Computer Vision
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Lecture – 34
Color Fundamentals and Processing Part – I

In this lecture, we will start a new topic on Color Fundamentals and Processing.

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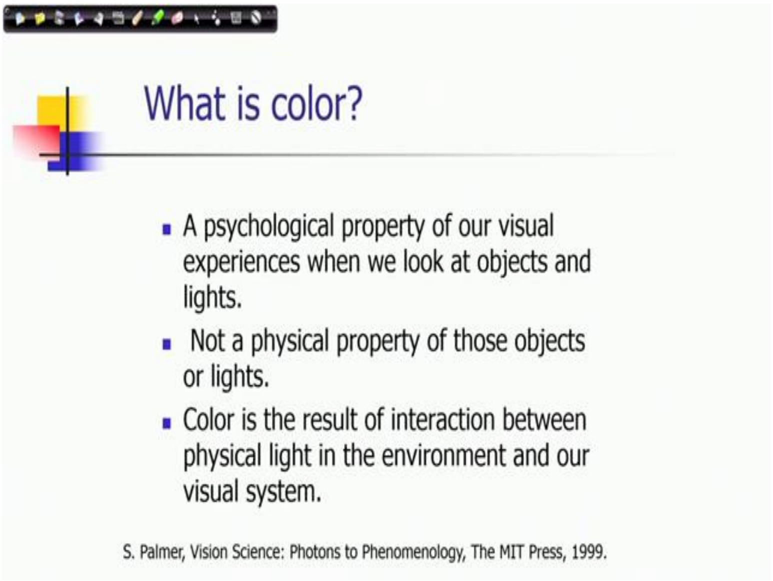

So, let us try to understand what is meant by color and how do we perceive color. Color is a psychological property of our visual experiences when we look at objects and lights. It is not a physical property of those objects or lights. It is the result of an interaction between physical light in the environment and our visual system.

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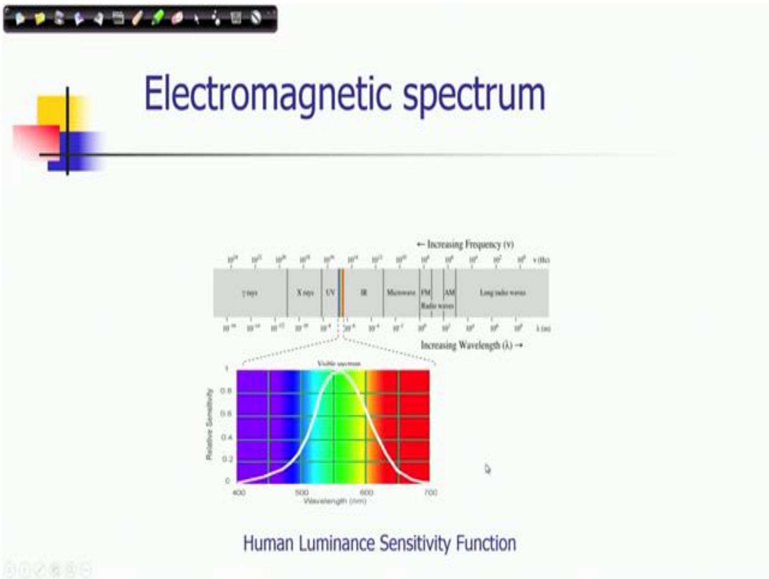

Consider the electromagnetic spectrum, the broad range of electromagnetic spectrum starting from a very long wavelength of radio waves, long radio waves to say gamma waves and you can find there is a very narrow interval in this particular spectrum at the higher end of spectrum frequency and that is that consists of the visible spectrum. Those are the frequencies of lights or colors what we perceive.

And, it has been shown here you know pictorially that how these wavelengths correspond to different colors. You can find that in our school textbook when we learnt about these phenomena of color in different optical bands. So, there are seven particular colors of rainbow that was distinguished and you can find out that from violet to red that famous acronym of VIBGYOR you can identify those spots in this particular picture.

So, interestingly our sensitivity to this part of spectrum is very high and if we see the curve of this luminance sensitivity function which is a function of the wavelength and we can find that it is maximally sensitive when in the green zone that is what it is shown here and later as we move towards the either towards higher frequency range of violet or violet zone and lower frequency range of infrared zone there this luminance sensitive function slowly gets decayed.

