Optical Engineering
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Lecture - 07
Aperture stop – Part 2

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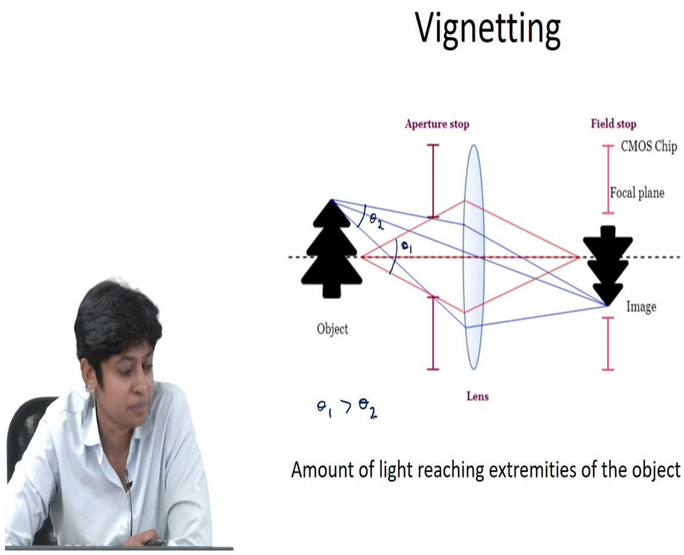

Now, what one of the things that. So, the aperture stop we are interested in because it affects so many different parameters of imaging. So, vignetting is one of the things that arises and let us look at what exactly this is. So, in this image I have an object and a set of rays have been traced only some rays are being traced through the system. A set of rays are being traced from an on axis object point those are the ones in red and another set of rays are being traced from one of the extremes of the object.

And you can see that the angle between this set of rays and the angle over here this angle let us call this θ_1 and , θ_2 . $\theta_1 > \theta_2$ Now, these set of rays are not chosen arbitrarily, you have the aperture stop of the system and so the cone of rays that has been chosen for each point on the object is such that this is the cone that makes it through the aperture stop which now we know and can say confidently. It means this is the cone of rays that are reaching the image plane, right.

But in every case so in every point if I took on this object, while there is a cone of rays from that point that reaches the image plane and the aperture stop will tell me. Now, what is that cone the point to take away from this image is that that cone is different for every object point, it is not the same. The point on the axis gives me the maximum size. So, θ_1 is the largest cone of light that will travel from any point on the object to the image. As I go away from the axial point the cone goes on reducing and the smallest cone is going to be at the extremity of the object.

What does that mean for the image, how is this going to affect the image, does it make the image blurred? So, it does not affect the quality of the image in terms of focus, but yes you are right it will lower the intensity of the image and this is an effect that we may see often when we take a photograph right.

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So, here this is just a photograph of a plane surface. So, that it is very clear actually this should have all been the same color. But you can see the corners are a little darker and here is a picture taken in the mountains and again you can see that it is darker in the corners and this is a typical example of vignetting ok.

So, it is something that happens regularly. It is not unnatural for us to see this, I vignetting could be an issue if you were trying to image say some tissue or cell and make some diagnostic based on that image. But artists or people taking photographs to highlight some point, may actually ensure this vignetting in the system because they want to bring the center of the photograph. You know they want to highlight that and they will actually make sures they will set the camera to enhance the vignetting effect or you even have digital tools where you can say add vignetting to the photograph.

So, that you can highlight the central part of the photograph and demote the outer region. So, it is either something useful or not useful depending upon your application.

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As I said people may use vignetting or not. Now, how am I changing that? I am changing that by changing the size of the aperture right, because clearly if I increase the size of the aperture stop, yes the central cone is always going to be larger than the cone coming from the edges. But the cone from the edges may be so large that I do not see the difference in the brightness. I might get enough brightness from the edges, right.

So, basically by changing the diameter of the aperture, I can change the intensity coming into the system. Now, in a lab experiment the aperture shown here is very typical. You can see this is a very set of thin blades if you will and by rotating the screw here you can change the aperture diameter and these blades will move out or move in creating different diameters ok.

You have something similar in a camera where you say you want to change settings and as we go along in the course you will see why you need to do that or the different effects you get from doing that.

