MITOCW | Lec 2 | MIT 2.71 Optics, Spring 2009

GEORGE BARBASTATHIS: So does anybody have questions from the last lecture? After some time to wake up, anybody still have questions? So I will start, and if you remember of a question that you had, please interrupt. I think if you push the button the button, I will hear a sound over here. So we will know that there's a question.

So I'd like to pick up the thread from where I left last time. We covered fairly quickly because we ran out of time. But we covered that the law of reflection and the law of refraction. So I'd like to go back to the low of reflection, and remind you that it is a very simple, very simple result. The minimum path requirement for the light rays force those reflections to be symmetric.

So this has a strange consequence that we're unfamiliar with from when we look in the mirror daily. And that is the fact that our left and right locations in our body. They flip when we look at the mirror. So we'd like to make that a little bit more quantitative by looking at this diagram. So to understand this, suppose that I am-- I have an object that is oriented. You can think of it as perhaps two pencils that are sort of following the ray paths and then they get reflected from the mirror.

So, for example, if you look at the central ray, it will be reflected symmetrically. So, again, what you see here is the front view of the mirror. And then I will draw a few ray a paths in perspective. So this is the ray paths that start from the object. I don't know if you can see me over there, but I'm trying to show what will happen with an actual pencil. So if this was a pencil that is coming towards the mirror, and this is the surface of the mirror. The pencil will go like this. And then law of reflection says that it will also come out like this again.

This follows very easily if you simply trace the rays. In the next step in my animation here, it paints the sort of positions of the pencils and their tops as they get reflected from the mirror. So what happened here is the following. As you can see, the pencil did not actually change orientation. This is a strange thing about mirrors. But what did change is the following. Imagine that you are walking together with this pair of pencils. As you are walking this way, you will see that the one that is horizontally oriented. The top of it is pointing to your right.

But if you walk all the way to the mirror. Go to the center of the ray, and start going backwards the other way around. Then all of a sudden, the top of the pencil appeared on your left. This is a simple consequence of the law of reflection. The way we interpret it in everyday life when we see through a mirror is the following. Of course, in everyday life, we don't talk about left handed and right handed triads. But the way we interpret it is because normally when we look at a good quality mirror, we do not know that there is a mirror there. We actually see a continuation of that are being reflected behind, back behind the mirror.

So what you're seeing then if we look behind the mirror is actually this triad, with the pencils oriented as shown here. And if we interpret it as being seen from behind, then, of course, left has become right, and vice versa. So another way to think about it is that when we look through a mirror, it is as if we're looking from the image from the back. So a better way to think about it is if you're looking at something that is written on my t-shirt. If you look at it from the mirror, it would appear as if I were hollow, and you would see the back of the writing on my t-shirt.

And you all know that if you look at the ambulance sign in ambulance trucks, ambulance whatever you call them, cars. Because it is meant to be visible through the mirror of a driver, they actually write the sign backwards. So when you look at it, it is as if you saw a transparency of it from the back. So this is a simple consequence of the law of reflection. This is a very simple silly question that sometimes is asked. And it actually takes quite a long explanation to answer.

And that question goes like this. If you look at the mirror, yes, we know that left and right flip, but up and down do not flip, right? You don't see yourself upside down in a flat mirror. You see yourself flipped from left to right. What is the reason? The reason is shown here. The reason is because of the flipping of the relationship between the left and right in the object side, as you interpret the projection of the rays that are coming from the opposite side of the mirror.

So this requires a little bit of thinking, so I'll let you think about it. Unless you have a question now, please ask it. If not, you can think about it and come back with more questions on Wednesday. Is there any immediate question about this? That's kind of a subtle and elegant point. I should have brought a mirror with me. Piper, do you have a mirror over there?

AUDIENCE: No, I don't have a mirror here.

GEORGE BARBASTATHIS: No mirrors, OK. But everybody has access to mirrors, right? It's the one optical element that we can find very easily. So I'll let you practice with your mirror in your bathroom, and then come back and ask me questions. OK.

AUDIENCE: I'm lying down. You're horizontal.

GEORGE BARBASTATHIS: That's right. Our producer like this. The other thing I wanted to talk about is expand a little bit on the law of reflection. Oh, I'm sorry, the law of refraction that we derived last time. So the law of refraction is the last equation shown on this line. It says that this quantity, the index of refraction multiplied by the sign of the angle of incidence, where the angle of incidence is defined with respect to the normal to the surface. It is preserved.