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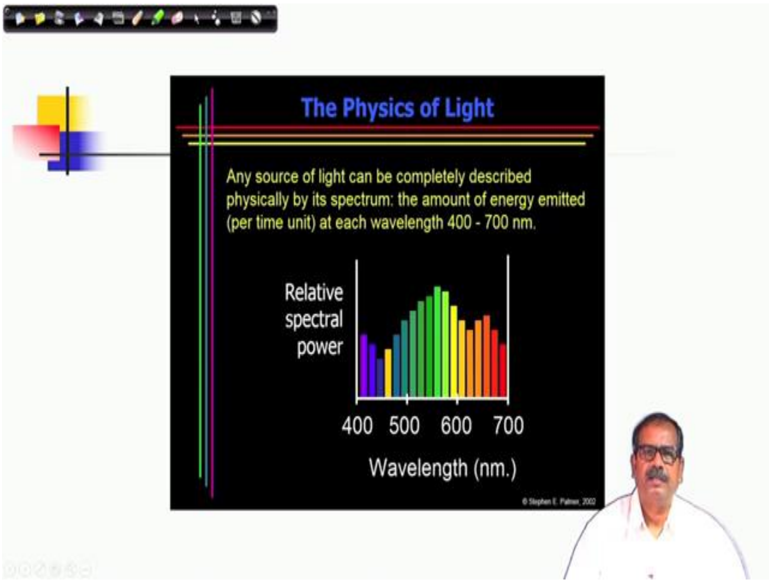

The thing is that the light which is causing the sensation that may not be also having uniform energy distributions over all the wavelengths. So, there is a relative spectral power we call it relative spectral power, it is energy per unit time that is what we need to you know consider here and for example, this could be a signature of a light source so, where you have a relative spectral power distributions over these wavelengths. So, this is how a source of light is described. It is the amount of energy emitted per time unit I mean that is the power at each wavelength from 400 to 700 nanometre and that is a visible band of these electromagnetic wavelengths.

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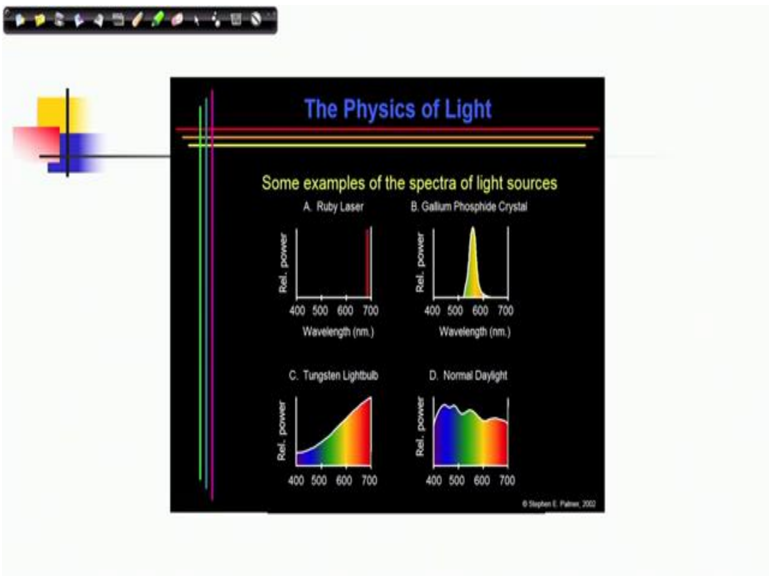

So, some examples of these light sources if you consider a ruby laser, it is a very pure electromagnetic wave radiator at the near about 700 nanometre which is the red in the red region, the color is red. Whereas these are other examples gallium phosphide crystal or if we consider a normal day light more or less this spectrum is uniform that you can see here.

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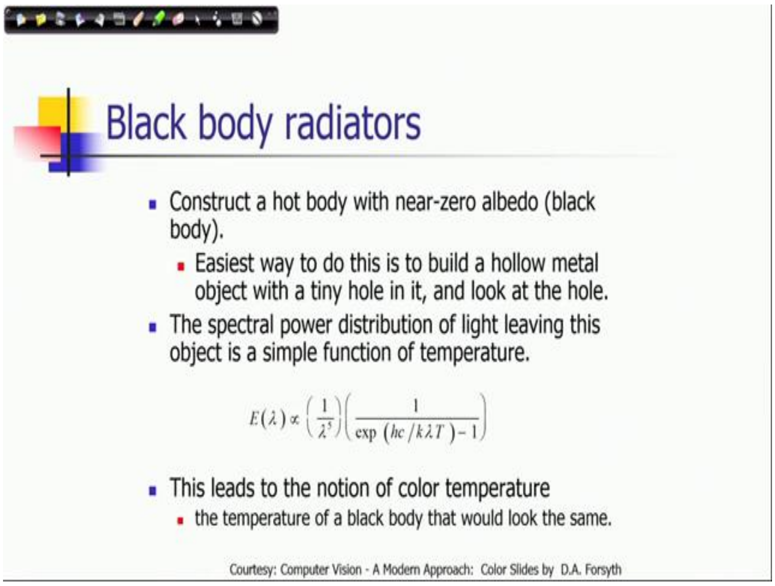