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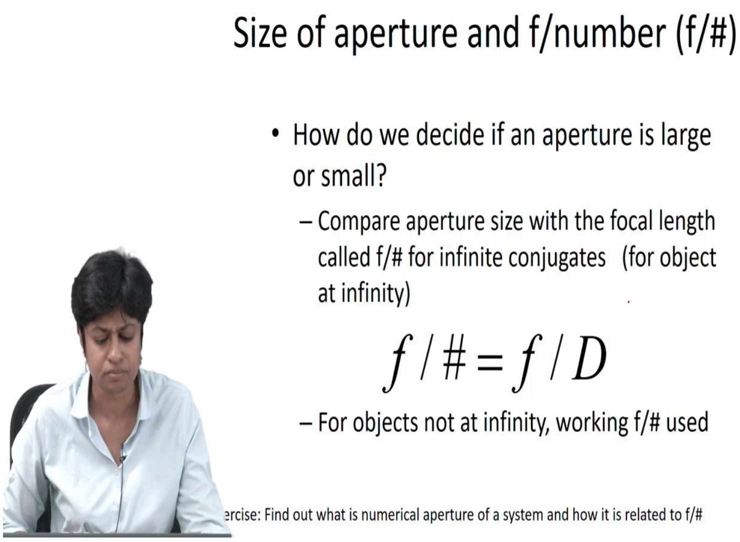

So, we come now to a very important definition right. We have seen size of aperture affects some things, we now can define a parameter called the f number it is written as f number like this or f sometimes f slash has sometimes f subscript hash and basically it is a way of telling us is this aperture large or small.

Now, as scientists know when you say large or small, it is always really in relationship to something, if something could be very large in relationship to another parameter. You might be saying 100 nanometers is large it depends on what you are comparing it to right. So, here when we talk about the f number, we are talking about whether an aperture is small or large and we do that in terms of the focal length of the lens right.

So, we had this concept earlier when we said is it a thin lens or is it a thick lens said. What are the objects in image distances compared to the focal length of the lens for example. So, the f number is defined as the focal length divided by the diameter of the lens, this actually is a definition really used for infinite conjugates, but very often in photography it will be used even if your object is closer to the lens and not really at infinity. We would not go into the working f number definition which is the definition you use for objects that are closer. But to understand the importance of the f number, it is enough to just take this definition with infinite conjugates.

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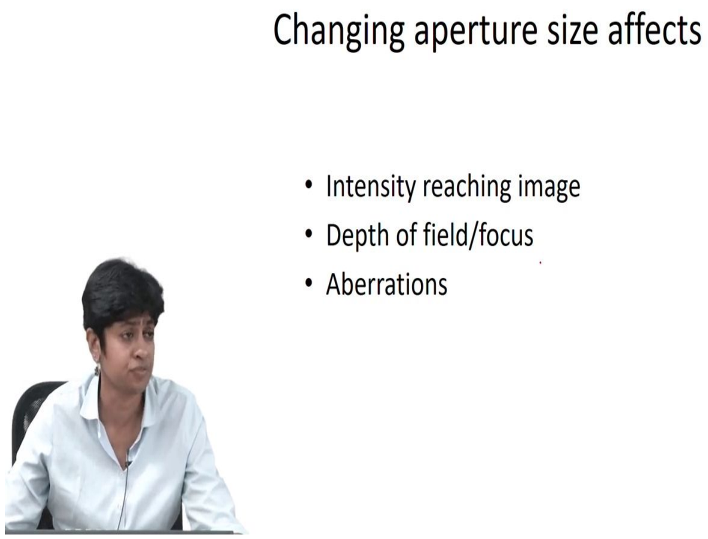

Now, this is also called the speed of the lens and we will see why it is called the speed of the lens. So, we know now that aperture size changes the intensity reaching the image at least at different points, it also controls something called depth of field and focus and we are going to see that it is also going to play a major role in the aberrations in the system. In other words the quality of the image, ok.

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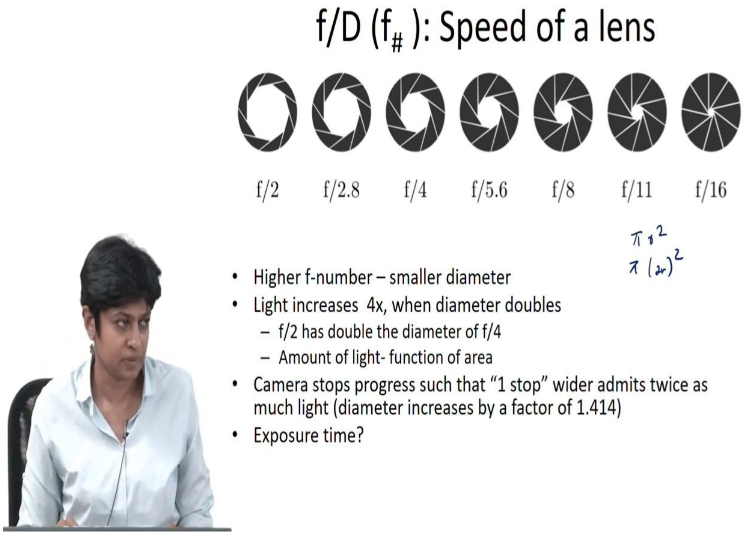

