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Lecture - 36
Color Fundamentals and Processing (Part III)

We are discussing about trichromatic representation of a color according to our perception or three-vectorial form of a color. In the previous lecture, we discussed how color could be represented in its natural space of RGB, natural in the sense that we captured the information of color into these three components, red, green, blue but the problem is that not all possible colors could be produced by using these three components in an additive mixture of those components. So, for a convenient representation of color, where some of these vectors even all these vectors could be represented by positive numbers in their components.

There is an hypothetical color space which has been designed by an international body of color; and in acronym it is called CIE, and that space is called XYZ space and there is a transformation which has been proposed by that body which has been suggested by that body or recommended by that body. Using that transformation, you can convert any color represented in RGB space to that XYZ space and since it is a linear transformation, so this is also a linear color space.

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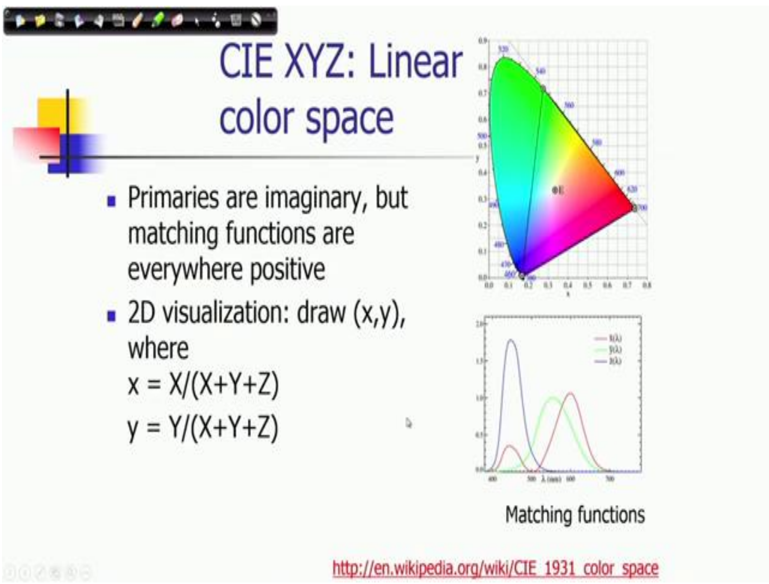

So, we call this space as CIE XYZ color space and here as I mentioned primaries are imaginary, but matching functions are everywhere positive that is the advantage we have. So, if I again plot those matching functions in terms of color representation of color in across the wavelengths, then we can see actually all these values are positive values here and so this is the for, so this is representing $X(\lambda)$), this is $Y(\lambda)$, and this is $Z(\lambda)$.

Now, one of the representation of color, you can consider also a two-dimensional representation because the part of the color representation as we can see using Grassman's law that if I scale the vector still you will get the same sensation of the color, only its intensity changes. So, if I can separate out this intensity from the other quantities, then also we can represent a color.

So, with respect to intensity or normalize the color representation with respect to intensity, then this normalized representation once again can be represented in a two-dimensional space, so that is a motivations of representing color in a two-dimensional space and as you can see that this normalization of XYZ component happens in this way, so this is normalized x and this is normalized y.

So, here I am showing you a normalized representation of all colors which has been converted to their respective x, y, z coordinate given these wavelengths, and they can be represented in a two-dimensional space. We call this space as normalized x, y space and a point is representing color here pictorially, even the color dots are representing the corresponding coordinates.

So, this phase is called CIE XY chromatic space, because here the intensity information is missing here, only we are interested on the relative representation of two components which is sufficient to identify a color uniquely in this particular space. So, this is what is a normalized representation.

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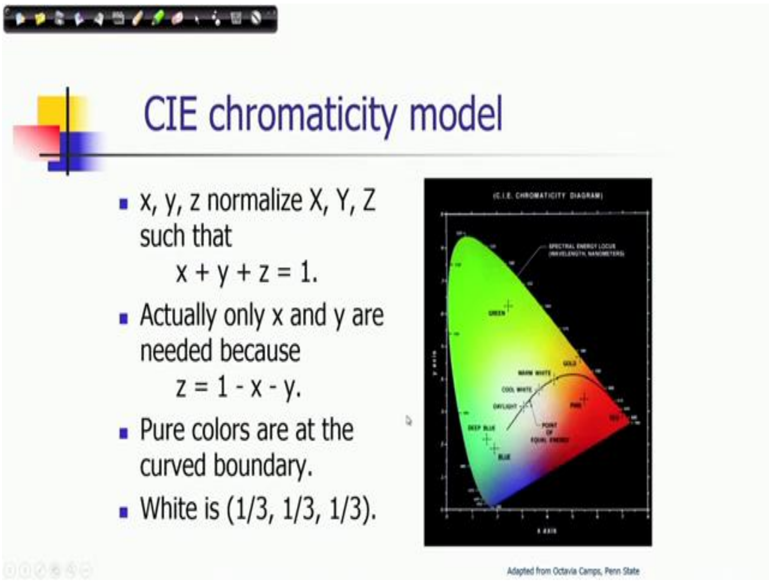

So, to understand this particular representation, we follow a model. we call it CIE chromaticity model. As I mentioned that it is a normalized x, y, z and since the sum of them is equal to 1, so it is sufficient to represent any point using x and y and in this model, you can see the pure color is in the boundaries. So, this boundary represents pure colors. In fact, this is the red zone of having 700 nanometer and as you proceed through this boundary wavelength is decreasing which means frequency of the energy is increasing or electromagnetic wave is increasing and red, green and this is a blue zone and wavelength is near about 360 nanometer. So, these are the pure representation of color.

In between it has other components of this color, I mean we will be again defining them. Actually the white point means you have all the components with equal magnitude and this point can be represented by $\left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$ in the three dimensional form but in a two-dimensional form it is simply $\left(\frac{1}{3}, \frac{1}{3}\right)$.

In this diagram, we are also showing a curve which is interesting it is showing the particular color in our visual perceptions there, as if their color remains almost same, only the purity of the color varies and this is the curve, this is a locus of same chromatic sensation in the sensor, no, I should say the pure color what is being shown here in the periphery of this curve. That sensation still carries over this curve. even if the point moves that sensation still carries. its whiteness of the color differs.