So, one of these particular characterisations of this luminance source is a blackbody radiators which is an ideal energy emitter in that sense and which has only observes from the environment and have its own energy spectrum.

So, one of the example of constructing a blackbody could be let us say first this is a hot body with near-zero albedo or that is why it is blackbody if it does not reflect the light from the environment then we cannot see it. So, that is the concept of blackness in this case. And the easiest way to do this is to build a hollow metal object with a tiny hole in it and we can look at this hole. So, the inside it becomes an ideal blackbody radiator.

And the spectral power distribution of a blackbody radiator it is a simple function of temperature. So, which is radiating and this is relationships of energy imitated in power wavelength energy power wavelength that you can see here. And, this is proportional to this factor where you know that this h is that you know Planck's constant and you can find and k is the Boltzmann constant; those are not defined here. So, it just shows that the kind of functional relationships between the temperature and the wavelength and the distribution of energy with respect to wavelengths given a temperature.

$$E(\lambda) = \frac{1}{\lambda^2}\left(\frac{1}{\exp\left(\frac{he}{k\lambda T}\right) - 1}\right)$$

So, this leads to the notion of a color temperature because if a light source has own spectral power distributions or if I say energy emission distributions over the wavelengths and then which one is closely resembling to this blackbody radiations of a particular temperature, we consider that source has equivalent to having a blackbody source of that color temperature. So, we can tag any luminant source by any color temperature, from there itself we can get its spectral power distribution.

So, this is the temperature of a black body that would look this same when you are considering the notion of color temperature.

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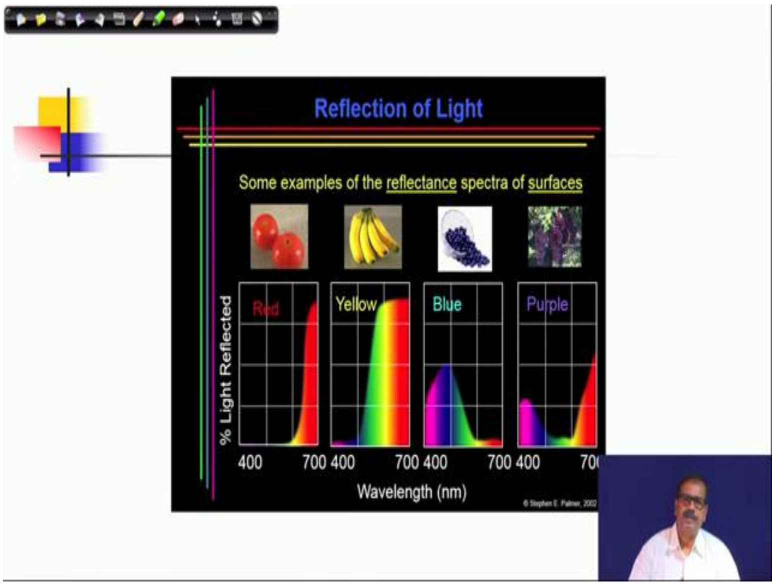

Let us now consider that phenomena of reflection in the environment because this reflection is the major phenomena by which you know we sense the environment we see the objects that we have discussed from the very beginning itself in our very first slide we considered reflected lights projection of 3-dimensional scene points to a 2-dimensional plane.

So, in our visual system also we are getting reflections of from a 3-dimensional scene and it is basically falling into our retina of eyes that I will be coming you will be discussing in my next slides, but the nature of that reflected energy that that also depends upon the kind of surfaces you have. So, every surface absorbs a part of its incident energy and also reflects and in different wavelengths it performs this job in different differently. So, if I consider the percentage of light reflected across wavelengths that also shows the material property of that surface with respect to this particular task.

