Virtual Reality
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Lecture – 8-1
Light and Optics (lens aberrations)

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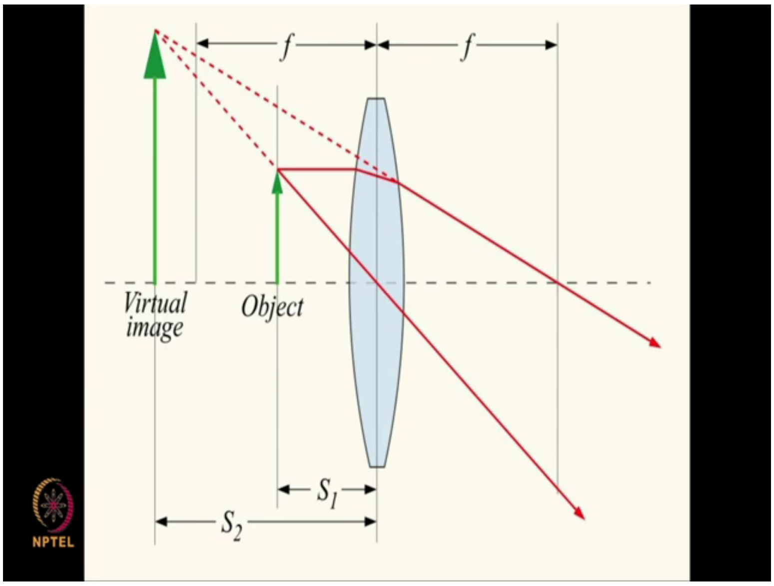

I would like to now get into; what are called lens aberrations. So, I talked about a simple lens and how it works in an ideal setting and that may be familiar to a lot of you already, but there are a lot of problems with lenses especially as we increase the field of view. So, if you have a very large lens or let us say, if you want the image produced by the lens to be very large.

The focal plane to be to be large, let us say, then there are a lot of imperfections and a lot of problems that arise and in virtual reality, we are highly motivated to do that right, if you take a virtual reality head mounted display and you put a screen up very close and you put a lens in front of your eyes and you would like to look through the lens in different directions, you would like to have a very wide field of view; that means, that these kind of peripheral effects of lens and perfections are going to become very important.

So, they are critical to the engineering of virtual reality systems and that is why I want to go through step by step and talk about different kinds of aberrations, right.

Aberration means what? Means something not right, something different from what we would like to have happen in an ideal setting. The professional optical engineers deal with aberrations of all source, right that is their sort of daily bread and butter let us say, all right of characterizing aberrations, trying to compensate for them, trying to keep the cost of the lens down in terms of materials and manufacturing, all sorts of issues come into this. I want to give you just an idea of this; of the kind of things that can happen.

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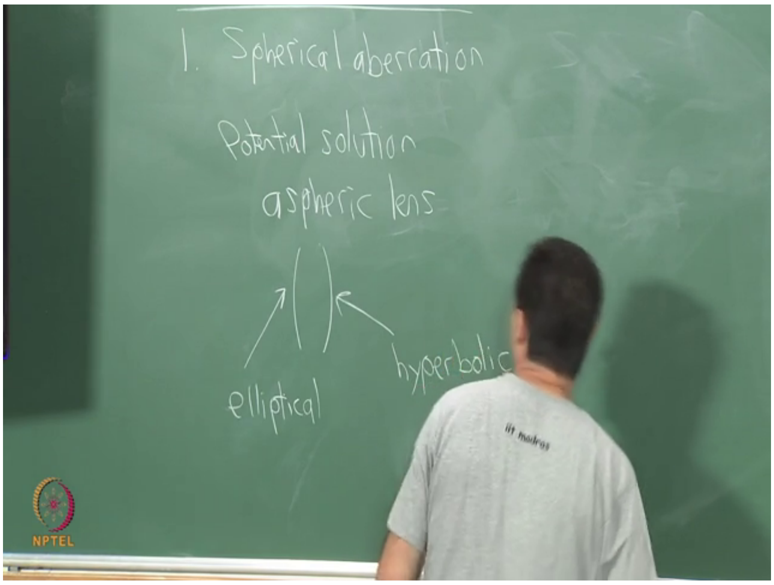

So, I will talk about lens aberrations. So, first one; I will talk about is spherical aberration. So, the cheapest surface to cut for 4 lenses is spherical; however, it is not ideal for generating a perfect image in the image plane.

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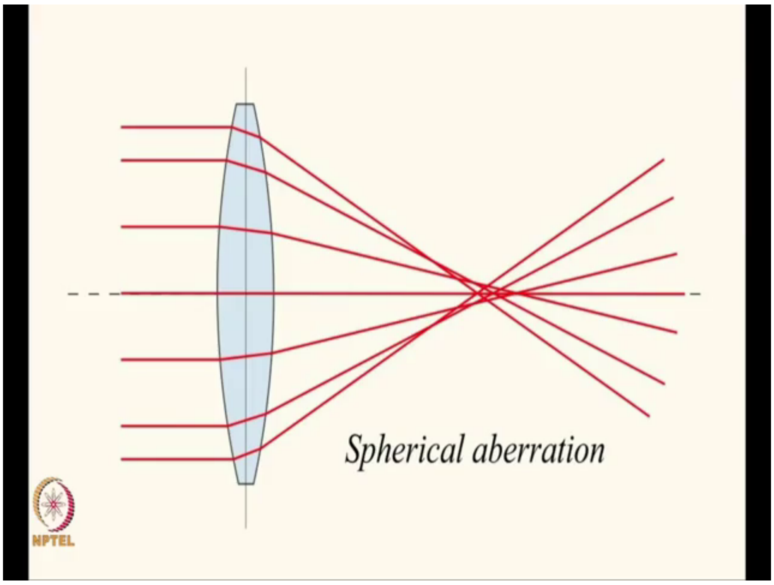

What tends to happen is the following. So, you have parallel rays of light coming in and then they do not converge at a common focal point. So, it tends to spread out.