So as you go through multiple surfaces, the law of refraction says that this quantity must be preserved. So there is a common problem that I have posted just a couple of hours ago that asks you to make an analogy between the law of refraction, and the problem of a lifeguard who has to save a person in the water. So recall the reason the law of refraction happens is because the light must minimize its path between two points, P and P prime.

So a very similar problem is if you have a trajectory that you're trying to design in a way that you minimize the time that you will spend going on this trajectory. So here, you have a swimmer who is sitting on the beach. I'm sorry, not a swimmer. You have a lifeguard sitting on the beach. And the lifeguard sees a person drowning in water farther behind. The lifeguard can run on the beach at some velocity, v sub r. They can also swim in water at some velocity v sub s.

Most people swim slower than they run, so we can assume here that the running speed is faster than the swimming speed. And the question is how should the swimmer plan his path so that he can reach the drowning person as fast as possible? Again, you can think that, for example, the straight path is not the best because he's spending too much time in water. I mean, water, he's slower. So he may want to spend a little bit extra time in the fast middle, and a little bit less time in the slow medium.

But, again, he cannot overdo it. If he goes a really crazy path, then, again, he will end up with a longer time. So light is trying to do a similar thing. It is time to optimize the obstacle path length, or equivalently, the time that it takes for the light ray to reach from a starting point to an ending point. And, again, remember this is almost an exact analogy here. The speed of light is faster in air, and slower in a dielectric medium. So if you had the air and glass here, that would be a very similar situation.

I'm going to skip the next line. And I'm going to go to this one, to number 34. So what I'm trying to say here is to point out two cases. They're not really different. They're just two cases of the same situation. In one, you are going from a medium of lower index to a medium of hire index. And in this case, obviously, because of the law of refraction, the angle of refraction will increase as you go from left to right, from low index to high index.

The opposite will happen if you go from high index to low index. OK, so this has two consequences, which you can think of as you reach the extremes. If you come in at the maximum possible angle here, 90 degrees, then you can imagine that you will not enter at 90, but you will enter at a slightly smaller angle. So basically, if you are coupling in light from air to glass, or in general from a medium of lower index to a medium of higher index, you have a limited column of approach that you can couple light into. And that is given by this equation over here.

When the exterior angle theta reaches 90 degrees, then this is the maximum angle, theta prime, that you can access inside the high index medium. The opposite is perhaps slightly more interesting, is what happens when you reach or exceed theta prime equals to 90 degrees over here. So if you look again at the law of refraction, you can realize that it is possible to arrange for a combination of n and theta, such that the product is bigger than the index of refraction at the medium side.

In order, now, to satisfy the law of refraction, you would have to require that the sine of an angle is bigger than 1. So since we are limited to deal with real angles here, not complex, this cannot happen. What really happens there is that the light will actually be reflected. If you satisfy this condition, this product becomes bigger than the index of refraction outside in the medium. Then when you satisfy this condition, then light will be reflected inside the high index medium. And that is known as total internal reflection, or TIR.

So let's look at TIR in slightly more detail over here. So I have a glass medium in there, and imagine that I have a wavefront that is arriving from glass towards the air interface. So there is a combination of index and angle, where the product of the index inside the glass times the sine of the angle equals exactly one. What happens then is the law of refraction does not break down yet. But what will happen is the light will be refracted, and it will propagate exactly parallel to the interface. This is known as a surface wave.

If you increase the angle now, then the product will become bigger than one. The law of refraction cannot be satisfied anymore. So what will happen then. Oh, and I should have said that the angle where this happens is called the critical angle. Because it is the angle just below which I still have refraction. If exceed this angle, then I get this phenomena of total internal reflection, where all of the light is reflected inside the glass, inside the high index medium.

So it is almost as if the interface here abruptly changes, and instead of being mostly transmissible over here, it becomes mostly reflective. So it starts acting like a mirror. There's one difference that makes it slightly different than a mirror. And the difference is that if you were to calculate the electric field on the opposite side of the interface, that is, inside the medium where light does not propagate. You will discover that there is some leakage. The electric field has non-zero values in the low index medium over here.