For example, you can see the picture of tomato here which is of red surface so, it is expected the energy what is reflected from the surface points they will have high content of rate wavelengths. So, higher wavelengths in the optical range those are the part of that energy of the reflected wave. For banana which is yellow it the spectrum looks like this. This is a percentage of light reflected in different wavelengths and it has high reflectance value of within this zone and particularly the yellow zone is very prominent including the red zone also as you can see here.

And, this are the blueberries and naturally this is expected that the reflection in the blue range of the visible spectrum, those will be high and this is another object which is a purple color. And, there we can see that the reflectance in this interval is very slow whereas, in this particular zone in the blue zone and also in the red zone is quite high, that is interesting that you have the purple reflections, but still you have sufficient component of red zones and blue zones. There are explanations of these behaviours of our visual response.

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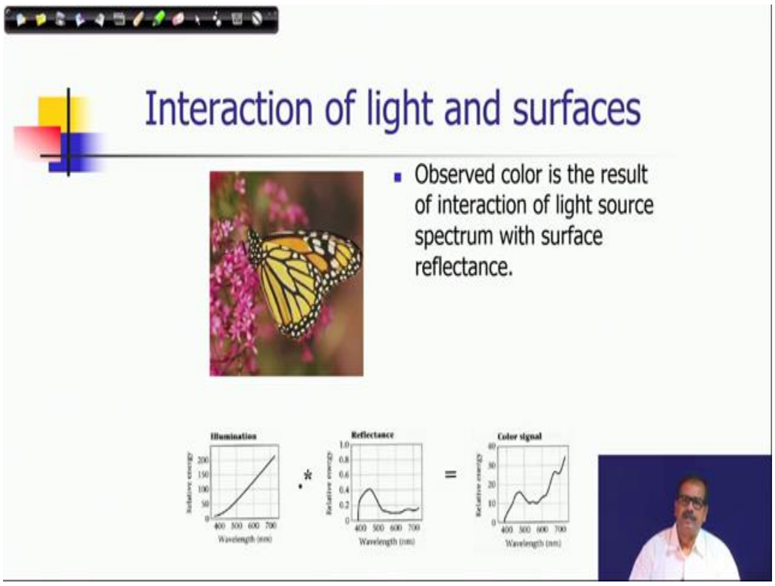

So, finally, as we can see that it is the interactions of light and also the material property of the surface, light source and the material property of the surface that results into our visual sensations. So, that is what we observe as a colour. So, if I consider a light source, the reflected energy distributions across wavelengths in a light source and also they consider the reflectance values or percentage of reflectance reflected energy from surface points and at the surfaces at different wavelengths.

So, for every wavelength the energy what we receive in our visual system that is simply product of these two factors that is the power of illuminations or reflect the relative energy of this particular wavelengths energy of this wave for any wavelength and also considered the corresponding reflectance value of that wavelength you multiply, and then you get the relative energy of that particular wavelength that figure you will get in the received signal. That is how the received signal or received sensation is received sensory signal if I say exciting signal that is how it is characterized in this way.

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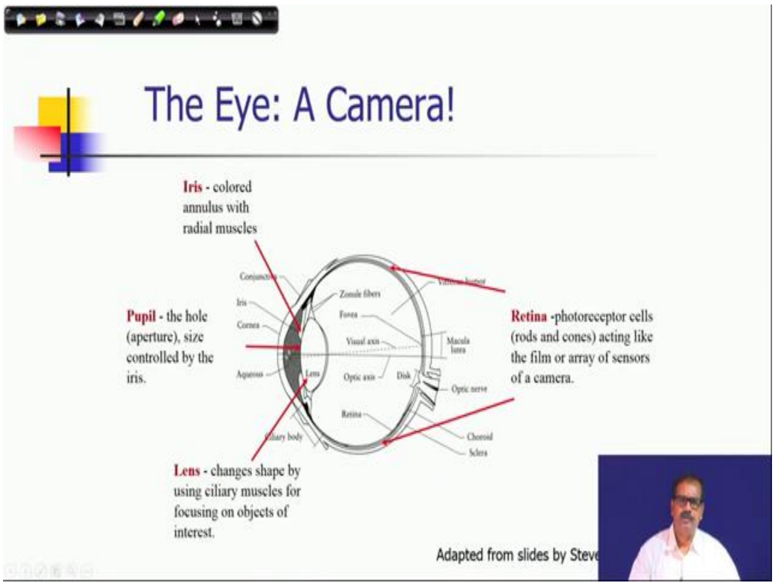

So, now let us consider the function of our eye in our visual system, now it is acting like a camera as you can see in its contraction. Let us say there is a lens and that project see 3-dimensional points in a environment to a 2-dimensional plane, it is not a plane I should say it is like a spherical screen why are these points are projected semi-spherical screen and that is called retina where these points are projected and sensation is carried out from that point through our nervous system to our brain to understand to which gives all the perception of this color and also we can understand the you have seen what is there in front of us.