So; that means, that there is no place where I could suppose I wanted to place my projection screen here and I try moving it back and for some kind of vertical screen, I am moving back and for here, there is no place where I could put the screen. So, that I would have everything perfectly in focus, if I just use the central part of the lens, then it would be good enough, but if I really insist on using all of the lens and we get all the way out to the exterior and that lens perhaps, you know, ultimately I said it could be a big lens very close to your eye, if we insist on using these extremal parts of the lens, then the errors tend to get worse and worse. So, that is one problem.

There is a solution. So, potential solution; you can make, what are called aspheric lenses, right, if the sphere is a problem you use something else. So, if you look for the word aspheric and lens, you can find all kinds of engineering literature, research literature on that; from what I have read the ideal way to fix that is that for the lens you make the incoming surface elliptical and the outgoing wind surface hyperbolic with very carefully chosen parameters obviously.

So, that is harder to manufacture than a spherical lens. So, it drives the costs up, but it may reduce spherical aberration significantly in an idealized setting, it should not in limit it all together, but spherical aberration is just one of many problems that a lens designer has to focus on.

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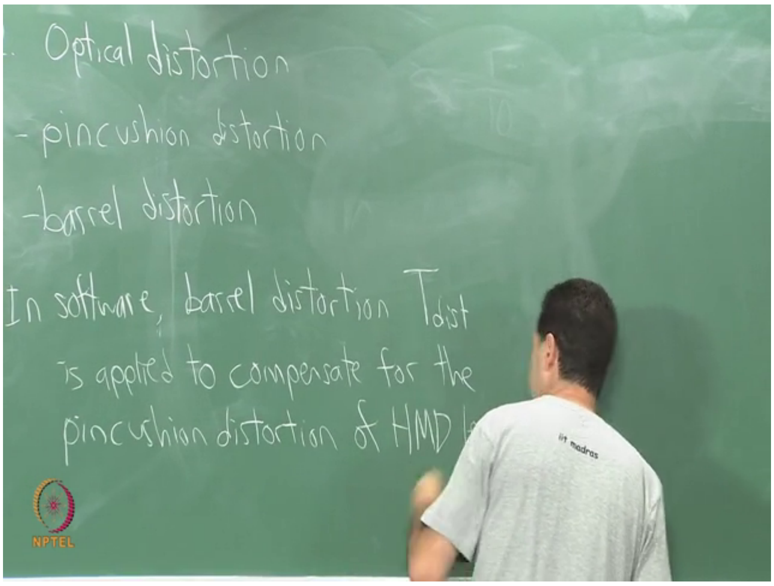

So, let me give you another one 2 optical distortion in this case when we have a high field of view this might happen.

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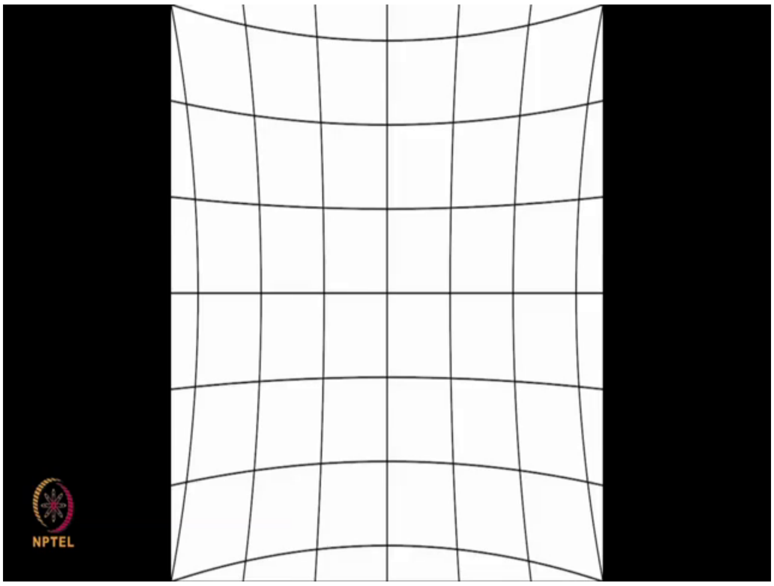

If we put perfectly square grid lines perfectly straight grid lines in front of the lens and if you do this, for example, if you take the head mounted display from the lab and you can do this; you can take out the lens cup and put it over some graph paper it will look something like this, right. So, these straight lines become curved this is a kind of distortion called pincushion distortion.

And notice that if we were just going to use the lens in the central part here it might be good enough and you might never notice you know this is a pretty extreme example, but you can see that the further you get away from the center, the stronger the divergence is between being straight and being curved and since because people in modern virtual reality systems want the field of view to be as wide as possible they have to deal with this problem.

