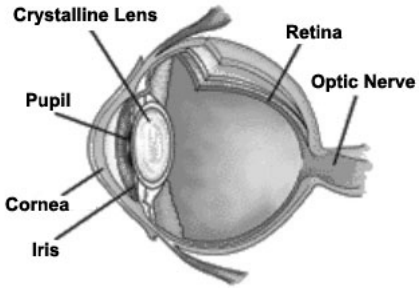
Are Atoms Coloured?

The monthly meetings in Eklavya throw up some offbeat questions, especially during teatime. Investigating such questions (or trying to) really plumbs the depths of conceptual understanding. During one such meeting at the Indore centre the following question was floated, “Are atoms coloured?” To me, a physicist, the answer was quite clear but it turned out to be not so easy to explain my answer to the resource persons who were basically biologists, chemists or engineers. All these people had used colour in some form in their work. Chemists regularly monitor the progress of reactions by the change of colour, they identify the presence of specific ions by flame tests, and biologists use the colours of dyes extensively for structural studies and so on. Most of the people felt that molecules and even ions could have colour of their own but single atoms could not. Then the question arose as to why bulk objects, which are after all made up of atoms, appear coloured. Somebody claimed that in a solid or liquid atoms (somehow) got coloured because of the other atoms surrounding them. This concept was probably deduced from the common knowledge that doping minute amounts of specific atoms or ions into another material can change the colour of the material. For example, corundum or aluminium oxide (Al_2O_3) is available as a mineral crystal. It comes in various colours depending on the presence of trace elements. If this trace element is chromium, the

crystal has a deep red colour and it is the gemstone ruby. If the trace element is vanadium

the colour becomes purple. If the trace elements are iron and titanium we get a rich blue colour which is nothing but the gemstone sapphire.

I found it difficult to get my views across, primarily because of some confusion between the rigorous, scientific meaning of the terms “seeing” and “coloured” and the meaning in everyday usage. This article is an attempt to throw some light on this question. I do hope that after reading the article readers will be able to answer it for themselves.



In everyday language when we define the colour of an object we mean the apparent colour when we look at the object through our eyes. This is a multiple process: let us say I look at a mango in daylight. The sunrays falling on the mango bounce off it, some of them enter my eyes through the pupil (see Fig 1). The lens of the eye focuses the rays on the retina and an image is formed there in the same way as in a camera. The photoreceptor cells in the retina convert the image to a series of electrical impulses which travel through the optical nerve to the brain. The brain decodes the impulses, compares with the information it already has and identifies the shape as that of a mango. The colour of the image is identified by the wavelength of light which can be discerned by one kind of retinal photoreceptors (the cone cells). Human eyes are sensitive to only a small part of the electromagnetic wavelength range (spectrum), understandably called the visible range. In this region the wavelength of light varies from about 400 nm to 700 nm (see boxes 1,2,3). One nm or nanometer is 10^{-9} of a meter; to give you an idea of how small this is, one nm is 1/100,000 of the average human hair thickness!

Human eyes can see objects as small as 50 microns across and we all know that atoms, or for that matter ions and molecules also, are much, much smaller (see box 4). So we cannot see individual atoms, ions or molecules with our naked eyes. Then does this mean that there is no point in asking whether atoms are coloured since we cannot see separate atoms anyway? Let us try and understand where the colour of an atom could come from first. Is it the same process by which we see the colour of a ripe mango as bright yellow-orange?

Well, not exactly. Think of a burning candle, the candle itself may look white and so also the wick but when I put a match to it a flame appears which throws out (emits) light. So what is the colour of the flame? It is same as the colour of the light that it gives out. In the case of the mango we were able to see the mango only if light from some other source fell on it and got reflected into our eyes. But for things like fire, flames, burning coal, iron heated in a furnace the colour as we see it is the colour of the light emitted by them. Such materials are called incandescent.