Even though the electric field that you find is not propagating, it is what is called evanescent. It is in exponential decay, but there is no wavefront. There is no wavefront of light propagating in the vertical direction like this. This is called an evanescent wave, and we will revisit it later when we deal with electromagnetics. Because right now, the way I defined it is not perhaps very rigorous, or very quantitative. But I wanted to give you a sort of a heads up that something slightly more than geometrical optics prediction happens here. But as far as geometrical optics goes, that we will be dealing for the next few lectures, there is a reflection.

This says what I just mentioned, that we will talk more about these evanescent waves a little bit later. One more thing that I want to say about evanescent waves. One way you can sort of realize the existence of evanescent waves is with a sort a related phenomenon called frustrated total internal reflection, also known as FTIR, because that's quite a mouthful to pronounce.

So FTIR happens if you have this situation, where you're beyond that critical angle, and therefore, your total internal reflecting into the medium. But you bring near the interface, you're bringing another piece of glass, another piece of high index medium in a way that an appreciable amount of the evanescent wave is allowed to enter inside the high index medium. If that happens, as we've said, the TIR is frustrated. What it really means is that the TIR stops happening now.

What would happen is a small amount of light will still be reflected, of course. You cannot avoid that. But the significant portion of the light will couple out into the next material, and it will actually be transmitted. So this is a very interesting phenomenon, because if you think about it, the light is forbidden to enter this region. Snell's law says that light cannot cross into air, yet because of the proximity, the light can actually couple out. And again, we will see a much more rigorous explanation and quantitative description of this phenomenon later, when we're doing it through magnetics.

Some of you who may have taken electronics or quantum mechanics, there's a similar effect called tunneling in potential barriers in quantum mechanics. The equations are very similar that describe this phenomenon. In both cases, you have a wave that is crossing a forbidden region in order to pass into an allowable region again. This may be actually be a good find for Piper to solve a demo of the total internal reflection. And Piper will actually solve it in the context of a prism.

Piper, maybe you can start setting up while I give a brief description of prisms. You all are familiar, I suppose. They're pieces of glass that are cut into various triangular and other polygonal shapes. And typically, prisms are-- they're arranged either so that the light passes through, as shown in the top diagram. Or if you bring the light from the bottom, and you manage to exceed the critical angle in the interface, then you can also total internally reflect the light, and create a situation like this that is known as a retro-reflector.

Now, a rule of thumb that is useful to know for glass, which has index of refraction 1.5. The critical angle is about 42 degrees. So if you are incident at 45, as shown in this case of what is called isosceles triangle, then-- actually, I'm sorry. This is equilateral, isn't it? If you're incident at 45 in an equilateral triangle, then you will satisfy the TIR condition, and you get this retro-reflector. And there's more complicated prisms that allow you-- for example, this is the pentaprism. After two bounces, the light will exit at 90 degrees angle. So Piper, maybe you can do the demo now?

PROFESSOR: Sure, sure. So just before showing the demo, I'm going to pass around this prism that has in these two surfaces, two images. So then what you see is that in this window here, you tilt it like this. You're going to see when you get a hold of it. You actually see two different images due to total internal reflection. So at a given angle, you basically get the light reflecting from one of the surfaces. And another angle, you get the other one. So it's actually very interesting to see.

OK, so we're seeing here the top view of the demo. We put together a wide light source and a laser source. And before showing you what actually happens, let me just introduce some of the components that we are going to be seeing in several demos from now on. First of all, we have the white light source, it's a lamp. And then this component here, it's a regular lens that you're familiar with.

So the job of these lens is to collimate-- that's the term that we use-- to convert this light close to a plane wave, similar to the light that is coming from the sun. So the sun, again, would be like a point source of light far away. So then these lenses are basically transforming in this light into parallel rays from the geometrical optics point of view. So we use these lens.

This is an iris, similar to the iris that controls the aperture in your eye. And this is just used to split the light into two-- I'm sorry, to reduce the diameter of the beam. Then this component, here this one. It's what we call the beam splitter, or more specifically, the non-polarized beam splitter. And it's a component that allows us to split the light into two paths. So here, this is one path, and another path.

So once we split the light in two paths, and in this case, it has equal ratios. So it's 50% to one side, 50% to the other. Then let's follow one of these parts. This part illuminates one of these prisms here. And again, there's going to be some refraction following the law of refraction that we saw. But in addition to that, as we'll see in the next couple of slides also. There is a phenomenon called dispersion that you're familiar with when you see rainbows in a rainy day.