So, the components in this part which has very direct analogy with the function of different components of a camera you can see lenses this part. Similarly, the retina which were there is a screen kind of thing or which acts like an image plane and there are photoreceptor cells. So, it carries the sensations which transduces this energy into the electrical signal form. So, the retina consists of this photoreceptor cells and from there the sensation is carried through our nervous system to brain.

And, there are different kinds of auto receptor cells in our retina they are called rods and cones. So, I will give more details in next slides. Here there is also an iris which is in colored analyst with radial muscles and there is this pupil the hole or aperture and apart like an aperture of a camera through which the optical lights the energy is transmitted through the lens or lights are coming to the system entering into the system and this is like an aperture of a lens and this its size could be controlled by the iris.

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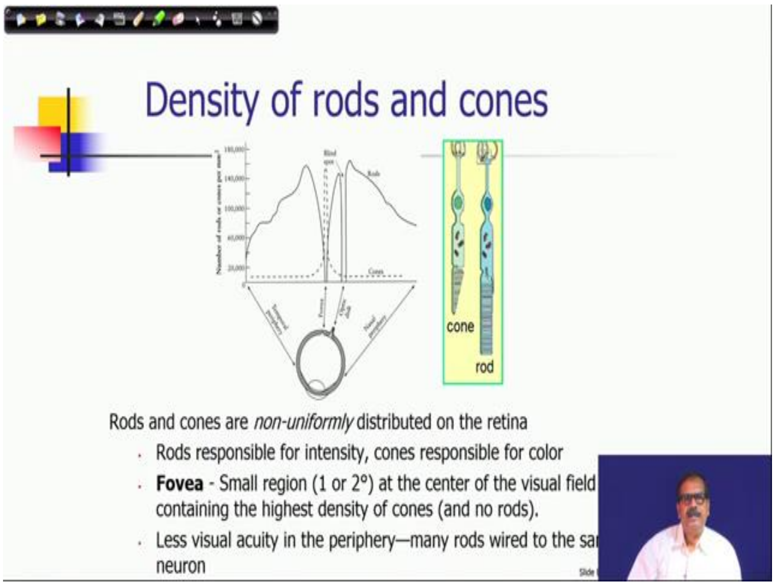

So, about the rods and cones there are two types of receptors in the retina that I mentioned the shape of cone and rod we can see here, their cells basically their cells and they are attached with the corresponding optical nerves which goes to our brain through optical through the nervous system there is a pathway through which the sensation is carried out it is carried towards them. And, this is attached to these particular retinal surface. This is an attachment surface what is there and the shape of this attachment as relate to the nomenclature of these kind of cells this is since this is a conical shape we call it cone and this is a cylindrical shape we call it rod.

Now, the distribution of these rods and cones is not uniform over this retina. So, you can see that the cones are highly concentrated over this. So, this is the distribution of cone and cones are highly concentrated over the retinal part. So, let me just point out. So, this is what you see is a distribution of cone roughly, this is the distribution of cone that is a curve what is shown here and the outside the curves they are the distribution of rods and it is very much concentrated on a particular region and which is a very small high visual acuity region and which is called fovea.

So, this region of the retina is called fovea and here the degree that is formed in this region is a very narrow degree. It forms a very narrow degree about 1 to 2 degree top range. So, the function of rod circuit is responsible for intensity and cones it is responsible for color and the fovea as I mentioned it is a small region that is 1 or 2 degree at the center of visual field containing the highest density of cones and rod.

So, this is how the structure is there and in the periphery you have less visual acuity. There are many rods where to the same neuron. So, that is the kind of structure.