To make things more clear think of a light bulb (the old fashioned 60 W type, not a CFL). When it is off it looks transparent or colourless but when it is switched on it gives out yellowish light and itself appears yellow. So is the case for the biggest 'bulb' we know of viz. the sun. Now atoms are in a way like miniature suns. If we heat up an atom (excite one or more of its electrons to a higher energy state, for those of you familiar with electronic structure of atoms) it will emit light and cool down (i.e., lower its energy by emitting light or radiation). The colour of the light thus emitted is specific to each kind of atom, for example sodium atoms emit mostly yellow light (589 nm and 589.6 nm), mercury atoms emit green, blue and yellow light in different proportion (435.8 nm, 546.1 nm, 579 nm and some other wavelengths). This wavelength depends on the energy difference between the occupied and unoccupied orbitals in the atom. However the amount of light given out by a single atom is very, very, very dim indeed. Our eyes can not sense such a low level of light. We need billions and billions of atoms emitting together for our eyes to be able to detect it. This is precisely what happens in a sodium vapor lamp. The vapor lamp is a glass bulb which has been evacuated (all the air removed from inside it by a vacuum pump) and then low pressure neon gas and some amount of sodium are put in it. Two electrodes are attached and a high voltage is applied between the electrodes. Sodium is a solid at room temperature whereas neon is a gas. The high voltage between the electrodes excites a discharge in the neon gas (like the spark in a spark plug). This energizes the neon atoms, which in turn hit the sodium and vaporize it into gas. The atoms in the sodium gas emit the yellow light we see. Thus when we see the glowing sodium lamp we are actually seeing a bunch of emitting sodium atoms. Do you agree? Then we have to wonder why we do not see neon atoms. Do they not emit? And why do we need to use sodium atoms only? Actually all atoms emit light once they are energized but only in a few cases the emitted light wavelength falls in the visible region. Many atoms emit ultraviolet light which is not detected by human eyes. Neon atoms do emit red light, remember the neon indicator lamps on appliances. In the case of a lamp required for street lighting red would not be a good colour choice as human eyes are not very sensitive to red colour. The yellow colour emitted by sodium atoms comes close to the colour for which our eyes are most sensitive.

You may be wondering if it is at all possible to 'see' unheated atoms by shining light on them from some other source in the way we 'saw' the yellow colour of the mango in the first example. Well, if we consider using light from conventional sources like the

sun or a bulb or a fluorescent light then it is not possible. The light from such sources is a mixture of a great number of colours. As we saw above any specific atom gives out light of one particular colour or a few colours. Because of the way our eyes and brain process the colour information it would be impossible to detect the difference between the light falling on the atoms and the light bounced off the atoms. However one can create the required conditions in a laboratory. Let us see how it is done with sodium as an example. This has to be done in a dark room.

We take a glass tube with glass windows at each end and evacuate it completely. Then a light beam of wavelength 589.6 nm is passed through one window and out of the other. (A single wavelength corresponds to a single colour. To generate light of a single colour we will need a special light source. The light should come out in the form of a directed beam like from a torch or car headlights. In this case a sodium lamp backed by a curved reflector should do the trick.) If the beam falls on the wall we will see a yellow spot on the wall (see Fig 2a) but the beam will not be visible within the tube if the tube is fully evacuated.

Next we fill the tube with a dilute gas of sodium atoms. When the light hits the atoms it would bounce off them but in all directions (Fig 2b). So now we will see a yellow glow within the tube which is due to the presence of sodium atoms. The glow will be very faint because we cannot fill too many gas atoms in the tube (gases are very dilute compared to solids and liquids).

If you are a typical Sandarbh reader, I am sure the foregoing discussion has given rise to more questions like, ‘Why can we not see very small things like atoms by our eyes?’, ‘Can we see atoms using an instrument like a microscope or a telescope?’, ‘Why is the colour of a piece of sodium metal different from the sodium gas?', 'If we heat up a piece of solid sodium rather than the gas will it also emit yellow light?', 'What is white light?' and so on. We will try to discuss some of these questions in future articles so please send in your comments and queries. If you want to go deeper into the concept of colour it would be very rewarding to go through any standard optics textbook and the two books referred to below.

References:

1. 'The Physics and Chemistry of Color: The fifteen causes of color', Kurt Nasau, Wiley Interscience
2. 'Colour and optical properties of materials', Richard J.D.Tilley, Wiley Interscience

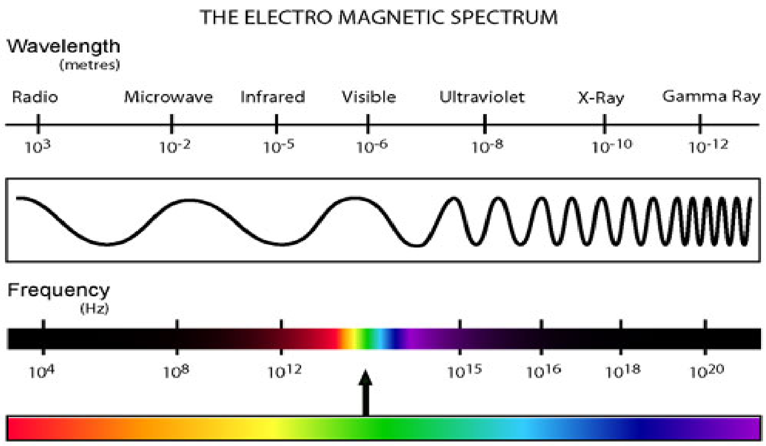
Box 1. The visible region

Light has a dual wave particle nature. Depending on the mode of observation light manifests itself as a wave or as a particle. In the wave like picture light is described as a transverse electromagnetic wave with a speed 3x10* m/s in vacuum. In other media other than the vacuum the speed is reduced to C where n is the refractive index of the medium. The light wave is characterised by its wave length (λ) and frequency (ν (nu)) such that νλ = C (in vacuum). In other media c reduces to c/n and it is λ which reduced to λ/n the frequency remaining unchanged. IN the particle picture light energy is quantized into particles called 'photons'. For light of different wavelengths, the corresponding photons have different energies given by E=hc or E=hν. Photons move at the speed of light and have zero rest mass. The wavelength/energy of light varies continuously as the colour is changed from red to blue some representative values are given below :