And basically, that has to do with the fact that different wavelengths see a different index of refraction. So if you go back to the Snell's law, they will basically bend in a different way. So therefore, you see a rainbow effect. So I don't know if you can see the side view in the camera please? Yeah, so that's a picture of it. OK, but here in the classroom too, please.

I don't know if you can see it. We're going to try to show it also in this. But I have here two components. This is a prism that is doing these, what we call the normal dispersion, which basically has that the biggest angle that bends is the blue light, or the shorter wavelength. And then we have another component here that we haven't talked about yet, but we'll see it in the next few slides. So this is just an introductory introduction to this element. It's called transmission grating. And this component is used in several systems.

They're a different principle. It's not refraction anymore. It's using the diffraction property of the light. And using that diffraction property can also create this rainbow that you could see here in the back, and hopefully, you can see the picture. What we are going to see here is that actually the opposite trend happens. The red angles bend more than the blue angles, and that's called anomalous dispersion.

So we have normal dispersion in the prism case, like in the one shown here in transparency, and anomalous dispersion showed in the grating. So I'm going to tilt this a little bit. OK, it's fine. I'm going to try to see. So I don't know if you can see it. Can you see the rainbow here from the back? If you're in the classroom?

GEORGE BARBASTATHIS: Yeah, we can see it.

PROFESSOR: All right, excellent. So this is just the rainbow from the grating. After class, you can just come here and play with the demo. And you're going to see the two cases. You can actually trace the rays and see which color is bending more, and distinguish between anomalous and normal dispersion.

So the last thing that I want to show here is the total internal reflection principle. In this case, this piece of acrylic here that we have. You can see that it's forming-- it's basically having a laser light coupling into one of the sides, so similar to that exit sign over there. And what we have is that the acrylic-- the piece of acrylic acts like a wave guide. So it conducts a light inside. And the reason the light doesn't escape is because it's basically suffering total internal reflection at the interface between the acrylic, which has a higher index than air, so stays inside.

Now, in order to couple the light out, I put some tape here, as you can see forming the letters MIT. And that basically frustrates the light, allows it to break the incidence angle. So a ray now instead of getting into a very flat surface at an angle that is larger than the critical angle, it basically reaches a surface that has a diffuser type of angle, so maybe it can escape out. So then, you can see all this light diffusing out forming like either this image, or the image of the exit sign. So that one, you can see it also in Singapore? The frustrated?

GEORGE BARBASTATHIS: Yeah.

PROFESSOR: OK.

GEORGE BARBASTATHIS: It looks frustrated to us.

PROFESSOR: From the side view, I guess. So I don't know if you want to add anything, George.

GEORGE BARBASTATHIS: So what you see on the slide that I'm projecting it now is an application of the same principle that Piper just showed. It has an application in a bunch of commonly used conventional devices, namely, fingerprint sensors. Where instead of the tape that Piper put over there, usually what you do is they place their finger touching the side of the prism. And then because our buddy, this may be surprising to you. It was surprising to me when I first heard it.

Our body is composed mostly of water, about 75% is water. So therefore, the refractive index of our skin is close to 1.3, which is, of course, higher than the refractive index of air. So what happens here is over here, for example, you have a glass and air. So therefore, light will be totally internally reflected. But at the ridges of the finger, of the fingerprint, you have glass and water. That is 1.5 to 1.33 or so. So therefore, the ridges appear dark because they frustrate the total internal reflection. The light couples into your finger. And therefore, a surprisingly sharp image of the finger appears in the camera.

Actually, what you see here, it does a disservice. The projector and the pixelation of my computer does a disservice to the quality of the fingerprint image that you get. So nowadays, most fingerprint sensors are based on this principle. In fact, we have improved it. Instead of using the prism in places like laptops that have fingerprint security, it is the same principle, but you slide the finger. But still, the ridge of the fingerprints as you slide the finger over the sensor is captured by the principle of total internal reflection.

Any questions about that? About TIR and FTIR? OK, one other use of TIR is in another very useful-- another extremely useful property of light is that you can actually capture it, almost like in a wire. And you can guide the light over a very long distance. Now, why this is very important is because we know from experience, and we'll also learn later as the Huygens principle, that light does not like to be confined. Generally, light, once you generate light in a source, the light would like to expand. It would like to open up and propagate in an expansive way.

For example, the sun, the stars, and so on. They propagate isotropically, all around them. And you know the same from the light bulbs and so on. The light expands. There's an exception, of course, called lasers. Lasers can be quite collimated. But even lasers, they tend to expand. If you leave a laser beam by itself, and you propagate it for a long distance, eventually, it will expand. It will become quite big.