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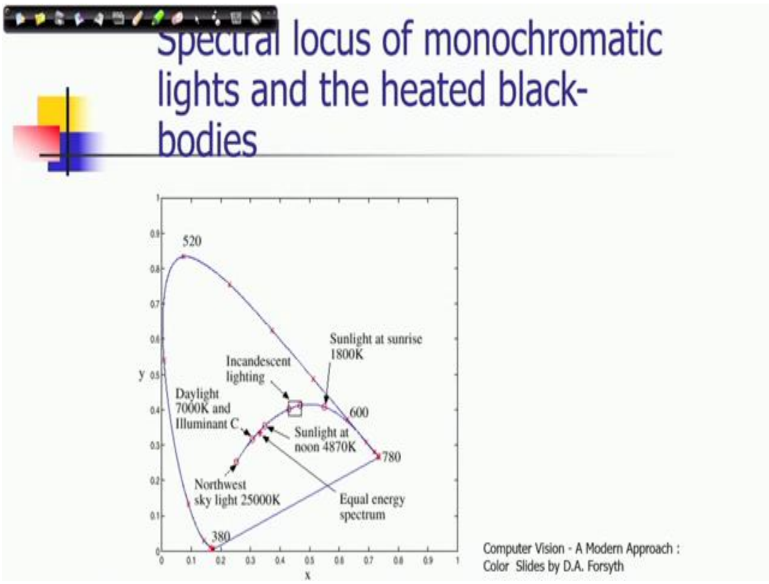

So, this is called the spectral locus of monochromatic lights. So, it is showing here that how different light source of different wavelengths that can be represented here also and you can see that. if I consider the representation of sunlight even the sun which is at noon which is equivalent to a blackbody radiator of 4870 Kelvin and which is almost a white light source but when it goes in sunrise or even sunset, it is becoming more reddish and you can see the (Refer Time: 06:55) trend captured in this particular curve.

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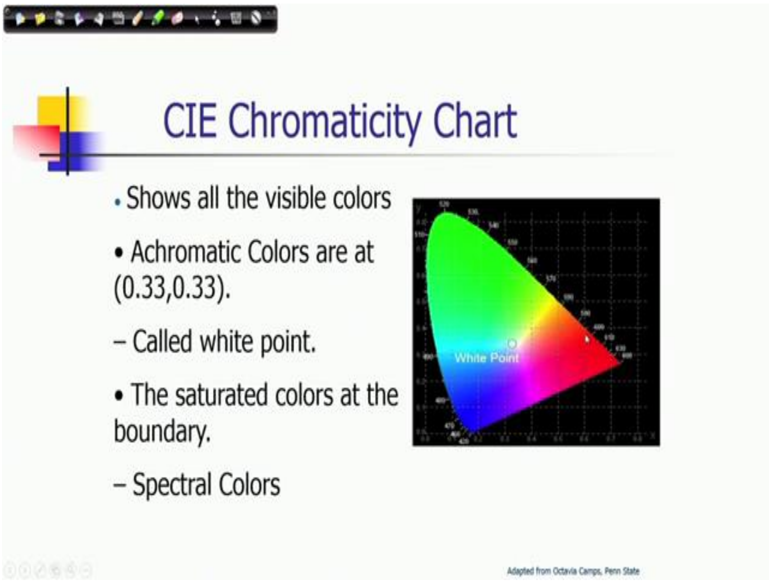

So, CIE chromaticity chart can provide you a simple representation of color using two particular components which is called saturation and hue; I will be defining them. So, any color which is achromatic means which does not have in the sense of our white sensation that is what is achromatic color, and that is represented by as I mentioned it should be $\left(\frac{1}{3}, \frac{1}{3}\right)$ and this is a simple representation whereas, the saturated colors means pure colors they are at the boundary and there is a spectral colors.

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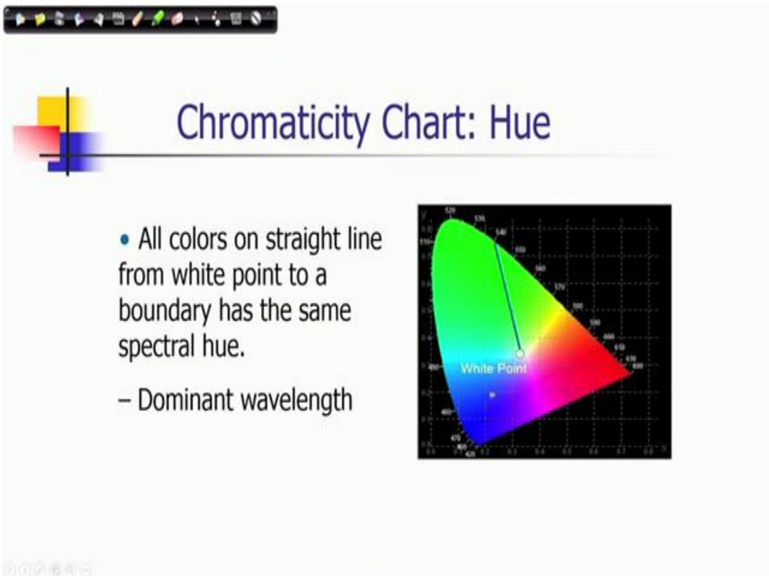

And so if I consider a radial point, a straight line from this white point connecting to any point in the periphery, now this is a simple model where it is representing the same color represented by this wavelength whereas, the whiteness of the color varies as you move towards periphery the colored is becoming more pure which means whiteness is lessened as it as it moves inward it whiteness is going to increase. So, the this is called saturation.

So, less white means less whiteness in the color means it is more saturated. So, the presentation of hue in this form it is giving the directions, it is remain, it is represented by the I should say a direction from the white point which is directing to a particular point in the periphery. So, we can represent it by an angle also with respect to a reference direction.

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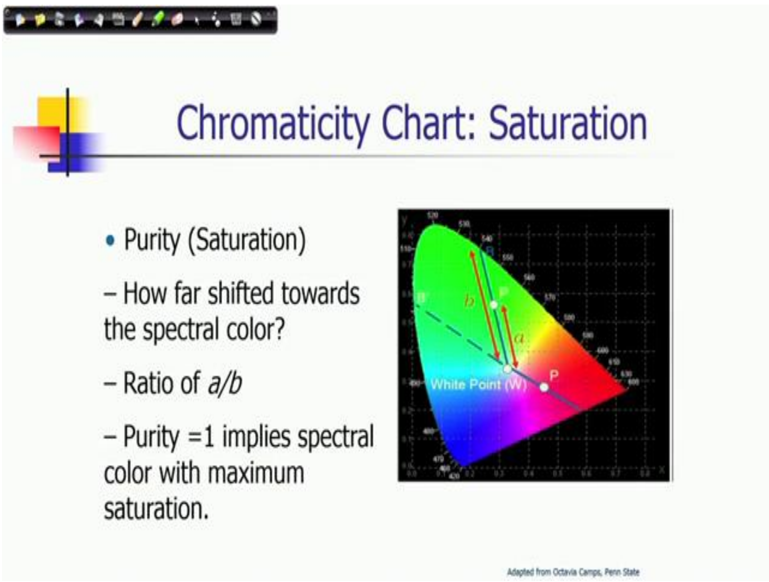

Whereas for hue it is the relative proportion of these two lengths how close it is to white point, and what is the total length of this particular radial segment which is touching to the periphery of the chromaticity chart. So, how far it is shifted towards the spectral color? So, this ratio of $\frac{a}{b}$ it is giving the saturation as you see that it is as it is moving more outward this is going to be increased.