And it might not have been a problem maybe ten or fifteen years ago in some other kinds of systems where the field of view is very narrow where it generally looks like you are just staring at a small screen, but if you want to have your entire field of view filled with the stimulus presented by the virtual reality system, you are going to have to deal with this kind of curvature.

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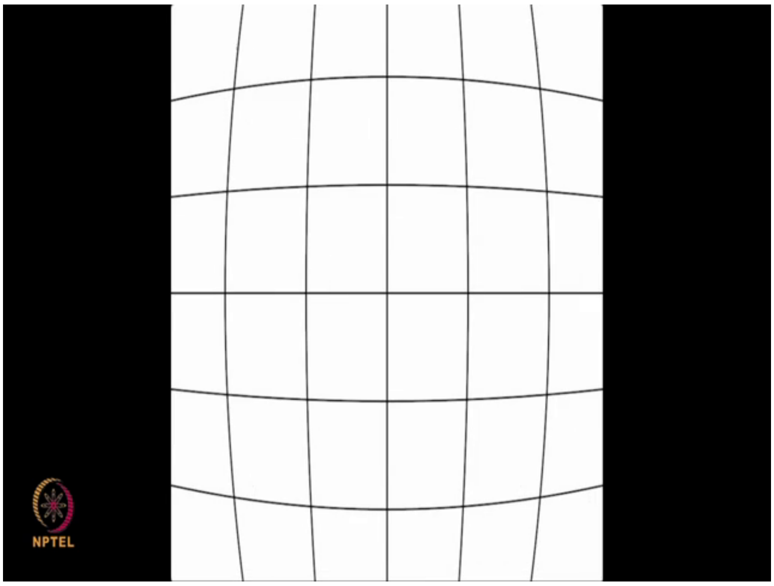

Another common case which is essentially the opposite is opposite or inverse is called barrel distortion the lens ideally is radially symmetric right. So, it as radial symmetry and. So, these distortions tend to be radially symmetric as well. So, then you can compensate for them by just making a kind of transformation that adjusts the radius in polar coordinates.

So, the felled part does not have any kind of transformation, but you just kind of perform from the center, if you want to compensate for this, you just perform some kind of radial stretching and the amount of stretching you do does not depend on theta that is generally how you would compensate for something like this. So, these 2 are inverses and what is actually done in software.

So, I will mention just a little bit. This is done in head mounted displays and now we will little more detail on this later on in the course, but in software barrel distortion and I think, I called this t just when I just gave you it as an example when I did the chain of transformations barrel distortion is applied to compensate for the pincushion distortion of a head mounted display lens.

So, it is you know, I like to think of it as a barrel pincushion annihilation, all right. So, the pincushion is one kind of distortion you apply the opposite distortion which is a kind of mathematical inverse and then when you put the 2 together you get the identity which hopefully should be everything is perfectly straight its easier said than done its very very hard to tune the parameters of your barrel distortion in software. So, that it compensates perfectly there are a couple of interesting reasons for that mainly the problem is that human perception is involved in a human optical system is involved and your eyes move all of this together causes some great trouble in trying to fix this problem which I will give you more understanding of as we go on questions about this, alright.

So, one more I have 5 aberrations; I am going to cover here. So, it is kind of a depressing topic, right, it is just more is it can be a list of 5 things that interfere with the performance of these systems and degrade your virtual reality experience especially if you demand having a high field of view which I think is reasonable to demand.

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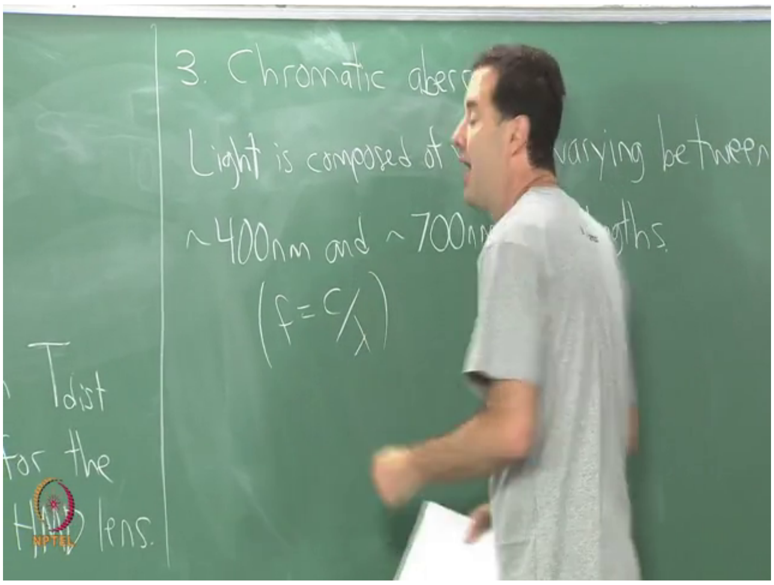

So, another one is chromatic aberration.

So, in order to explain this I should start talking about light waves and frequency decompositions of them. So, remember that light one way to look at it is composed of waves varying between about 400 nanometers and about 700 nanometers in wavelength, right.

So, we gave the formula for converting between frequency and you may remember just a simple formula f equals c over lambda frequency is a speed of light divided by the wavelength. So, you can convert back and for between these now you have seen the visible spectrum before perhaps, right.