Colour	(nm)	(Hz)	Energy (J)	Energy (eV)
Deep red	700	4.29×10^{-14}	2.84×10^{-19}	1.77
Orange	600	4.62×10^{-14}	3.06×10^{-19}	1.91
Yellow	525	5.17×10^{-14}	3.43×10^{-19}	2.14
Green	525	5.71×10^{-14}	3.78×10^{-19}	2.36
Blue green	500	6×10^{-14}	3.98×10^{-19}	2.48
Blue	450	6.66×10^{-14}	4.42×10^{-19}	2.75
Violet	400	7.50×10^{-14}	4.97×10^{-19}	3.10

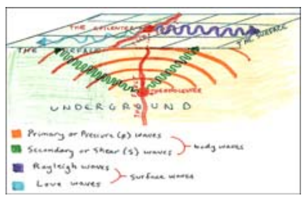
Box 2. The electromagnetic spectrum

Visible light is a small part of the vast electromagnetic spectrum, which extends from radio waves (which we use for long distance communication) to gamma rays (the radiation emitted during radioactive decay of nuclei). Fig 1 shows the electromagnetic spectrum with the wave length and frequency ranges of each range marked on it. If we do a bit of calculation, we can see that throughout the spectrum the product of wavelength and frequency remains constant. This is nothing but the speed of electromagnetic waves (in vacuum) which is nearly $3*10^8$m/s. There is no fundamental difference between “light” and other electromagnetic waves. The reason we think of light as different from say radio waves is because our eyes are sensitive only to the wavelengths lying within this ‘visible’ region. Within this visible region, light of different wavelengths is “seen” by us as light of different colours (Table 1/Box1). So one meaning of colour is the colour or wavelength of the light itself.

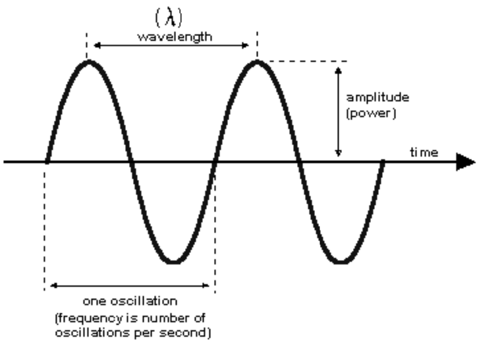


Box 3. Waves

What does the word ‘Waves’ make you imagine , ripples on water, Tsunami , a heat wave or a friend waving goodbye? Have you ever thought about what exactly is a wave as such? A wikipedia definition says, ‘A **wave** is a disturbance that propagates through space and time, usually with transference of energy’. There are various kinds of waves; a sound wave is a periodic disturbance in the positions of air molecules, a flag rippling in strong breeze is a disturbance in the cloth of the flag, earthquakes are related to seismic waves, we communicate through radio waves. Electromagnetic waves are basically disturbances in electric and magnetic fields which can propagate in vacuum, that is, they do not need any physical medium to travel form one point to another.

Waves by themselves have specific properties independent of the medium they travel in. In fact, a branch of Physics is called Wave theory which discusses the properties of waves in general. One fundamental property is the wavelength. For a periodic wave the distance between peaks (high points) is called wavelength. See the figure below.



You can see from the table in Box 1 that the wavelength of visible light is of the order of few hundreds of nanometer or a fraction of a micrometer. Compare this with the wavelength of audible sound in air which is about 35 cm (it changes somewhat with temperature and frequency) which is equal to 350,000,000 nm! The huge difference in wavelength enables sound to travel round the corners of buildings whereas light gets blocked. Next time you take a bath, carry a pebble and drop it in a bucket of water, see if you can measure the wavelength the waves generated in the water.

And do not forget that waves do not have to necessarily 'travel'. There are standing waves also. In many musical instruments sound at a particular pitch is generated by standing waves.

<u>Box 4.</u> How small is an atom?

To get an idea of how small atoms are see the picture below. It is a sphere with a diameter of 1/100000 mm, consisting of 17000 atoms of Copper, prepared at HASYLAB at DESY. Mini-spheres of this kind, called *clusters*, are nowadays an interesting object of research. Assuming both the sphere and the atoms to be perfect spheres you can calculate that the diameter of a single atom is about 0.4 nm.