So, it in this scale particularly saturate varies from 0 to 1 in this definition. So, this is it this definition may vary also this is one sort of simple representation. So, periodic well to 1 implies spectral color with maximum saturation.

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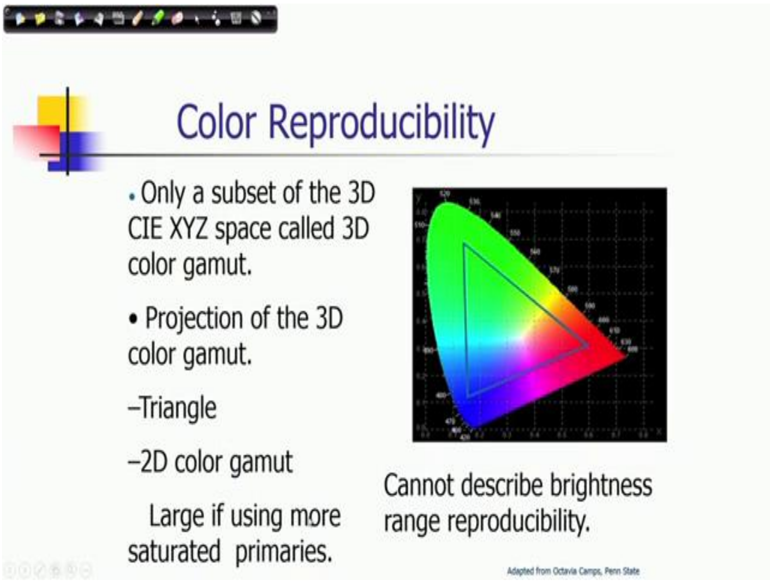

So, as I was mentioning that color reproducibility depends upon the choice of primaries because once you choose a set of primaries then in the XY chromaticity chart itself, we can represent them as three points. Now, these forms a triangle, so any linear combination of these primaries that would be any linear combination means additive combination, that should be represented by a point within the interior of this triangle, any point should lie within the interior of the triangle or in the edges of this triangle. So, this is the limit of representation of color by these set of primaries, so that is what this particular fact is described here.

So, if I project the 3D color gamut, then you will get this triangle and we call this also a 2D color gamut. So, color gamut is a set up reproducible colors given a set of primaries. So, it could vary, this set could be large if I consider the primaries are more saturated, because if it is more saturated, it will be moving towards the periphery and you can see the area of this triangle will be increasing in that case.

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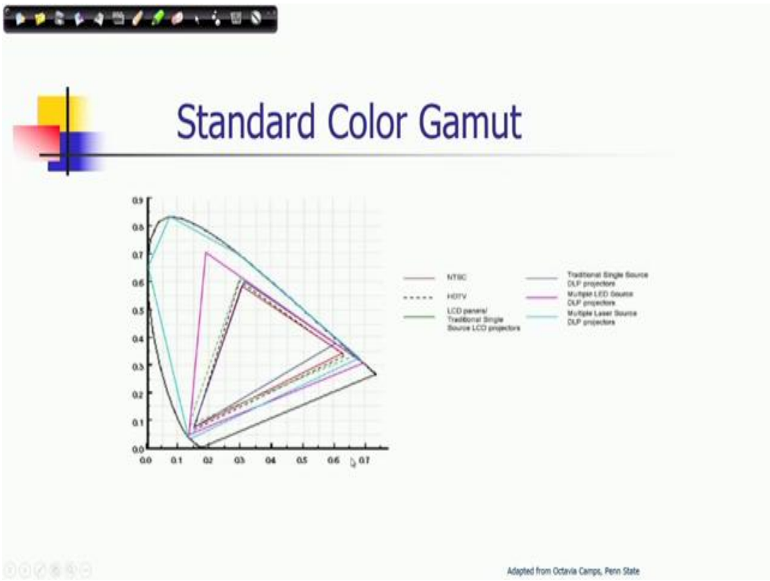

So, there are various primaries are used and which increases the scope of color gamut for displaying colors, and in fact, there could be a some kinds of display or where you can have more number of primaries instead of rate, that means, you do not have an independent set of primaries, you can have some dependent set of colors also whose combinations are also considered and in that way you can increase the range of color reproducibility.

One such example has been shown here. So, this is a multiple laser source DLP projections where you can have multiple primary. So, it is given by the we should not call them primary color in that sense, we should call those color sources whose linear combination is producing the other colors and, so these are showing you these vertices are showing you this number of colors.

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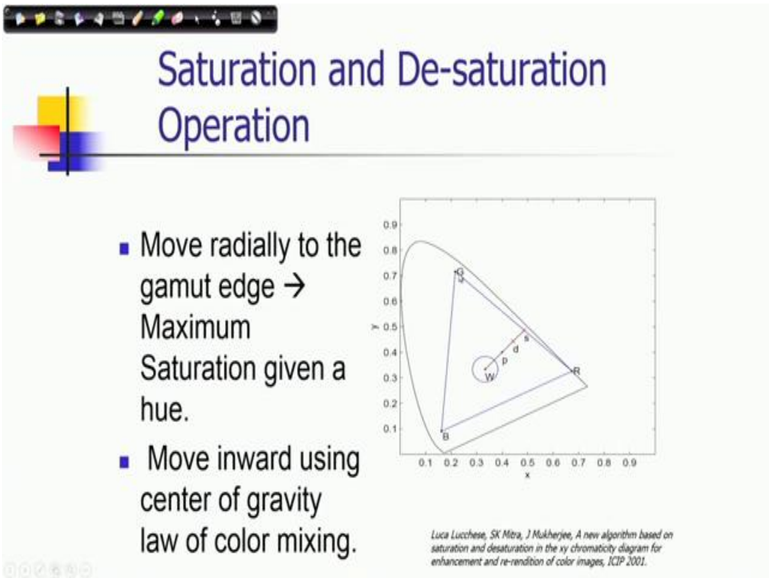

So, one of the interesting operations from the processings point of view is called saturation and desaturation operation. So, let us understand this particular operation. As we can see that given a color image, we can represent the color of any pixel we can get them into this color gamut. We can represent by any point which will lie within this color gamut and when we consider the primary of the corresponding color system is given by this points here, which is shown as RGB here.