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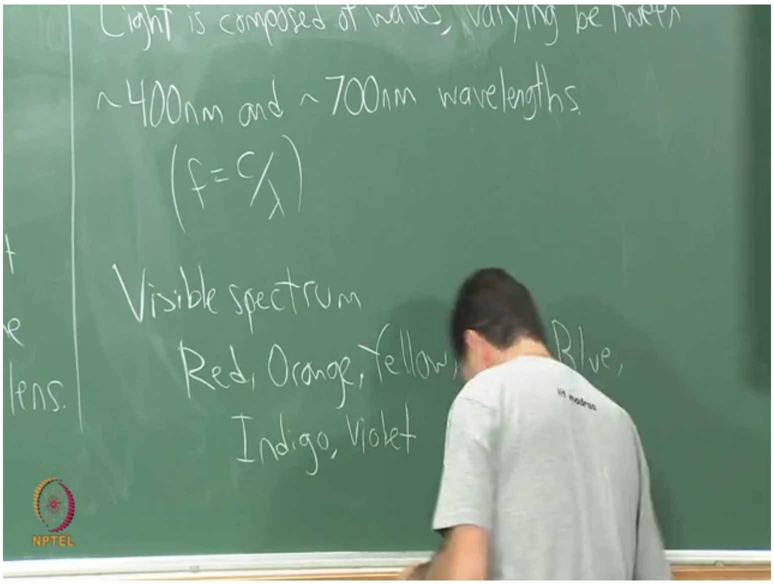

We talked about the basic colours of the visible spectrum.

Right the colour is a red, orange, yellow, green, blue, indigo. So, when people talk about the spectrum of colours, right and you have seen light shining through a prism before show examples like this in a bit they are talking about pure sinusoids that correspond to one particular frequency or one particular wavelength, right.

So, that is a very unusual situation that I have it may happen if you generate a light using a particular laser for example, for light that is bouncing around in this room right now there is many many different wavelengths all propagating at the same time right. So, there is a whole mixture of those and that is called the spectral power of the light that is propagating, right.

So, those of you with signals and systems background should understand analysis of signals in the Fourier domain and you can talk about the frequency components of that right. So, if you have done some Fourier analysis kinds of things before this should not be surprising it applies to light it applies to sound it applies to all sorts of problems where there are propagating waves. So, that is something to consider the spectral power of light.

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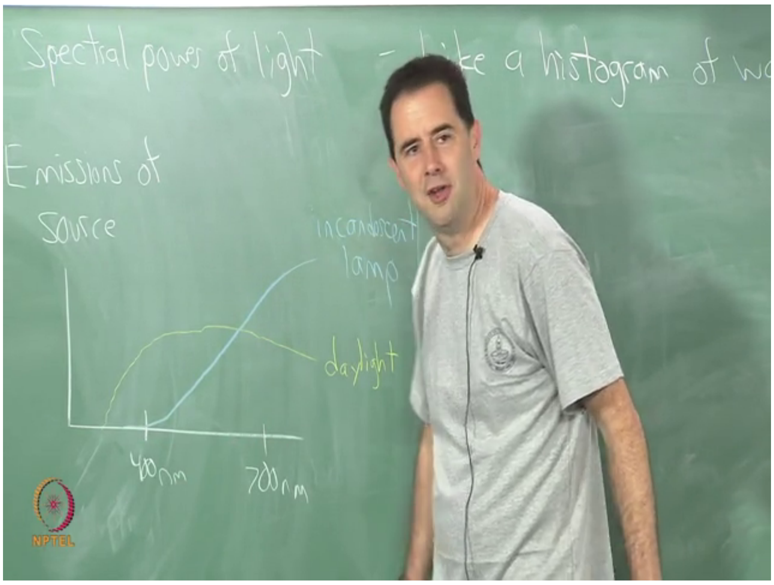

And in terms of the spectrum say once again we talk about the visible spectrum and we pick a particular place along it, we are just talking about a single blip in terms of this overall spectral power of light. There is one place along the spectrum where there is light at a specific frequency or wavelength.

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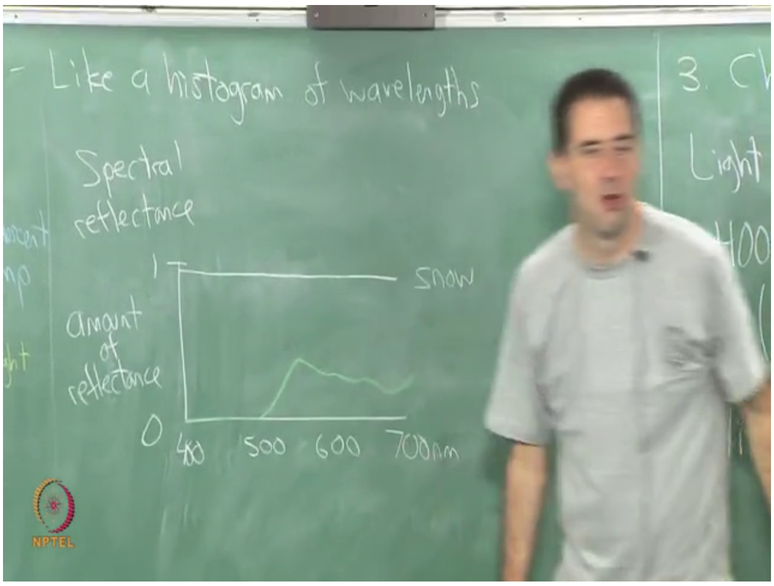

There is not a mixture, but more generally there is a mixture. So, spectral power of light you could say that that is like a histogram.