So, why do we say the f number is related to speed of the lens? Well if I am changing the diameter and this image here shows typical camera settings, if you will see a camera there you have already told me none of your photographers apart from cell phone cameras. So, you are now going to see these numbers on a cell phone camera, but if you take what was earlier the standard camera. You will find that on the lens you would have these numbers and you could change a setting and that would change this f number of your lens from either f_2 to f_{16} these are standard numbers.

Now, you can clearly see that the higher f number f_{16} has a very small diameter right. Where exactly do these numbers arise from? Well, they arise from the fact that every time you double the diameter you are doubling. So, you can say this is a circle. So, I have an area of πr^2 now every time you double the diameter you are actually increasing the area fourfold. That means, the amount of light that is coming in is four times more and that is where the speed of the lens starts coming into play, because with all of these systems you are doing imaging.

So, you say a certain amount of light is coming in and then there has to be an exposure, earlier you were exposing a photographic film. Nowadays of course, we do not do that but even there the digital sensor needs to have the light on incident on it for a certain amount of time for it to capture a good image ok. How much time depends on how much light, you have a low lit situation or object being imaged you need a longer exposure time and vice versa.

Now, it is not just how much light is the ambient lighting, it is also the setting of the camera right. If you say auto set the camera will sense there is a sensor which says there is so much light present, because there is so much light we will choose this setting. There is a lot of ambient light. So, we will use the smallest diameter, however if the setting has very low light it may choose a much larger diameter right.

You can force the camera to have a certain diameter, depending then on the lighting it will choose the exposure time. So, say the lighting is very low and yet you choose f by 16. So, the diameter is also very small. The camera will then take a longer time to expose or to capture the image. Now, for photographers that mean several things. Normally you want to take a photograph before the handshake changes the position of the camera. So, you want the camera's exposure time to be in the odd less than one second one fifth one two hundred and fiftieth of a second let us say ok.

If you take it at that speed so the shutter of the camera opens and closes in one two fiftieth of a second, that image will be captured before your hands have moved as always with some movement right. But if I force the camera in a low light situation to have a small aperture like this, it may take several seconds to take an image and if I am taking the image holding the camera the camera will move around and you can get some funky effects where you see sticks of light right.

Otherwise you have to put the camera on a tripod, so that it does not move during the exposure ok. So, people exploit these saying you are taking a picture of some stars moving, right. You want to keep it open for a very long period of time and it is taking a picture continuously as there is a movement of the stars and you will see that track as the stars are moving right.

So, it depends again on your situation, but we call it speed of the lens because clearly a faster lens is a lens with a larger diameter, where the aperture is larger this is a faster lens right. So, the faster lens has the smaller f numbers keep that in mind ok. Now, you can see doubling the radius makes the light intensity go up by four times. So, the camera settings are such that every time you go up one stop. So, f 2 to f 2.8, where do these numbers come from you are actually saying let us double let us change the area such that the exposure time doubles right not goes up.

So, I am not changing I am not going this radius is not half of this radius this radius has been changed such that the area has only gone up to sorry the area has gone down two times right. So, if I am going from f/16 to f/2, the area of this has doubled compared to the area of this; the area of f/8 has doubled compared to f/11. And that means, you keep going down in exposure time by half and that is where these numbers come by it is you are not doing the area by four times but by two times.

So of course, the exposure time is going to be really large for f/16 compared to f/2 ok. So, it should be pretty clear that changing aperture chain is related to exposure time right ok.