So, if I consider say p is a true color, which is the color of the source image. And then using our model, if I draw a vector or draw a line connecting the white point which is at the point $\left(\frac{1}{3},\frac{1}{3}\right)$ of this color space that is a coordinate or you can see here (0.33, 0.33) is a coordinate point. So, if I know connect these two points W, p and extend it, when it intersects the edge of the color gamut, so that is the maximum possible reproduction of a color of this same hue; and in the same direction, this is a maximally saturated color in this representation.

So, we can compute this point and then again you can convert it back to RGB, and you get the corresponding RGB component. In that way, in this way, you can get the maximum saturations. However, if I again any point in this straight line itself can represent a color having the same hue that means the color corresponding to the wavelength which is represented by this vector.

So, there is another operation called de-saturation that means saturation may not give you always pleasing sensation. So, it is not true that more saturated colors and more pleasing there in our perception. So, we feel comfortable with the right balance of colors their saturations as we are accustomed by perceiving different phenomena of nature. So, sometimes it is required even to reduce the saturation and move inwards towards the white (Refer Time: 14:21) point following the same vectorial direction or along the same line, so that is called de-saturation operation.

So, in this diagram, what it is shown that say p is the point which is a color of the pixel and if I connect W, p and extend it, and when it intersects with this edge B, G, then it is a maximal saturation point; and if I move inward also it is the de-saturation point d and this circle is showing here. I explain the algorithms of saturation de saturation, usually the color within this circle most of them are like whitish. So, it is very difficult, it is not visually pleasing if we disturb these points.

So, sometimes for the processing of saturation and de-saturation, we leave out these points which are very close to white. So, some empirically chosen threshold we can model it as a circle around that I mean it is a threshold radius around that point W and we can leave out from this processing.

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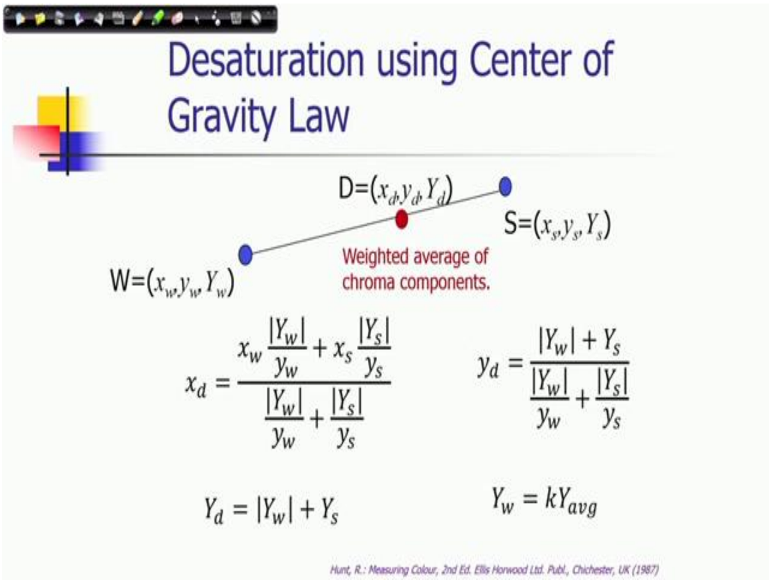

So, this operation of saturation desaturation that is used for enhancing color images. So, we will describe this algorithm before that. let me explain the desaturation a process, there is a work which proposed a particular intuitive way of obtaining the weighted combination. So, giving these two points W and S color point in the x y chromaticity space, you can get a desaturation point between them because as you see that this is desaturated with respect to this S by following a property called center of gravity law, which means that it is a weighted combination and weights are chosen in such a way. So, these are the weights, so $\frac{|Y_w|}{y_w}$. So, I will explain this notations or symbols.

So, this is the weight. If multiply with the corresponding thing you know values and take the weighted average, you get x_d, similarly you get y_d. You note that , this value is nothing but multiplication of this weight into y_w and this value is multiplication of this weight, weight y_s.

So, you get this weighted combination of x_d , y_d whereas Y_d is the intensity part is defined as the sum of these two values ($Y_d = |Y_w| + Y_S$) and the intensity of whiteness can be also estimated as the average of Y of the image a fraction of it k. So, empirically which you can choose, for example, you can choose k equal to 1 also.

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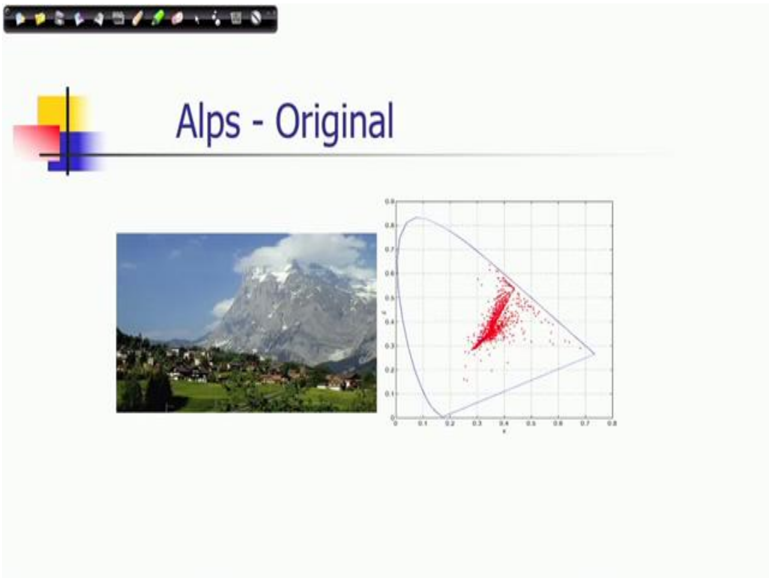

So, one example of saturation process has been shown here. There is an image where we named this image Alps because this is the image of a particular mountain and speak of Alps and this is the original image. And in the original image, if I plot the colors of the pixels in the x y chromaticity chart you can see this is a distribution and you can see from this distribution itself, the triangular gamut is perceptible because all these points they lie within the triangles of these primaries which have been assumed to some values considering the properties of the display.