If you like to think that way it is not necessarily discrete like this, but you may you may helpful to think of it as in a continuous way, but think of it as kind of a histogram of wavelengths and we are alternately going to have light going into our eyes through the pupil and hitting the retina. So, what is the spectral power or spectral distribution of that light, what does it look like right are there more greens more blue some reds you know how what exactly do we have as we look at the range of wavelengths.

So, there is 2 things that affect that one is going to be the light that is emitted from sources and the second thing is going to effect that is the various materials in the environment, how do they reflect the light that is going to affect our perception of the colour of something right this board appears to be green and white in some way, I think, we all see it like that that depends on the properties of the board and the properties of the lights that are shining on me, now which as I see them they are mostly white and there is a good reason for that. So, these are the 2 things. So, I will write them as there are the emissions of the light source. So, for example, maybe I write 4 hundred here and I write seven hundred here. So, these are in nanometers.

So, I want this to be the wavelengths and then one example I will draw which are just rough plot they give you some kind of idea on the based on reality in some way here this plot can correspond to daylight and this may correspond to an incandescent lamp all right. So, we consider the light source and generally when we have a light source if we are going to engineer one if we want to do a photography or videography then we would like the light source to contain as much of the spectrum as possible in the visible range and it is also best to have it close to equal you know. So, that it does not overly emphasize let us say red instead of green, right.

So, you would like it to be we call white light which would be a perfect balance across the spectrum with the entire visible spectrum represented, when we get off to the extremes down here maybe; what is that called; shorter wavelengths is what infrared wait a minute.

Student: (Refer Time: 16:38).

Let us see where is the lower frequency long longer wavelengths is infrared right. So, that is over here I guess yeah again we can always change using this f equals c over lambda formula.

So, I guess based on the way this is drawn this is the infrared part and incandescent bulbs are they tend to get hot right they generate a lot of heat which should generate a lot of infrared radiation which is why it seems to be peaking here would be my guess.

So, ultraviolet would be on the other side all right. So, that is one part is the emission of the source and then there is the spectral reflectance of the material now both of these subjects emissions of the source in spectral reflectance become very important in computer graphics when if you want to make a completely artificial scene a kind of virtual scene and you want to render how that might look you need to make models of these things, right, we make artificial or virtual light sources, we will make virtual materials and then decide what its spectral reflectance property should be and then hopefully, it will look or could convince our brains that it looks reasonable much like it would look in the real world

So, even if to graphics this is very important, but it is also going to be important just in our understanding of how human vision works in the real world because it is part of this optical system I am going into all of this explanation because I need to explain chromatic aberration, but this is also going to be useful in many of the things, we do in the course here its useful generally for virtual reality. So, spectral reflectance will be another kind of plot maybe I have at the top of the plot one for total reflectance and zero for no reflectance. So, this is the amount of reflectance maybe I could call it the coefficient of reflectance if you like. So, for example, up here for still let me write my. So, have my wavelengths here and one example of put along here is a snow how is that right.

So, snow generally looks very very white it reflects pretty much reflects everything very nicely right, but it is not it is not a specular reflection and that when I look at the snow it does not look like a mirror it is a diffuse reflection, but it tends to not look like it is some special colour, right. So, so that is because it has this kind of very ideal spectral reflectance ideal in terms of looking perfectly white or just reflecting back whatever the light sources.

If I shine up perfectly red light with only one wavelength in it on the snow; what colour will the snow be was that green.

Student: Red.

Red; it will be exactly the light that I shined on it right that is how it should look ideally you know there may be some distortions and things if I take something else like say I take a look at grass, I realize maybe this is not the idealized colour here for grass, but a should show up a bit may tend to peak somewhere and it may peak right in the area where that wavelength should correspond to green if the grass is green the grass turns yellow because it is too dry, then I guess it will move somewhere else, but it may have a more distinct signature if it is something we perceived to be a particular colour. So, that even when you shine white light on it, you still get you may still get a very distinctive amount of emphasis along a particular part of this visible spectrum.

So, those are the things we perceived as having a particular colour you shine a white light on them and not everything is reflected back its very specific the more specific it is the more we perceive a particular pure colour does that make sense all right. So, we have these spectra now. So, now, think about it. So, there is some light sources the lights been bouncing around and it could have multiple inter reflections off of different objects based on the spectral reflectance and how much power gets dissipated remember I said some of the light gets absorbed as well.

So, there is less and less as it goes along well by the time it is all done; let us suppose now that light decides to hit a lens, right.