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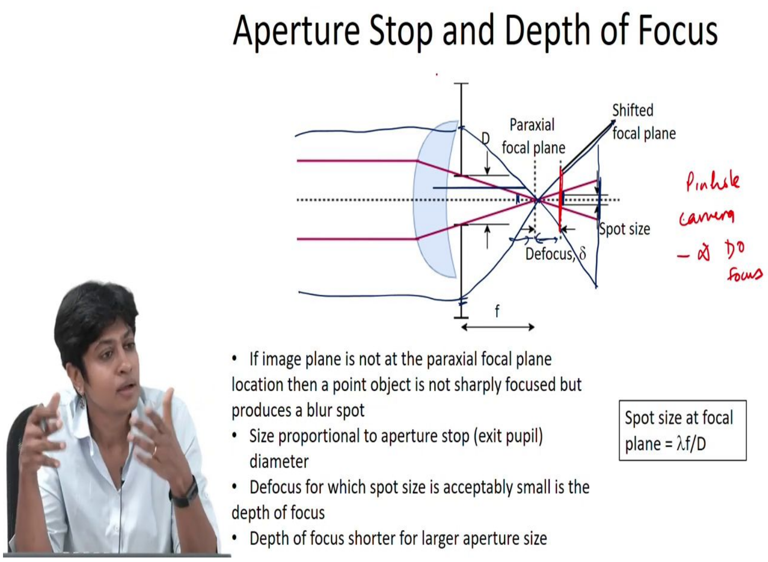

But that is again not the only thing that the aperture size effects right. So, here let us look at this image. I have a lens and I have an aperture. So, maybe this is the mount of the lens, maybe this is what is holding the lens and it is acting as aperture stop of the system.

So, I have a beam that is incident and this beam is the largest size beam that makes it through the system. Now, the ideal focus is this plane here called the paraxial focal plane, you can see that this beam is focused to this point over here. If I go a slight different or distance away let us say a D focus. So, instead of putting my image plane here I go delta distance away.

Now, you can see that instead of having a point focus the beam has diverged. So, the focus now has this size there is now a finite spot size, right. It may be that this blur is what is blur, but it may be that this blur is still acceptable. My eye will not see this as blur; it is larger than a point, but it is smaller than what starts impacting my vision, right. So, if I go further let us say I went to this plane, here I have a point, here I have this size and now here I have this size this may be totally unacceptable. That means, I have everywhere in my image instead of having sharp points in focus I have a blur circle everywhere clearly it is a completely blurred image, right.

So, for this particular system with this aperture stop maybe this is an allowed displacement. So, we call that the depth of focus I can move. So, much distance away from the ideal the paraxial focus plane and of course if I can move this much on this side I can move an equal distance on this side, because that is this distance the blur on the other side. So, with that much distance I can displace the focus focal plane and still say the image is acceptable, we call that the allowed depth of focus.

So it is how much, so this is not going to happen in a camera or actually you could think of this as the distance from the camera manufacturer this is the error he is allowed in placing the CCD sensor into the camera. He could be at the paraxial focal plane, but if there is an error in his manufacturing system that does not place it exactly there. But place it anything at the most plus minus delta away from this point or less than plus minus delta away from this point, then he will still be able to sell this camera because the images will be acceptable ok. So, this is the tolerance that is allowed.

I can see that if I changed the aperture stop dimension, let us say the aperture ended here right. That means, this beam of light is coming in right. It is still the same lens so it is still focusing at the same place, but you can see what was just a blur of this size over here has now become a blur of this size, for the same lens but for a different aperture stop.

Now, this lens if this δ no longer an acceptable depth of focus, the image is blurred even having moved the same distance away from the paraxial image plane. What changed the size of the aperture stop and you could take this argument a step further and say well if I did not increase, if I had not increased the size of the aperture stop. But I had decreased it, then I would be able to have a larger maybe two delta I could go, so I would have a larger depth of focus.

So, the depth of focus is related to the diameter of the aperture stop and one of the very first cameras was a pinhole camera right, have you heard of the pinhole camera no lenses all you had was a pinhole. What is the depth of focus of a pinhole camera? It should have a very large depth of focus because the aperture stop is this pinhole this very small hole. So, it actually has an infinite depth of focus, it has really only paraxial rays coming in right.

So, a pinhole camera has an infinite depth of focus and I will put focus right. But what is the downside of a pinhole camera yes it has an infinite depth of focus, but does that mean it is wonderful to let us all use a pinhole camera. What is the downside of the pinhole camera.

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It allows very less light, so it also you could almost say has an infinite exposure time well it is not really infinite. But you need a long exposure time in order to capture an image with a pinhole camera, because of course the amount of light coming through is very very low ok. So, there is always a tradeoff, there is always a compromise, maybe you are taking a photograph of a waterfall you want to capture the moment. So, you want to make it look like the water was frozen in time right, you then and you and you want the mountain of the rock behind it to be blurred right, then you want to very quickly capture it. So, you want a fast lens right.