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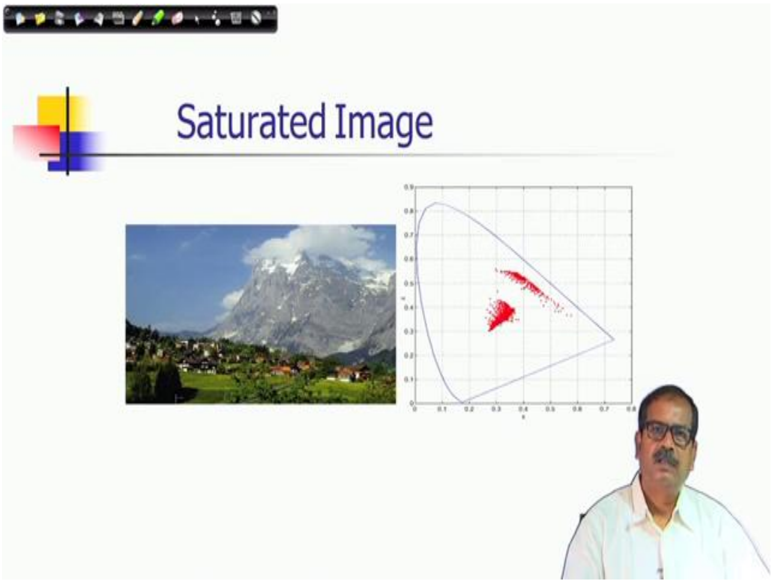

So, if I saturate and if I leave out those points as I mentioned without processing and saturate other points, we can find that they are lying at the edges, and then this is a saturated images. You can see some of the reddish points are if I look at the previous one. So, this point is becoming more reddish in the saturated images.

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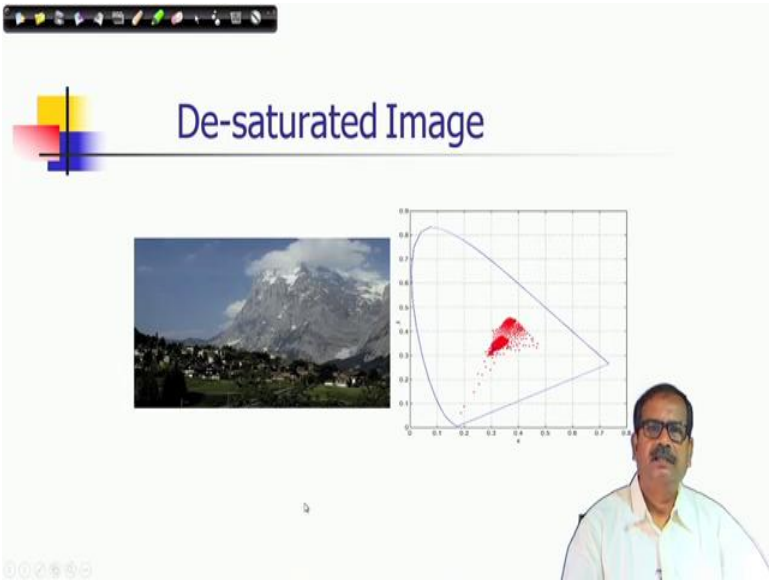

And following desaturation operations using that central center of gravity law, you get a desaturated image like this and where the chromaticity chart, the distribution of color is showing in this form.

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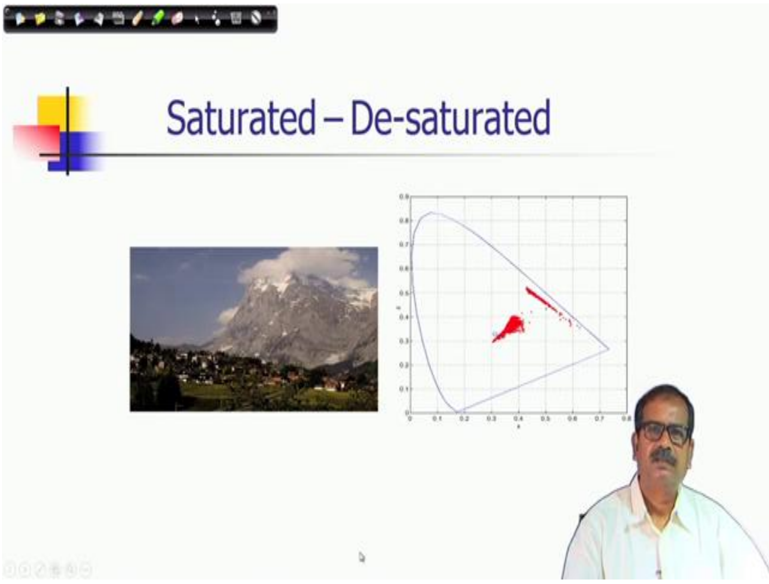

So, that is just desaturated, and saturated, desaturated, after saturation then you performing desaturation, then it looks like this.

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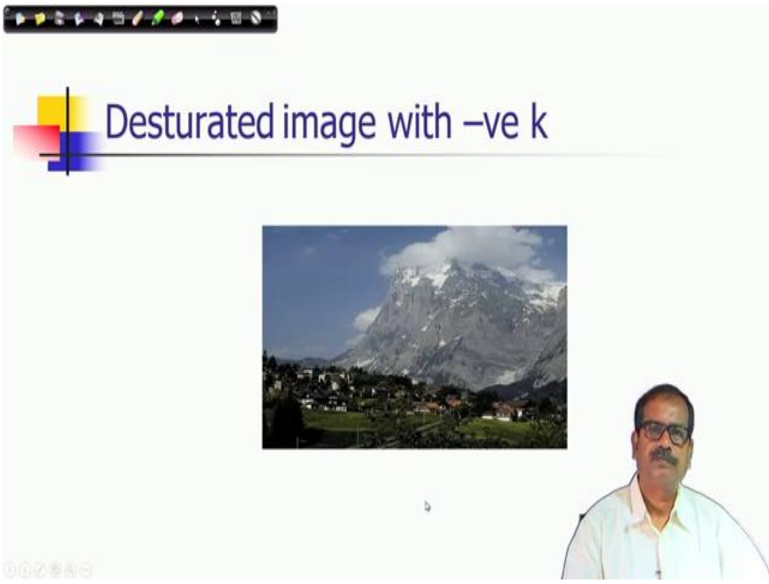

$Y_w = kY_{avg}$

There are some variations you can make. So, if I use the negative value of k as the you know intensity at the white point that you remember kY_{avg} . let me show you the value of the effect what is defined by k. So, this is what is k. So, it is a multiplication factor with the Y_{avg} value and that is giving Y_w and this is how the intensity at this point is determined.

So, this component of course, this component is negative means you are not taking the modulus in that sense. So, you are subtracting it in fact. So, if I use that negative k, so you have to modify that definition, it should not take modulus and then what we get, we get these kind of images. This is the effect.

