of the particular electron orbits within that type of atom. Long wavelength (red) is on the left, and short wavelength (blue) is on the right. (Notice, for example, that neon has lots of emission lines in red, orange, and yellow. That's why neon lights have those colors!)



On a Clear Day You Can See Forever

On a clear sunny day, go outside and look around. You can see other people, buildings and cars, trees, distant hills, perhaps a jet trail from a faraway airplane. And at night, you can look straight upward through a hundred kilometers of the Earth's atmosphere to see the stars. But how can you see all this? The light from these objects is not travelling through empty space to reach your eye: it has to pass through uncountable zillions of air molecules. Why aren't all these light rays absorbed and scattered in all directions by the atoms in the air, so that all we see is a hopeless foggy blur?? In fact, how can you even read the page of a book a few inches away from your face?

The answer is in the phenomenon described above. The air around us is a gas consisting of (mostly) nitrogen and oxygen molecules. Most of the light rays passing through them cannot be absorbed, because they do not fit the particular set of energy levels which the electrons within those molecules have. If they don't fit – it's as if the molecule is not even there. *(Footnote: actually, a molecule has a larger, more complex list of energy levels than a single atom does, because there are more ways the electrons can rearrange themselves inside the molecule. So, a molecule can absorb a wider range of photons than an atom. But most of the energy differences that the molecule can absorb are rather tiny ones, corresponding to low-energy, long-wavelength photons in the infrared or radio part of the spectrum. The higher-energy visible light that our eyes can see is not affected. However, what this means is that if we could magically "see" with eyes tuned to the infrared, the air around us really* would *look like a hopeless foggy blur!)*

In summary, *a gas which is made of neutral atoms is almost perfectly transparent to light*. This is all because the rules of quantum mechanics say that electrons within them can only have certain specific orbits, and the only way they can interact with light is to jump between those orbits. *(Footnote again: what we've just said is a bit of an oversimplification. In fact, some photons do just "bounce" off molecules in the air and go off in all directions. This is why the sky is blue! Blue, short-wavelength light does this more easily, so we see blue light in all directions. However, it's a relatively small effect compared with the main process described above.)*