So the way to undo this property of light-- if you want to transmit light over a long distance without expansion-- is to use a wave guide. So wave guides typically, they use this phenomenon of total internal reflection. In the simplest case, you have a slab of high index-- dielectric middle sandwiched between two other pieces of lower index medium.

And what happens there provided that the light is incident at the sharp enough angle that is beyond the critical angle between the two media. Then the light will sort of bounce back and forth between the two interfaces. And this way, you can actually transmit it over a very long distance. So, of course, if it is not true. If the light arrives at a shallower angle, then, of course, it will actually couple out, and it will not be guided anymore.

The way you establish whether the light will be guided or not is by using these properties called the and numerical aperture of the wave guide. So this is a term, numerical aperture, that we'll hear again and again in this class, at least in three different contexts. But they all mean the same thing. Actually, they mean an angle of acceptance of an optical system.

So in this context here of a wave guide, compare the two rays. One is sort of the solid ray, and the other is the dotted ray. The solid ray comes in from air, then is refracted at the vertical interface. And because this angle is fairly small, by the time it gets into the middle, the angle it makes through the perpendicular surface of the interface between the slab and the cladding. It actually satisfies the TIR condition over here.

You can see a little bit if you familiarize yourself with the way Snell's law works. You can see that as you increase this angle over here, this angle over here actually decreases. So the dotted ray actually can arrive at below the critical angle. So therefore, the daughter ray is not guided where the solid ray is guided. So the numerical aperture is the maximum angle, theta naught, that you can tolerate before you stop satisfying that TIR condition. And therefore, the numerical aperture is the maximum angle that you can couple into the wave guide. If you tried to bring light at a higher angle than that, it will actually not be guided. It will escape into the cladding, and it will get lost. It will disappear.

So with a little bit of algebra, which I haven't done here. I will let you do it by yourselves. In years past, I used to give this as a homework, but I didn't do it this time. But anyway, with a little bit of algebra and playing with Snell's law, you can find out that the numerical aperture in this case is given by this quantity over here. The square root of the difference of squares between the two indices of refraction. And as I mentioned earlier, physically what it means. This quantity is the angle of acceptance of the wave guide for the light that you want to couple in.

Typically, wave guides in practice, they have a very small difference between the index of the core, where the light is guided, and the index of the cladding. This difference is typically in the order of 10 to the minus 3, or 10 to the minus 4. So therefore, the numerical aperture is what? It is small or large for a typical wave guide? If the index difference is very small, is the numerical appearance or a small or large? Small, right?

We're going to set up a competition here between Singapore and Cambridge. So you guys, when you have an answer, please push the button. On either side, please push the button. So the numerical aperture is actually very small, as our colleagues here correctly said. And what is on the slide is the opposite. If you have a high index contrast, then you get a high numerical aperture.

There is one more type of wave guide, which is actually the same principle, but a slightly different implementation. It's called a gradient index wave guide. And the way to understand it. Imagine that I stack a bunch of different slabs of glass with index that varies from a small value. This I denoted as the sort of light gray. Then to darker gray, denoting higher index of refraction, and then back to light gray. I mean, back to low index of refraction.

So if you imagine the ray coming in from the top here. It will refract into the guide, and then as it goes in, it will keep getting refracted. Now, we can adjust the numbers here, so that one of these interfaces, the light will exceed the critical angle. And therefore, it will be totally internally reflected at this interface. And if that is true, the same thing will happen also at the top interface. As I mentioned before, this quantity, n sine theta, is preserved.

So therefore, if this quantity, n sine theta, was such that the TIR condition was satisfied over here, then the same will happen over here. Because everything else is symmetric, correct? The reflections are symmetric, and the quantity, n sine theta, is preserved. So therefore, if you put a light in this kind of arrangement, it would actually follow a periodic trajectory. The light will sort of be periodically reflected from these interfaces, and will follow a periodic trajectory down the stack of slabs.

Therefore, this is also a kind of wave guide. It is commonly referred to as green, where green is not for the facial expression, but stands for gradient index. And there's a special case of a gradient index where they don't normally do it this way. The way they do it is with a continuous variation. And they manufacture it with diffusion. It's very interesting. They take a piece of glass, and they diffuse ions. Because the ions change the index of refraction of the glass, then they can sort of get a continuous profile of gradually variable index.