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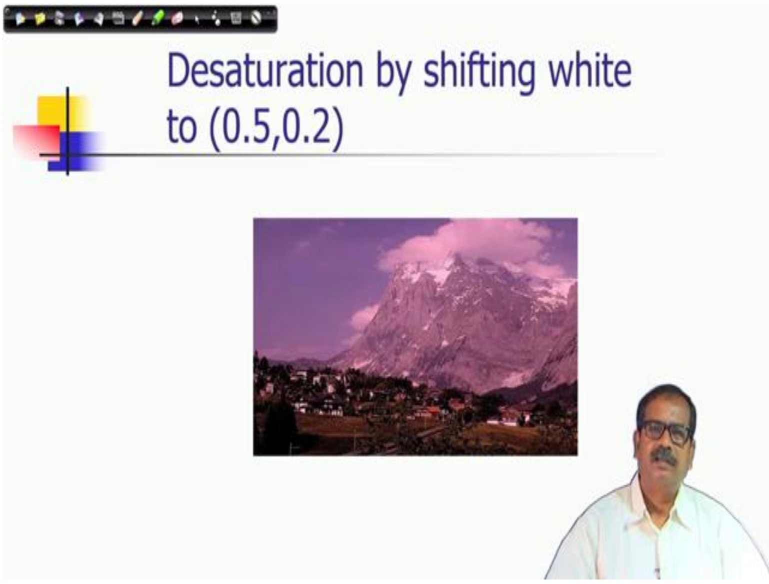

If I shift the white instead of $\left(\frac{1}{3},\frac{1}{3}\right)$ as the white point, the same process we carry out same computation you carry out by considering your white point is (0.5, 0.2), which is towards say reddish zone or and then now you can see that the effect, effect of reddish.

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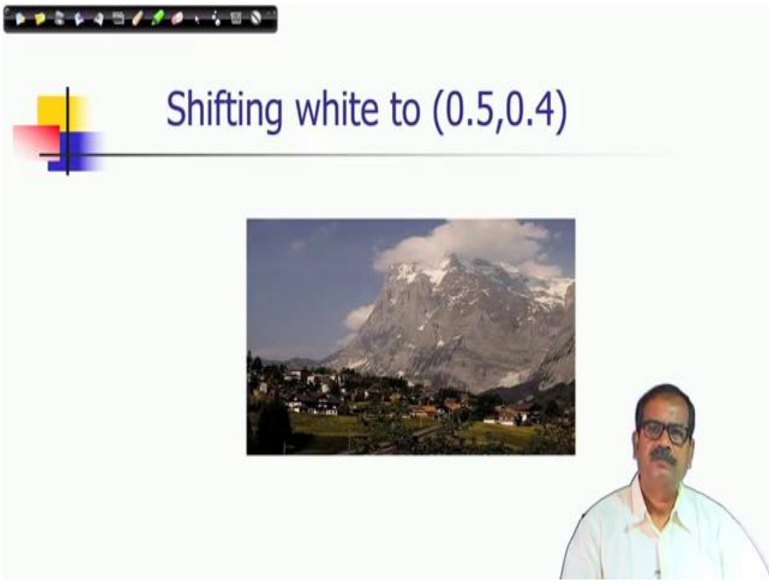

Similarly, if I shift white towards greenish zone, then this is the effect or towards bluish zone this is the effect.

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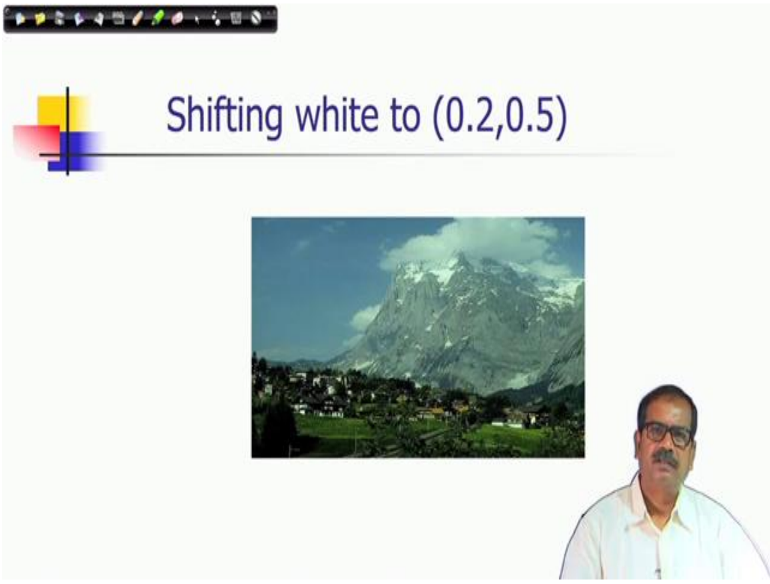

So, there are different effects those are possible by varying this kind of points.

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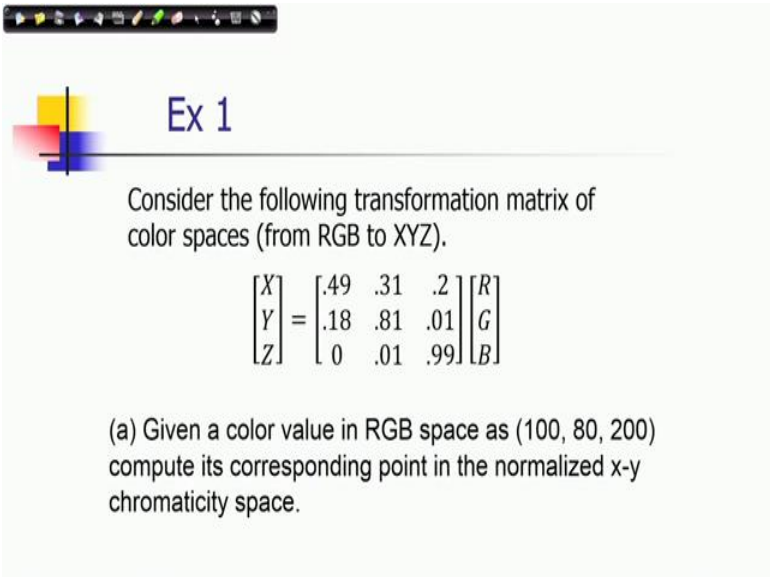

So, this is one example of processing with the color images by using the normalized CIE chromaticity chart and let me discuss one exercise how do we compute this chromaticity point, it will show you those computational steps, so if you can solve this particular problem. So, in this case the problem says statement says in this way that considered the following transformation matrix.

So, this is the RGB to XYZ transformation matrix, given any RGB color you can convert it to XYZ. So, first given a color value in RGB space this is the three vector representation (100, 80, 200) compute its corresponding point in the normalized x-y chromaticity space. So, this is what we would like to solve.