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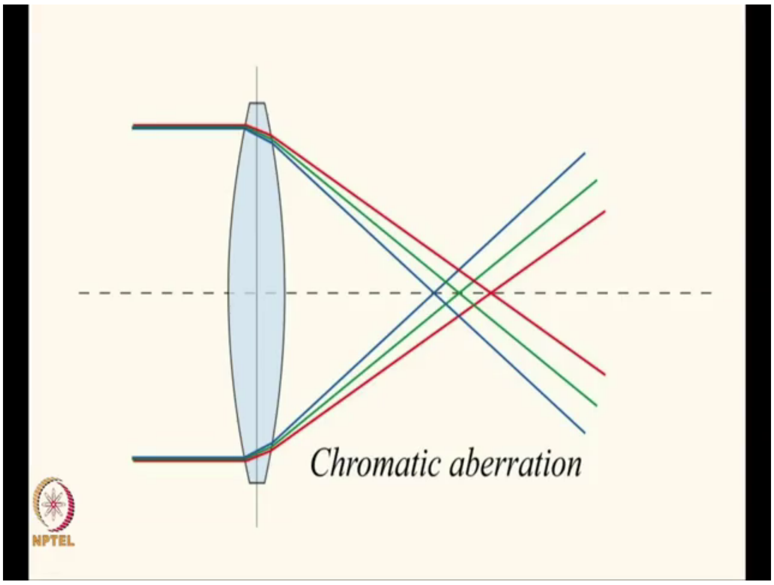

So, if the light hits a lens then here we have parallel rays coming in and let us do it here off of the extreme you may have seen a picture like this for a prism before. So, as the light comes in it turns out that the speed of propagation of the waves through the medium depends on the frequency, right or depends on the wavelength if you like either way which ones going faster here.

Reds going faster through it and blue is tending to get more stuck is that right or is it the other way around right. So, red seems to be going faster through here if it were going straight through, then it would be essentially no effect right. So, the shorter the wavelengths the slower it goes through the material for the way this picture is drawn.

So, that is the case then you will have a focal length for pure blue you will have a focal lengths for pure green you will have focal lengths for pure red and if you generally have some kind of distribution some distribution that corresponds to the spectral power of light or some histogram of various wavelengths then the focal plane will really be distributed in some kind of way, right, you may want to put it in one place to really focus the reds well and in another place to focus the greens well that does not sound very satisfying right, but that is what you have to deal with what are some potential solutions to that. So, they are still under chromatic aberration I shown you a picture there of it possible solutions.

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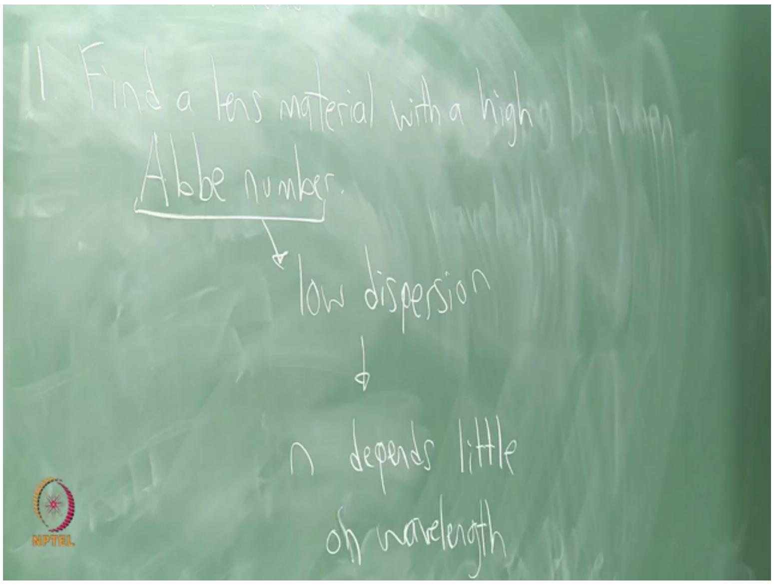

So, one find a lens material find and use the lens material with a high what is called Abbe number; what; that means, is that its low dispersion what; that means, is little dependency well let us see.

Let me put it this way the refractive index n depends little on wavelength.

So, there are some materials that refract the same way the speed of light through them does not vary much based on the frequency or wavelength. So, that is one way the trouble with that is that these materials tend to be very expensive. So, in mass produced consumer products, this is not very reasonable unless someone find some new material that is all of a sudden cheap easy to manufacture and all of a sudden saves us.

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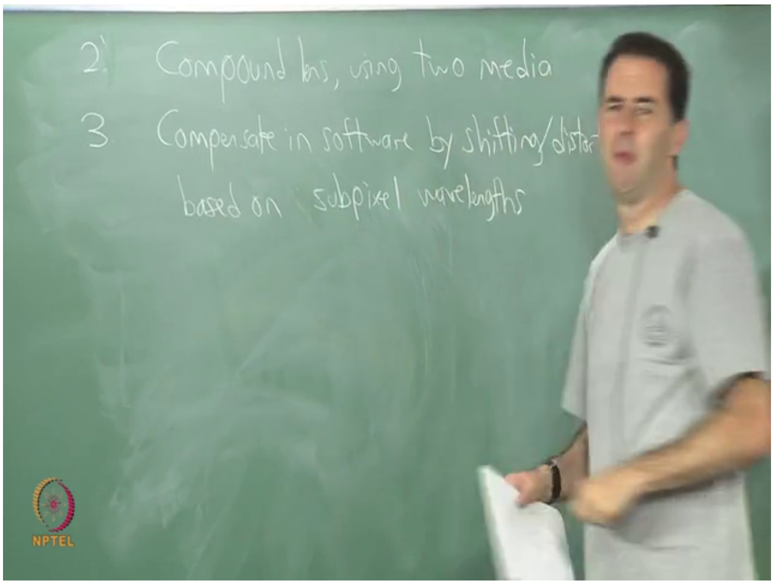

Number 2; form a compound lens with 2 materials.

All right; 2 different materials or media.