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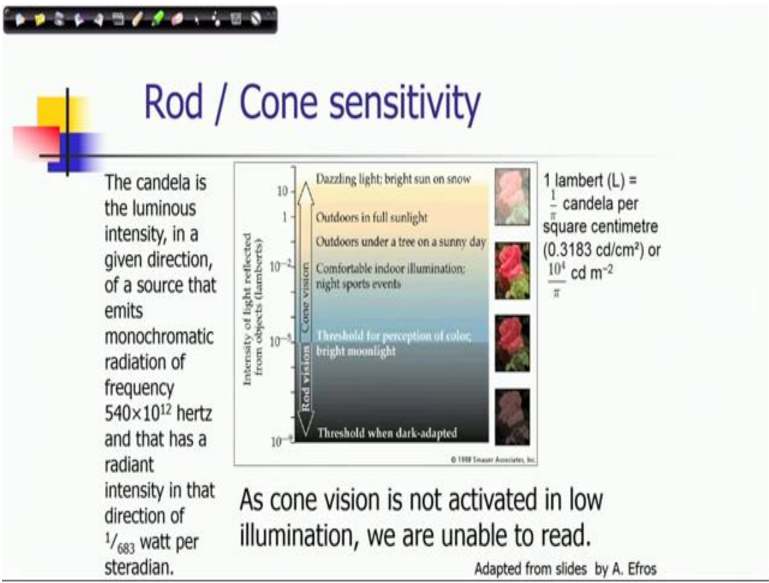

So, let us try to understand how rod and cone they are responsible they function they are responsible for sensing the light and their sensitivity we can see it varies. Rod vision is sensitive to low illuminated environment whereas, cone vision is more sensitive in a very in a bright or highly illuminated environment.

So, you can see from this particular variations it is shown here that this is their zone which is for the rod vision zone and this is a zone which is for cone vision zone. And, this is the scale which is showing the intensity of lights reflected from objects and follows the lambert, you know the unit is a lambert unit. So, if I say what is a lambert, 1 lambert it is basically the definition is in this way. It is $1/\pi$ candela per square centimetre; candela is an again unit of energy radiation.

So, it is the luminous intensity in a given direction of a source that emits monochromatic radiation of a frequency of this 540 terahertz frequency and that has a radiant intensity in the direction of a particular power per steradian that is being emitted that is 1/683 watt per steradian. So, if this is a kind of a intensity, this is a kind of intensity or energy emitted form this is the amount of energy emitted per steradian at that frequency and from a source then that unity is you know one candela in that given directions that is and if it is 1 by candela per square centimetre, then the intensity of that you know surface at that 0.1 lambert. So, that is the definition.

And, for very high intensity object points we will be able to perceive through cone whereas, low intensity visions or through rod. So, visual acuity is more active in the cone sensitive zone and that is why we cannot read we are unable to read in low illumination because rod vision is not visual activity of rod vision is less.

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So, now let us understand that with this background the physiology of color vision. So, as we have seen there are three kinds of cones so, in our visual system and you can see that there are three responses like this is a one kind of wavelength this is one kind of response which is shown here as the S and or short wavelength response and that is the response in the you know blue zone. There are medium wavelength response which has been shown here as M and there are long wavelength response. So, there are three types of cones. So, it is cones are also there are three categories and they have different types of wavelength you know responses.

And, so, the ratio of this long wavelength, medium wavelength and short wavelength cones they also widely vary. As you can see that more number of you know long wavelength cones are in the red zone that is the ratio is 10, whereas in the medium wavelength it is 5 and short wavelength it is 1 and almost no S cones in the center of the fovea. So, in fact, there is a nice picture which shows the distribution of different types of cones by showing the colored dots in this particular two-dimensional point.

So, if we flatten the retinal surface near the fovea particularly and we can see in the centrals part hardly there are blue cones or a shorter wavelength cones; mostly it is red and the green cones or medium wavelength cones that we can see in this picture.

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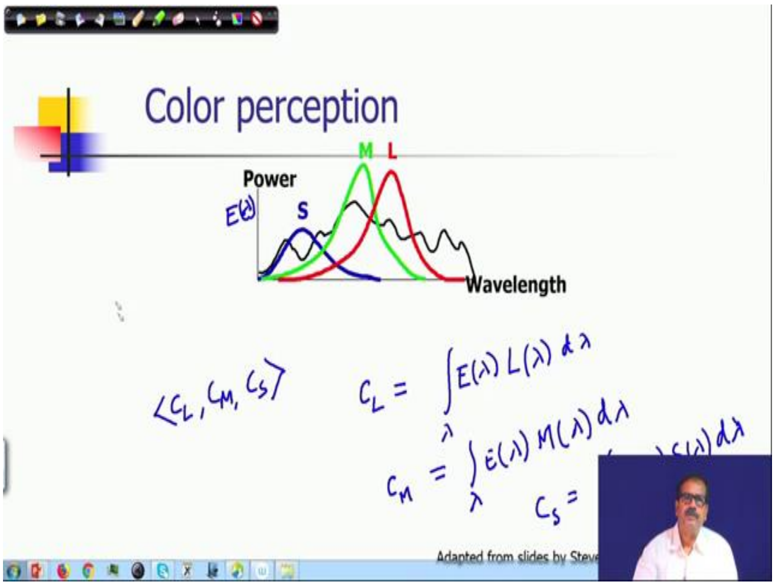

