Blackbody Radiation
and
The Ultraviolet Catastrophe

We ~~have now~~ will set ourselves the task of predicting in a precise way some observable behaviour of electromagnetic waves. Once again (as we did for the basic behaviour of a gas) this can be done for a relatively simple situation. Last time we stored particles in a box; this time we will store *the radiation waves* in a box.

The question immediately arises "how do you store a wave?" A wave isn't the same as a particle; it can't just simply bounce back and forth. However, if we think about it, we can see that a wave can be "stored" in much the same way as a particle. Let's generate a travelling electromagnetic wave by making a dipole (atom) oscillate in one wall of our box. We can easily do this by heating up the wall. This will start an electromagnetic ~~(E-M)~~ wave moving to the other wall as we discussed before. When it reaches the other wall it will encounter other dipoles-charges-atoms. These will be set into motion, and will themselves radiate waves back into the box. Effectively the wave is "bounced" off the walls. There is a big difference between particles and waves, however, and if we think of this reflection - or reradiation - process carefully, we will realize that after a while the space between the two radiation sources that we have mentioned will be filled with a *very large* number of radiated and re-radiated and re-re-radiated - etc. etc. waves.

The net amount of radiation due to these various reradiations is the sum of all of the individual radiated waves, but it is not immediately clear that the sum will be a simple addition of all the wave "sizes", or amplitudes, or

Diagram

whether some waves will cancel each other out. In fact, there are only certain values of wavelengths which will add up to give a total wave which permanently reflects back and forth between the two radiators - or walls - without cancelling itself out to nothing. These are called standing waves, and are determined in a simple way by the relation of the wavelength to the distance between the walls. If the distance between the walls is an exact multiple of half the wavelength, then all radiation and reradiations will be just right to add up together, to give a constant wave in between them. This means that for a given distance, L , between two walls, it would be possible to "store" waves with wavelength λ such that

(These are the kinds of standing waves you can make on a skipping rope.)

For all those wavelengths it will be possible to set up a standing wave, i.e. "store" the wave disturbance.

Now we can easily make such a box (although we can't expect it to have "perfectly" parallel sides), and can cause the atoms that make it to radiate by heating up the walls.

What we would then be able to observe experimentally (and therefore should try to predict) in the intensity of the radiation (light) at various wavelengths ~~frequencies~~ by making a very small hole in the side and peering in. What we will therefore have to calculate is the relative energy stored in the box at the various wavelengths. ~~frequencies.~~ (We can quickly recognize that there is energy of some form stored in the waves as they are able to do work on the atoms - i.e. make them move.)

In order to decide how much energy is stored at any wavelength ~~frequency~~ we must decide exactly how energy will be distributed into each of the standing waves that we found will exist or a given wall distance L.

The answer to this question is that each standing wave will store the same amount of energy as any other standing wave in the box. We may be able to see why if we think of each standing wave as something which stores, or possesses, some amount of energy - i.e. it has a "temperature". Now if the temperature of any one of the standing waves is higher than the others it will "heat" them up until it is no longer hotter; hence all standing waves will end up at the same "temperature" - or they will contain the same amount of energy. This process happens because ~~by~~ the atoms, when accelerated by the wave, tak~~ing~~e up all possible kinds of motion and so ~~of~~ reradiat~~ing~~e at all wavelengths, ~~and hence~~ redistributing the energy among the ~~to other~~ wavelengths until all standing wave wavelengths are at the same "temperature".

Now, to arrive at our final answer, knowing what wavelengths can be stored between walls of a given separation and how the energy will be distributed among the standing wave wavelengths, we need only recognize that any real box will not have perfectly parallel sides, and that there will not be just one value for L but a whole range.

Therefore there will be a *continuous* range of standing waves available not a set of discre~~et~~te values. It is capable of radiating and absorbing *all* wavelengths. It is called a *blackbody* radiator or absorber, since black is the colour which represents the absorption of *all* wavelengths of light.

The picture we must make of the radiation distribution within our blackbody radiator, then, will be effectively that for a *collection* of perfect boxes of different dimensions

This ends up being a continuous wave, when enough standing waves are added in, that looks like the following

At very long wavelengths there should be very little energy stored, and at very short wavelengths there should be great amounts - in fact, as can quickly be realized, the energy stored ~~is predicted to~~ should increase without bounds as the wavelength approaches zero.

What do we actually see when we perform such a measurement?

The two curves agree for the longer wavelengths, but for the shorter wavelengths there is a strong disagreement. There is zero intensity observed at the short wave limit whereas an infinite amount is predicted! Our model has not predicted nature! Perhaps we just haven't made the box hot enough, so that we want exciting all the motions possible. If we repeat the measurements for a higher temperature, the agreement improves at intermediate wavelengths but the basic disagreement at the short wave limit persists. No matter what temperature we perform the measurement for it persists.

This is a catastrophe! It is a catastrophe in the sense that we have made a prediction which was directly contrary to observations and therefore means that we either don't understand what is going on, or have mistreated the processes in our calculations in some basic way. Of course this was immediately recognized historically as being of the utmost importance to physics, and the problem was called the ultraviolet catastrophe, because the basic disagreement between observation and prediction occurred in the high frequency, or ultraviolet end of the spectrum. It is also a very real catastrophe in the sense that physics was put in the position of predicting for example that anyone who opens the door of a heated oven would be met by a very unpleasant blast of X rays and γ rays. There is little doubt that this does not happen.

This became a celebrated problem in the late nineteenth century which no-one could understnad. A solution *was* proposed by a man name Plan~~k~~ck, but to solve the problem he had to assume that radiation was *not* emitted continuously, and that furthermore the energy of the radiation was directly proportional to frequency i.e., $E_{light} = h\nu$. These assumptions seemed outlandish even to Plan~~k~~ck and little insight into what must be occurring in nature ~~is~~ was given us immediately by his solution.

We must examine the problem and try to see what could be wrong. All that ~~has gone~~ went into our calculations was: the identification of the standing waves, which is geometry, and unassailable; the assumption of equal "temperature" for all standing wave frequencies, also unassailable. What we must not have ~~managed to describe~~ described properly is the ~~process~~ emission of radiation at high frequencies, and the distribution of energy to these high frequencies by the walls. Something must surely be wrong there.

Why?

What does high frequency, or short wavelength, radiation come from? Our everyday experience is that increasingly shorter wavelengths are associated with increasingly smaller antennas (or absorbers). The short wavelength absorber is also the short wavelength radiator. Our problem could lie with the smallest radiator we can think of. This, of course, is the atom. We must surely find out now if our picture of the atom itself is all right, because if it isn't, this may be where our trouble lies.

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Of course we are taking a tremendous advantage of hindsight in deciding what to worry about at this point. In the actual course of events there was no such easy choice; all assumptions, all thought processes involved had to be opened to the most basic of questioning, for if no solution to the catastrophe could be found, the very foundations of what was now an ardently believed science would have to be reconsidered.