The fast lens means it has a large aperture it captures very quickly. So, the rock or if there is something moving behind that is not going to be seen only this water is frozen in time. On the other hand I could have a long exposure and then you are actually taking the picture over a long time, it will look like the water will blur out because that scene is changing as the image is being taken right. So, again depending on your application I am giving the example here photographs. But it could also be that you are viewing a sample and the sample has live cells and some life back bacteria and you want to capture the bacteria frozen in position. Or you want to see how they move and that will change the setting of your system ok.

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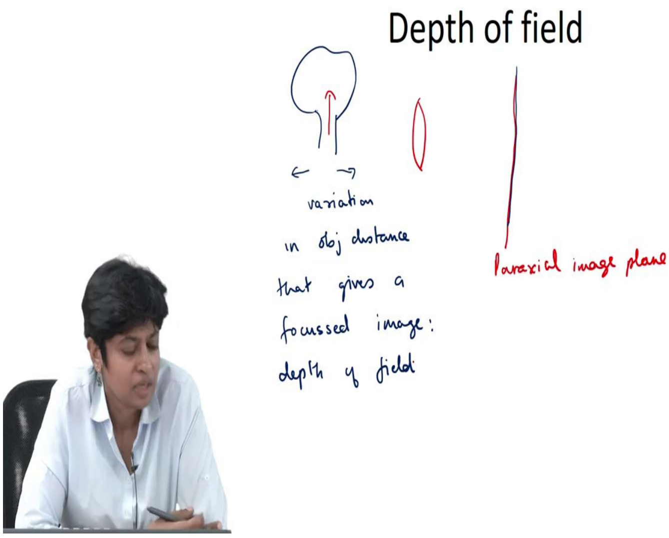

So, aperture stop affects depth of focus, but I also have depth of field. Now, what is depth of field? I said and I showed in the previous image that for a particular optical system you have the paraxial focal plane and the depth of focus allowed you to move a little bit away from that plane and still have an acceptable image. I can say how much can I move away from my perfect object plane and still have an acceptable image.

So, again I have an object lens I have an object and I have the perfect image plane, this is my paraxial image plane right. Now, let us say this object is not exactly a planar,we are not always photographing two dimensional things right. Let us say the object is like this does that mean only one part of that object is in focus and everything else is blurred? Of course not right. There is some distance here that I am capturing it on one plane, but all of this should come as in focus right.

So, the variation allowed here variation in object distance, this is the depth of field and just the same argument we used with the aperture stop and the depth of focus that is exactly what I will use over here, right. So, again aperture stop is controlling depth of field as well ok. So, I have some images here to emphasize what we are seeing, here is a photograph that is taken of a billiard table you know at sort of a glancing angle.

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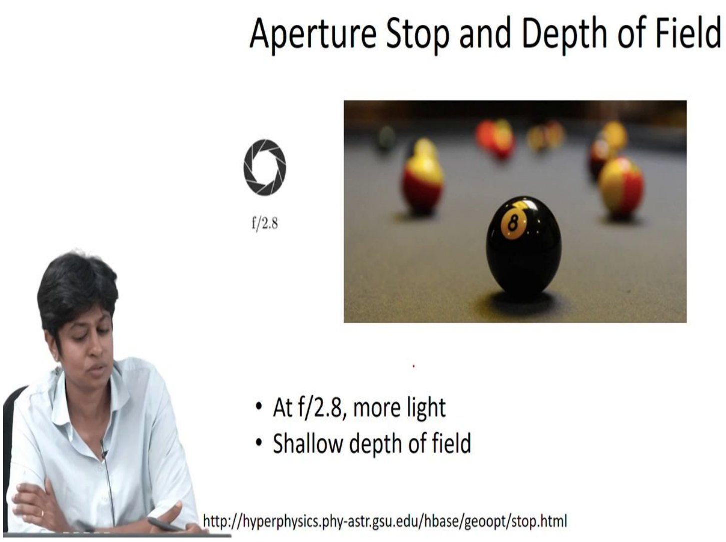

And you can see it has been taken. You have been told it has been taken with f/2.8. In the image the billiard ball in the front is clearly sharply focused and the ones behind a blurred ok. So, it is you could say this was taken with the camera set to have a very shallow depth of field, this is the entire object that I want to image is this entire billiards table.