So, just to model this color perception we can consider this particular you know simple mathematical you know explanation or mathematical model, that let us consider the incident energy in our retina a having is relative you know spectral power distributions as shown here across the wavelengths. And, then you have the same you know sensation is received by three different categories of cones. So, we will be explaining the color perceptions only using the cone vision. So, we are not considering rod vision in perceiving colors.

So, the color perception is a phenomena due to our sensations through cone cells and there the same sensation is you know same energy is received by different kinds of cones, but they have different you know different effects or responses because they are wavelength response they are wavelength or there they are response of to their wavelengths are difference. For example, this is the long wavelength cells, this is the filter response for long wavelength cells and this is the filter response for medium wavelength cells and this is a filter response for short wavelength sense.

So, as we have considered the simple model that what we can do if I consider this received energy is can be shown as see $E(\lambda)$ then in our long wavelength rest filters in the long wavelength cones the received energy can be modelled as $E(\lambda)\ L(\lambda)$. So, what is being finally, received the output of this output from the long wavelength cone is $E(\lambda)\ L(\lambda)$. So, it is an integration over λ and that should be the response from long wavelength cones. So,

$$C_L = \int_{\lambda} E(\lambda)\, L(\lambda) d\lambda$$

$$C_M = \int_{\lambda} E(\lambda)\, M(\lambda) d\lambda$$

$$C_S = \int_{\lambda} E(\lambda)\, S(\lambda) d\lambda$$

So, this is what we will be obtaining from a long wavelength cone; mathematically this is the operation that has been carried out there.

Similarly, for the medium wavelength cone we can write it as E(λ). So, this is a response this is the output of the of the filter with spectrum frequency spectrum and say M(λ)or wavelength spectrum as E(λ) that is a filter response and then this is output we get from the medium wavelength cone and for short wavelength cone in the same way we can write it as E(λ) S(λ).

So, now you can see that given a particular energy particular or particular energy from the environment which is received by all these cones we get we can finally, this can be coded into three factors one from the long wavelength cones another from the medium wavelength cones, another from the short wavelength cones. And, those sensations are carried to our in our brain through the nervous systems and those are perceived as a color.

So, finally, color perceptions can be you know considered into this from that it is the effect of these sensations which is giving the ultimate you know our which is resulting into the perception of the color of that particular light and this actually leads to the trichromatic theory of color which I will be describing next.

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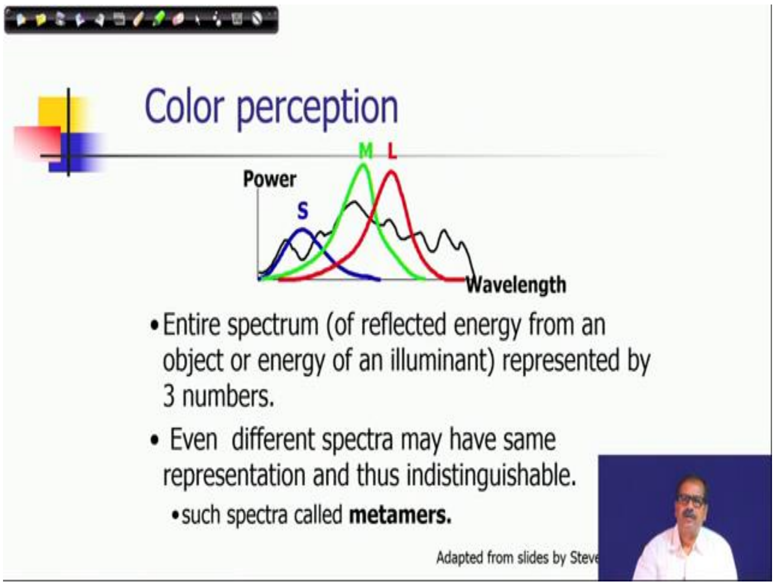

So, just to summarize once again, in this color perception we have entire spectrum and entire spectrum of reflected energy from an object or energy of an illuminate that could be represented by three numbers, as I explained how these numbers could be mathematically computed given all these facts. And, then the it also know tells us that even if we have different spectra it can have the same representation because finally, as you can see there are it could lead to the same set of triplets by doing that product and sign integrations over accumulations of this product of the corresponding response and also the power over the wavelengths that would give you the same vectors.