And in the special case where this profile is quadratic, it turns out that the trajectory of the light paths is kind of like a helix. It become sinusoidal. And the light sort of bounces in sinusoidal fashion between the two interfaces, this one and this one. We will do this in more detail four lectures later. If you look at your syllabus, there's something called Hamiltonian optics. We will actually see in action how this sinusoidal periodic trajectory comes about. Yes.

AUDIENCE: So what is the [INAUDIBLE]?

GEORGE BARBASTATHIS: Yeah. That's a very good question.

PROFESSOR: Can you repeat the question? Because they didn't press the button here. Can you repeat the question, please?

GEORGE BARBASTATHIS: I'm sorry. Could you repeat with the button? Yeah.

AUDIENCE: Yeah. What is the advantage of using this type of wave guide compared to step index wave guide?

GEORGE BARBASTATHIS: So the advantage, which I cannot describe yet because we have not done wave optics. But in wave guides, there's a phenomenon called dispersion. It is very similar to the dispersion from a prism that Piper showed before. But in telecommunications, when you transmit signal down a wave guide, it has the effect of basically lowering the speed, the effective speed at which you can transmit information. So it turns out that the step index wave guide has a higher dispersion than the gradient index wave guide. So you get a much higher speed in fibers of gradient index. So that's one reason why people use it. This will take a while.

And, of course, more practical wave guides that are shaped like a wire. Literally, they are known as optical fibers. Again, you have two types of fibers. You have the step index fiber, where you have a higher index core, and the light is kind of bouncing back and forth between the core and the cladding. And there's also gradient index fibers, where the light is following a helical trajectory.

The phenomenon of wave guiding, again, I have to defer to electromagnetics. It is much easier to describe with electromagnetics than it is with wave optics. But for now, we can get a sort of a preliminary description with the means that we have available to us. As a sort of a curiosity, it turns out that these gradient index wave guides. They appear in the nature in certain animals. I mean, insects, actually.

Their eyes, they're composed of several wave guides, each one of which is actually a gradient index wave guide. And the way the animal eye works is it captures-- remember, the wave guide has a limited numerical aperture. So each one of these guides, each one of these small eyes, they're called ommatidia, these little wave guides.

So each one of those captures a very narrow angle of light sort of within the field of view of the eye of the insect. And then sends a signal down to the optic nerve of the insect. So basically, the insect with this kind of eye, it forms a very bloody picture of the background, because it integrates a relatively large range of angles. But still, the range of angles is small enough that it allows it to quote unquote see.

Now, insects, of course, they don't see the way we see, at least from our everyday experience. And the reason, of course, is that the insects have a very limited brain. A typical insect might have about 10,000 neurons in his brain. Show of hands, does anybody know how many neurons we have in our brain? 10 to the 11. So we have about eight orders of magnitude more neurons.

In case you are wondering, whether you are smart or educated, it does not have to do with a number of neurons that you have, but it has to do with the connections between neurons. Neurons are connected with wires. It turns out an educated person has approximately 10 times more connections than an uneducated person. The same number of neurons, but more connections.

And so it's a sad fact of life that every day, adults-- that is, after age six or so, even at childhood-- would begin to lose neurons. In fact, each one of us every day will lose about 100,000 neurons. Nothing to worry about, because we have 10 to the 11. So even with all this loss, we can still survive until a fairly old age. But anyway, it is true. So [INAUDIBLE].

Anyway, the insect, on the other hand, has about 10,000 neurons altogether. So it has to make do with these 10,000 neurons. It has to move. It has to feed. It has to mate and all of these things. So the way they handle it is they get very simple vision, and they navigate according to differences in lighting. So the typical example is an insect flying toward a tree. Nature has evolved the insect to avoid this situation, because if it flies into the tree it will crash and die.

But if it flies towards a tree, the insect sees a dark background-- the trunk of the tree-- surrounded by light, which is sort of leaking on the sides of the tree. As it flies by, it sees an edge of light that is very rapidly expanding, because it is approaching the tree. So the insect is wired. It as actually automatic. The insect doesn't think, oh my god, I'm going to crash. Let me turn. It's automatic. As soon as the neurons of the insect register a difference in lighting between successive ommatidia over here, they turn on the motor-- the flies or whatever, the legs and so on of the insect, the navigation of the insect. And the insect turns and avoids the obstacle.