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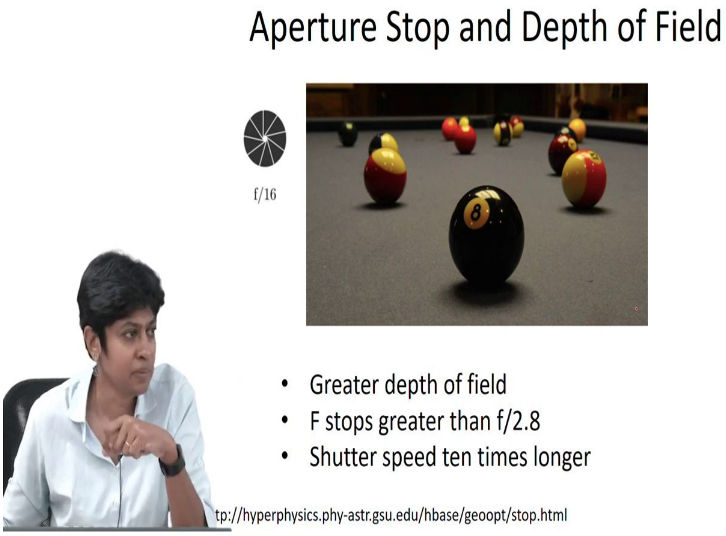

You can stop down the camera setting. So, you have gone now to f /16 f number 16 and now the whole field is in focus right. But clearly whoever took this photograph had to take this one with the longer exposure time, because now the amount of light coming in was less right. Again in movies people use this technique, so if two people are talking they bring you how they direct your focus to something, they will have the camera set to a shallow depth of field.

So, the background is blurred and only one thing or one person is in focus. So, naturally you tend to look there and then they want to shift your focus somewhere else, they either change the focal position and they still have a shallow depth of field. But they have changed the entire focal setting. So, that the shallow depth of focus is now shifted to somewhere behind or they change the setting. So, everything becomes focused right. So, you can play around with depth of field depth of focus simply by changing the aperture stop dimensions right.

And you should be able to extend this idea to aberrations, because what are aberrations we have using optics to design an imaging system and you want the image to be crystal clear and sharp with no blur. We know we are not using the perfect or the correct lenses for that, the correct lenses should have a Cartesian oval shape, we are using spherical shaped lenses and we are saying as long as the rays of paraxial they work pretty good, all the rays from any point have the same optical path length.

But that is not really the case and many times the rays we are using are not exactly paraxial. We are going to have blur in the system. We are going to have a lens or a function of refractive index; refractive index is different for different wavelengths. So, you can have aberrations in your image because the wavelength of your light source is not a single wavelength, you can have aberrations in your image because your rays are not paraxial.

But you should be able to now get the idea the aperture stop limits rays traveling through the system and by controlling which rays travel through the system, I should be able to improve the quality of my image. Because some rays will definitely make the image worse and if I cut them out I will improve my image ok. And that you will see over the next few classes how what are aberrations and how using an aperture stop would actually help us, I think yeah.

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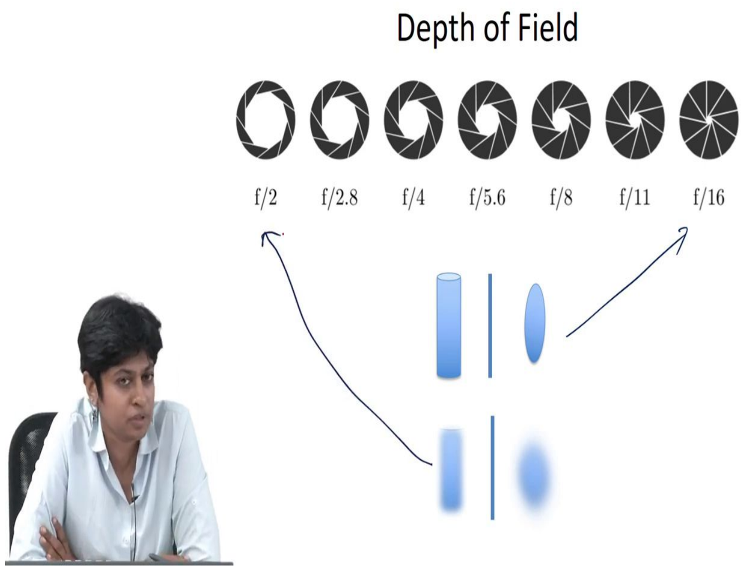

So, I just have this. It is basically a summary of what I said. If you have these different aperture settings and this was your object which of these would you say has been imaged by, let us say the upper image was created using the f by 2 setting or the f by 16 setting. So, the top one is the f by 16 right because it has a large depth of field right and maybe this was created by this with a very shallow depth of field.