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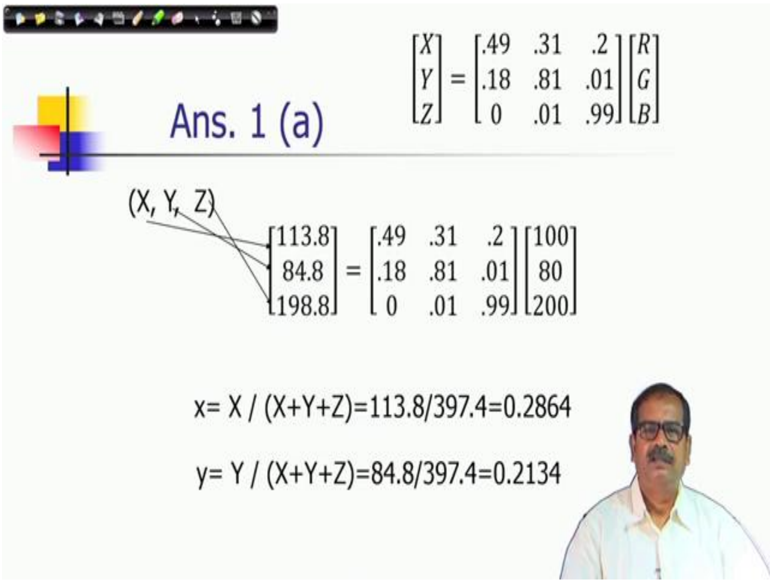

And this is very straightforward what we have to do, you have to simply multiply the RGB vector with the transformation matrix, and then you will get corresponding XYZ vectors and then you have to normalize with the definition. So, we know that the normalized, so these are the XYZ components and this is a normalized X which has to be; which has to be divided by the sum of these components. So, you get a value say 0.2864 and y you get a value similarly 0.2134. So, this is a part of the assignment and of that problem.

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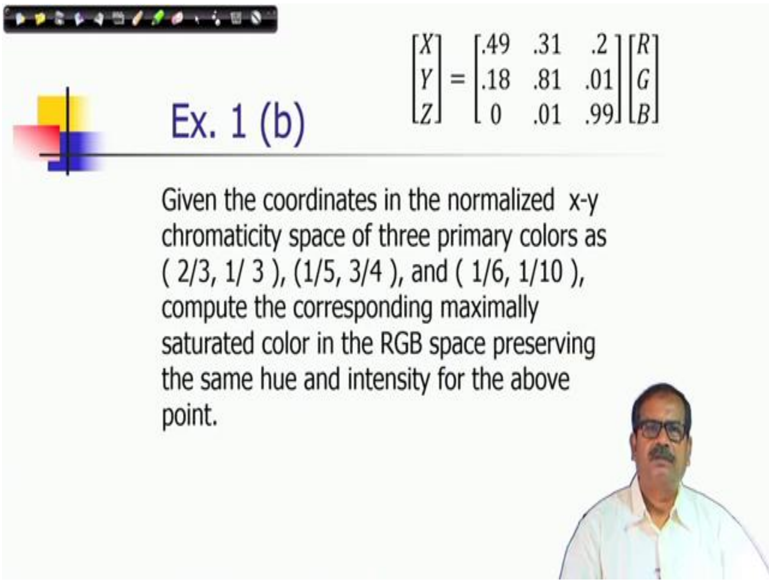

The next what you need to find out that we need to find out a maximal saturated point of that particular color. So, where you get the points of the no vertices of that color that triangular gamut in this way. So, let me read out once again given the coordinates in the normalized x-y chromaticity space of three primary colors as these $\left(\frac{2}{3}, \frac{1}{3}\right)$, so note it is it should be for R; $\left(\frac{1}{5}, \frac{3}{4}\right)$ it should be for green; and $\left(\frac{1}{6}, \frac{1}{10}\right)$ it should be for blue.

So, in our representation, we will be using in our discussion using those three notations. So, what we need to compute the corresponding maximally saturated color in the RGB space preserving the same hue and intensity for the above point.

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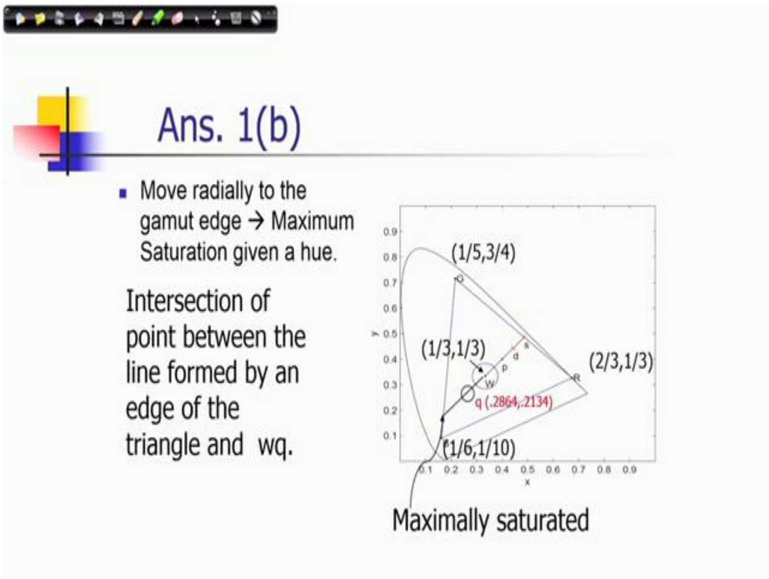

So, if I perform this operation, so once again this figure is explaining what should be done but consider that you have a point, so, this is the red point, this is a green and this is a blue in the chromaticity chart. So, this is how the triangular gamut is specified, and consider this as a white point $\left(\frac{1}{3},\frac{1}{3}\right)$ and this is the point you have computed already of that color vector in the x-y chromaticity chart and the thing is that you need to find out the maximally saturated point of connecting and say w, q, and which is connecting the triangular edge.

Now, it may happen that it is difficult to say the exact position of this point, it may happen this point is here, and it is intersecting this one and actually the intersection of this edge is, outside the gamma triangle. So, you need to consider all these options or even it can intersect in this direction this edge and now you have to find out that in which direction this point is there, that means, you have to consider the corresponding angle and then only choose that direction for the maximally saturated one.

So, there are several options. Now, in our case we will be considering only intersection with these two because by looking at the coordinate positions we can identify that these are the two possible candidates of edges, and we will be considering and the solving this in that fashion. So, we have to find out the intersection of point between the line formed by an edge of the triangle and wq. So, let us proceed with this computation.

You should note this maximally saturated as I mentioned that point or whatever the intersection is there, then you have to decide before declaring it as maximally saturated.