So this is what I say about insect. More precisely, I'm referring to the fruit fly, which has been very broad, very extensively studied in this context. But anyway, this is a very, very interesting story of how the insects use what we now consider as a rather sophisticated optical instrument, a green wave guide in order to generate a very simple type of vision based navigation.

The next thing I was going to say, Piper already mentioned it. The index of refraction of most dielectric media turns out to be a strong fraction of the wavelength. So I stole from a book, actually, from the Soto website. Soto is a glass manufacturer. They make glasses that are used very commonly in optical instrument lenses and such, and prisms and so on.

So they have this picture on online of the index of refraction as a function of wavelength for a relatively large range of wavelengths going along the wave from ultraviolet into the deep infrared over here. So you can see that the index varies quite a bit. Also, with the plot here, the absorption coefficient of the material. And you can see that they are kind of correlated in the sense that when the index does something interesting, the absorption also seems to do something interesting. It is not coincidentally. It turns out to have a very interesting theoretical foundation. I will go into it. Perhaps I will go into it later in the class.

But anyway, the point I've been trying to make here is that you can see that the index can have quite a bit of variation. So because of that, if you send broadband light that contains multiple colors into an element, such as a prism. Then you can observe these phenomena that Piper showed. Different wavelengths, different colors, they experience different index, and therefore, the Snell's law applies differently to them. That is why you have this-- it's called analysis of white light. It becomes a rainbow.

For most materials, it is true. Longer wavelengths actually have a lower index of refraction. Now let's see, does this make sense? If you look at this picture over here. Does it make sense what I said? Which wavelength apparently has the lower index, blue or red? It better be right, or I-- either I made the wrong slide. But anyway, I have taught this class for several years. So you would think that if I had made the wrong slide, I would have fixed it by now, right? So the slide is correct.

The way to figure it out is you have to imagine a normal to the surface over here. So which wavelength appears to have the stronger refraction? Blue or red? Blue, right? So the blue wavelength suffers a strong refraction. That is, the blue wavelength has what index? Higher or lower? Higher. And indeed, the blue wavelength is softer than the red wavelength. So this is consistent with the curve that you see here. The blue wavelength is probably somewhere around here. The red wavelength is somewhere around here.

It is not a dramatic variation in the visible range. And that is typical for most glasses. In the visible range, they have a relatively slow variation of the index of refraction. But nevertheless, it is there. And you saw evidence of it in the experiment that Piper just did with the prism. And the last thing that I want to say. I don't want to belabor this point. People use various quantities to characterize dispersion.

And typically, they characterize them with respect to the various emission lights-- emission lines, from atomic spectra. So they use this as reference [INAUDIBLE]. The reason, I suppose. The reason is that back when people developed these measures, lasers were not available. So the best way to define wavelength standards was with emission lines. So they use typically the hydrogen C line and F line, and the sodium D line. And then they define these quantities, the dispersive power and the dispersive index, which are defined according to the index at these three different wavelengths.

So this is very useful for people who do optical design. And it gives you sort of an idea of how dispersive is a glass. These quantities are actually inverse relative to each other. And this an example. For ground glass, typically, you want the V number, the dispersive power, to be low, if you want a dispersion free element.

OK, any questions? OK, so I'm not going to go over the second lecture. We will postpone it for Wednesday. Basically, we have slid back by about an hour, but that's OK. We'll catch up later. But what I'll do is I would like to get you started thinking about next Wednesday's lecture. So next Wednesday, we'll basically see a bunch of applications of Fermat's principle. Namely, the principle that says that light chooses its trajectory trying to minimize the optical path length.

So we saw already two applications, one in the law of reflection, and the other in the law of refraction. So the next applications will be in focusing. So the question we'll ask the next Wednesday is how can we design a surface, or reflect a surface such that if light is arriving from infinity in parallel rays like this, this surface upon reflection focuses all the rays. So they pass from the same common focal point F.

So you can look it up into the notes, and then I will go over it again on Wednesday, how we can use the Fermat's principle in order to design. You can actually design. We can come up with an analytic expression that has to be a parabola for the sacrifice that gives the perfect focus onto a point.

So the homework has been posted. The first three problems you can do without a need for any of this. Actually, I think the first four problems. You don't need any of this. The problems are not due until actually the next Wednesday. Not this Wednesday, but Wednesday the 18th, nine days from today. So you're in good shape with regards to the homework.