So, it becomes in the indistinguishable and such spectra they are called metamers.

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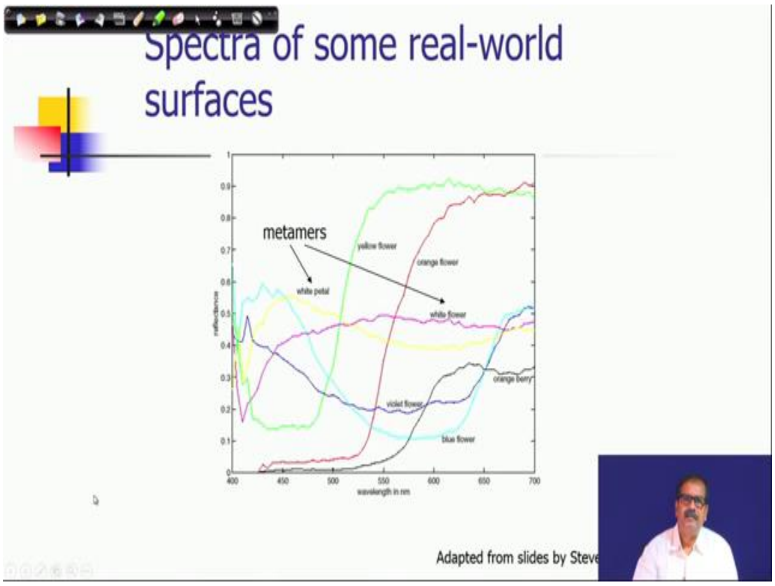

So, there are some examples of this metamers we can see here. Consider this spectra or the relative power spectra for different kinds of reflected waves. See this is a white petal spectra which has been shown here by this particular color and another in this pink curve this is a this is a white flower and we our sensation of white petal and white flower is similar it is a white sensation. And, but as you can see there is it there is a lot of variations over the distribution of the relative power over the wavelengths in these two different sources, but still we perceive them as white and this is an example of metamer.

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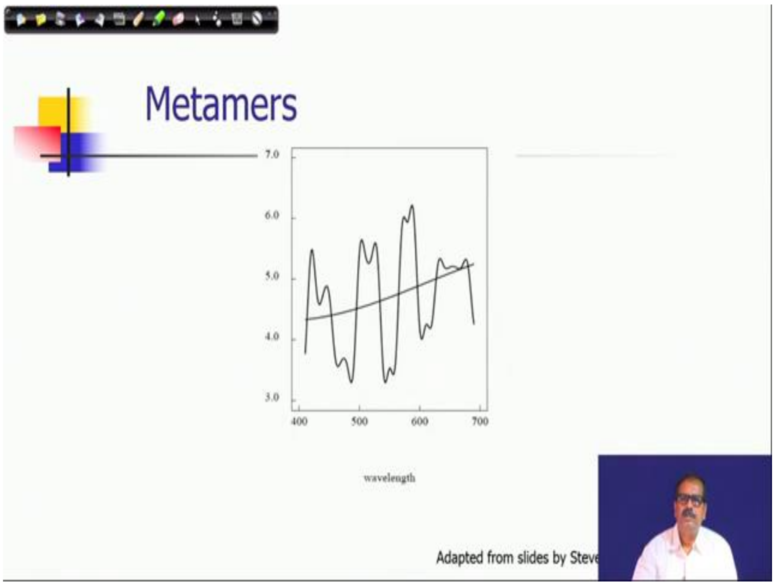

There could be another example that you know you can see that this is a widely varying relative spectral, relative power over the wavelengths whereas, there is a smooth variations. But, final effect of integrations of the product of our cone response and with these you know energy distributions, with these power distributions of a particular at a particular wavelength final effect would be would may be same and that is how that it could be also another pairs of metamers.

So, with this let me stop at this point for this lecture we will continue this discussion of color perception. Thank you very much for your attention.

Keywords: Electromagnetic spectrum, black-body radiators, color perception, rods and cones.