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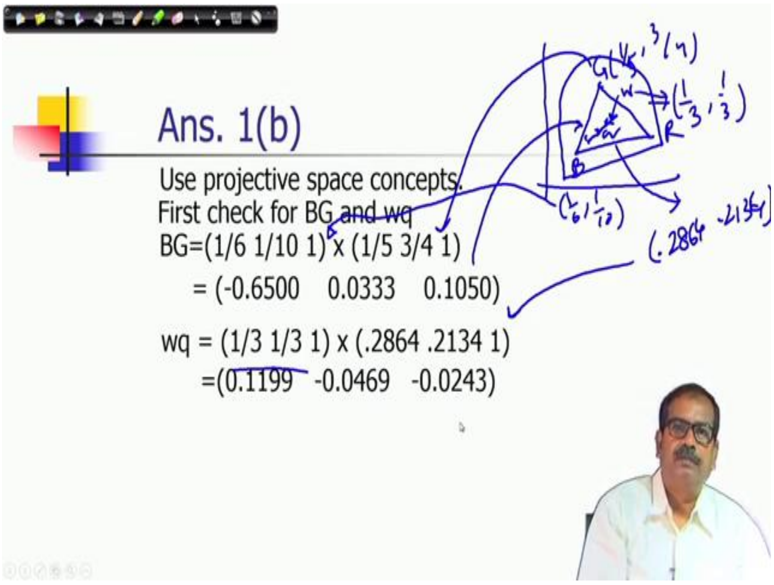

So, for computing this intersection, we will be using projective space concepts. We have already studied that how you can compute the intersection of lines in a two-dimensional coordinate space, if I extend it into the projective space representation. So, first check for intersection of BG and wq. So, note here once again let me draw. we have a CIE chromaticity chart, and then there is a gamut triangle and say this is R, this is G and this is B, and this is w and say this is your q.

So, we are trying to find out intersection of this edge with respect to the corresponding triangular edges. So, the BG these computations could be computed as with respect to BG the intersection could be computed as the cross product of these two vectors. As you can see that this point is represented as this point is represented as $\left(\frac{1}{6},\frac{1}{10}\right)$. So, in the homogeneous coordinate system, this is $\left(\frac{1}{6},\frac{1}{10}\right)$, and then G is $\left(\frac{1}{5},\frac{3}{4}\right)$. So, this is the representation. So, if I take cross product, this is giving you the equation of this line BG.

And similarly I will get the equation of wq. So, this is the equation of w q. So, this is w which is $\left(\frac{1}{3},\frac{1}{3}\right)$, so this is the homogeneous representation and q is (0.2864, 0.2134) as we have computed earlier. So, this is a homogeneous representation. So, if I take the cross product of these two, then we will get this particular representation and value which is representing the straight line wq.

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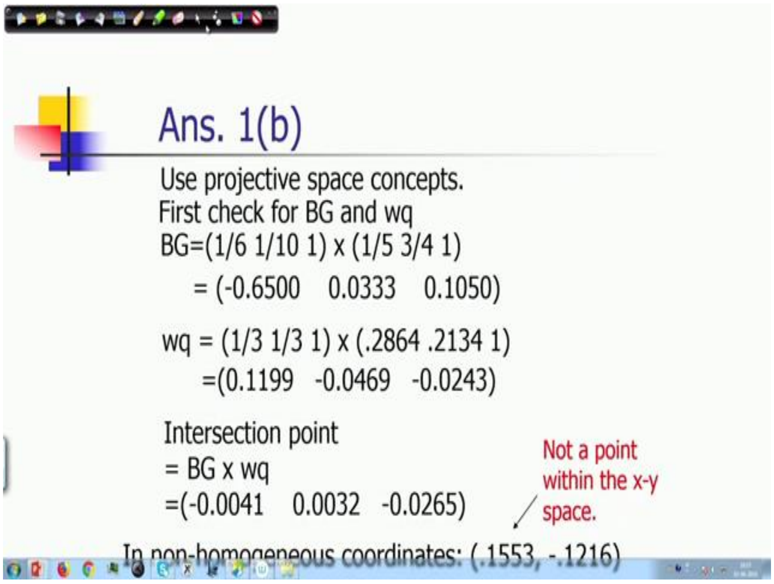

So, now intersection of BG and wq will give you the point, this is the point, again this is homogeneous coordinate representation. So, in the non homogeneous form, this is the point. Now, you observe that there is a negative and as you know that all the points are to be positive and there is a range between 0 to 1, it should lie within that range. So, this point is not within the x-y chromaticity space.

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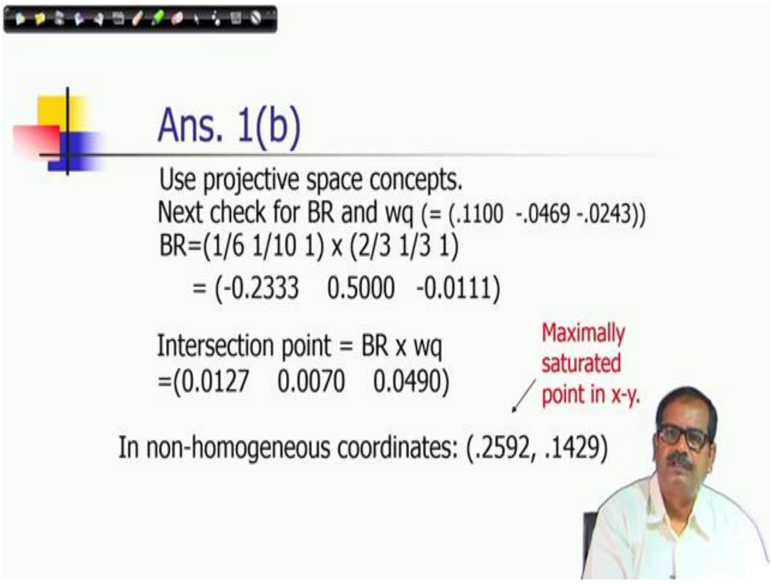

So, we should not consider these points. So, now, we should consider the other edge BR, and find out the intersection with wq. So, wq we have already computed which has been shown here and now BR is given by this again in the same way we are computing the cross product of these two points in the homogeneous representation; one is representing B; the other one is representing R and then you get this is a straight line in the projective space.

So, now, the cross product of these two lines BR and wq that would give you the intersection point and this is the intersection point you will get. In the homogeneous coordinate representation in the non homogeneous coordinate representation it is (0.2592 , 0.1429). So, finally, this should be your answer, so it is a maximally saturated point in x y. So, this is an example by which you can see that how this point maximally saturated point could be computed using x-y chromaticity chart given any point in the RGB color space.

So, with this, let me stop here. We will continue this discussion of you know Color Fundamentals and Processing in our subsequent lectures.

Thank you very much for your attention.