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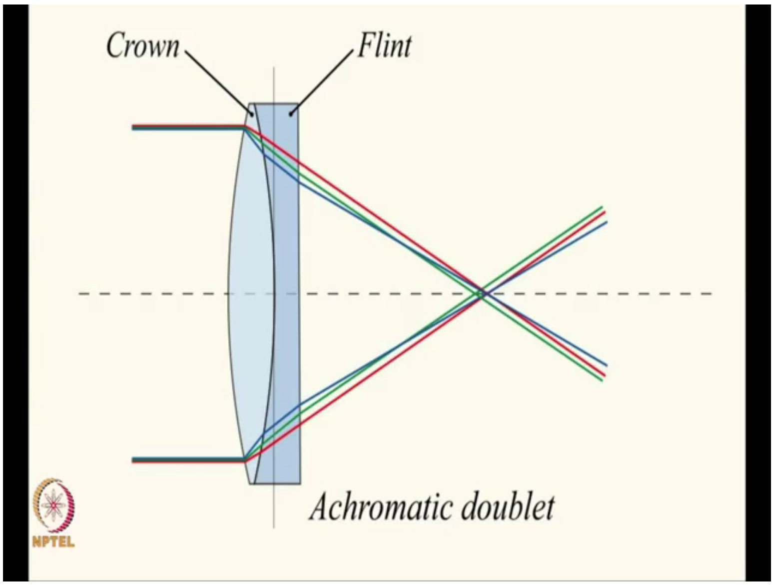

So, this is commonly done in lens design. So, there may be one material which is causing separation the crown glass and then another kind of glass called flint glass which is put right up against the lens to try to bring them back together again. So, you can use 2 materials play some kind of tricks, it is a kind of delicate art for the design of the lens.

So, optical engineering becomes very difficult because of these and again if you can get the costs right and the materials correct not too brittle and you know whatever other things you need the optical properties you may be able to make a compound lens like; this called an achromatic doublet and you see even in this picture, it does not show it being perfectly compensated, but it may greatly reduce the chromatic aberration a third trick which would be a computer science kind of solution, just fix it in software, right and that is being done, right. Now in current ahead mounted displays.

So, compensate just as we talked about the optical distortion the barrel distortion compensating for pincushion distortion you can also compensate in software by shifting or distorting based on the let us say sub pixel wavelengths.

No quite want to put pixel there because the if you if you hold a magnifying lens up to a screen which I suggest you do and then you can study the pixel structure very carefully you see that what we call one pixel in computer graphics actually corresponds to several sub pixel elements that are lighting up right in you know all the all correspond perfectly they are not just it is not such that r g and b r, just all superimposed in one place it is a kind of pattern a tiling pattern for example, the screens in the lab use a pentile display, you may observe, all right questions about this. So, I think that all of them have some kind of flaws the software compensation is not perfect on these other solutions are costly and again not perfect it is something that we unfortunately face, yes.

Student: In the human eye, do we have this chromatic aberration or is it (Refer Time: 27:34).

That is a wonderful question yeah yes we do. So, in the human eye we have chromatic aberration, but your brain learns to compensate for it. So, you do not see it and this is one kind of theme that will happen over and over again there are all kinds of problems that our eyes have that our brain is just fixing the most interesting one or most well known one probably being the blind spot that is due to the optic nerve.

So, that part of your retina is essentially missing.

But do we see a blind spot, I can show you some experiments where you can try to find it, but it is a interesting, but our brains are repairing all of these flaws. So, that would be analogous to number 3 here. So, we the software can fix it your brain also fixes it no its very very nice question sure, all right. So, that was also these one 2 and 3s are inside of the big number 3 which is the third aberration which was chromatic aberration.

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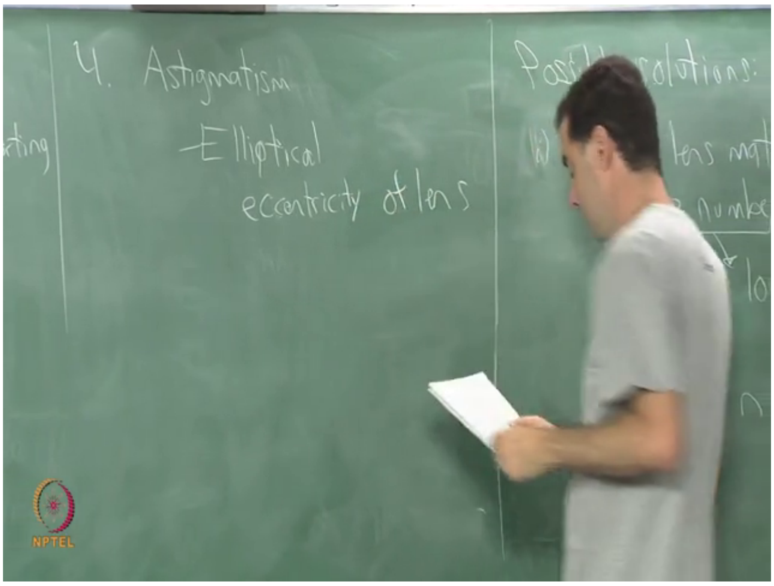

So, I probably should make these you know should have been little 1, 2s and 3s in that sense for the record here was they are just inside of my main numberings. So, number 4 is astigmatism which corresponds to a lifter elliptical eccentricity all the lens.

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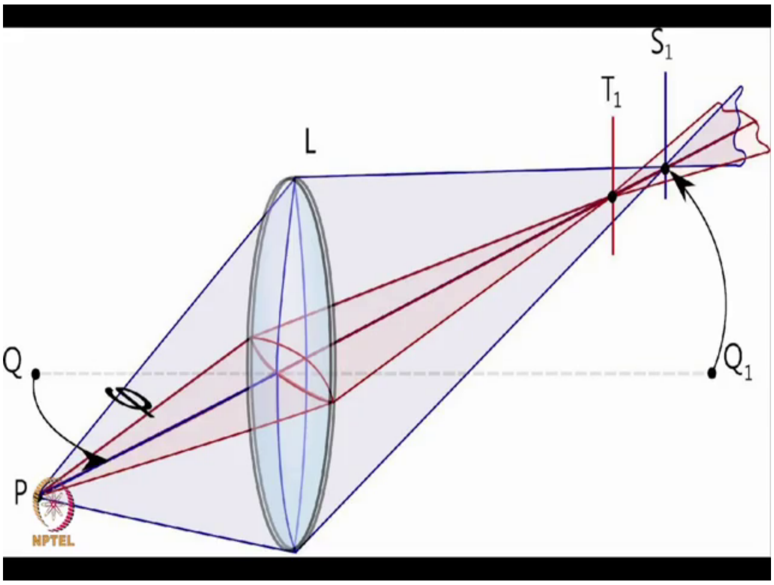

I will just show a quick picture of this. So, instead of having perfect radial symmetry do not do that instead of having perfect radial symmetry when you have light waves propagating in the horizontal plane going through the lens, there will be one focal point, but when you have light waves propagating in a vertical plane there will be another focal point and. So, this will mean that there is no place where you can get a perfectly focused 2 dimensional image.

Those of you in the audience who have who are wearing a corrective eyewear some of you may have an astigmatism and that cannot be fixed by just changing the diopter right. So, any problems of nearsightedness farsightedness you can just play around with the diopter do some adding and subtracting and fix it; however, you like and then in a head mounted display if it has adjustments you could move the lens forward or backwards away from the screen to compensate for your nearsightedness or farsightedness.

However you cannot a compensate by just moving lenses back and forth for a stigmatism you have to design some kind of corrective asymmetry into the lenses to fix this. So, there is some examples you may have seen before where some letters may look sharp along one direction then blurry along the other or vice versa and there is no way to your brain may try to find an intermediate focal length your eyes may try to find an intermediate focal length to try to bring everything roughly into focus.

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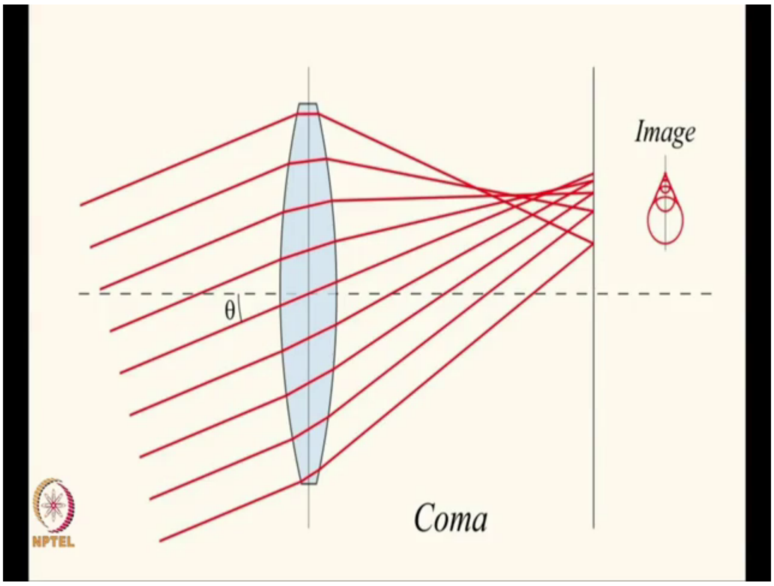

So, a stigmatism is the fourth one and the fifth one is called coma sometimes called co matic aberration instead of chromatic aberration I will just call it coma that is derived from the word comet because it appears as a kind of comet image here and this tends to happen when the imp when the part of the image you care about is very far away from the optical axis.

So, this is a central optical axis here and these rays are coming in at an angle we are still looking at parallel rays for this and. So, at the focal plane you get these kinds of patterns that emerge this, but gets particularly worse for thicker lenses because the waves are getting offset and shifted as they travel through the lens and you get these kinds of this kind of repeating patterns you might have if you have ever played with a magnifying glass on the sun you may have seen some kind of repeated patterns like this you may also see it sometimes in photography or in movies you may see some what appears to be a bright spot, but then a bunch of smaller bright spots trailing off from it.

So, that is an example of you know this does coma pattern you get its an example of what is called an airy pattern a i r y pattern this will also happen in a diffraction. So, you may have seen very simple examples in physics classes where you form a slit in a material and then look at how the light diffracts as it goes through that and the wave fronts will tangle in some kind of complicated interference pattern and it will generate stripes.

So, that is the kind of thing that is going on here and that is an example of an airy pattern this coma is an example of an airy pattern and you will indeed see these kinds of things if there is a very bright distinctive say one pixel is lit up and its over at the periphery it may appear as some kind of comet pattern. So, it is harder to find those, but I have seen it happen before. So, that is all of the optical aberrations that I want to cover any questions about that.