Introduction to Photonics
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Lecture No 01
Introduction

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Hello and welcome to this course. This is Introduction to Photonics. I will start the lecture today by just giving you a little bit of background as to how to this course was conceptualized in the first place.

You go through a certain level of optics in, as part of your high school education, where you learn about the basic laws of reflection, refraction and based on that you cover a few topics.

And then when you come to college, you are typically experiencing more advance courses such as optical communications, photonic integrated circuits, optical sensors and bio-photonics and so on.

And what we thought is that we actually need a bridge between the two because certain level of fundamentals that are taught in the high school level is not enough to clearly appreciate the kind of concepts that you are encountering at the advance level courses.

So, we decided to float this course as sort of a bridge between the two and, of course, this course has been now offered for several years to several sets of students where we have clearly had an opportunity to look at the finer aspects of the course and try to patch them up.

Now before we move on, let me ask you this question. Why are you in this course? Why photonics? What are the typical things that you use light for? At that point, if some of the students present here can participate, I would appreciate it. What do we use light for?

Surely, a very, very good example is Optical communications, which is clearly one reason why, in certain ways, we have all these wireless communication at this level because what you do when you have your mobile phone.

You take a mobile phone and do a phone call. You are trying to use electromagnetic waves in the RF region to communicate to a nearby antenna. And chances are, from that antenna on to the exchange or from that exchange to other exchanges at different parts of the country or different parts of the world, that it is going to be carried through optical communication.

So, in certain ways, optical communications have revolutionized this whole field of communication. So that is a very good example says why do we need to study about light. What else?

So, a simple example is how you are able to see things? The whole process of human vision is, is based on light. So, you have a light source, you have all these lights, LED lamps and fluorescent lamps that are illuminating. Light is falling on things, getting scattered and you are actually able to see this image in your eye. So, your eye is your detector in this case.

So, the whole process of human vision is based on the fact that we are able to use light and we are able to detect light. And of course, an extension of that, you can say, is all the imaging that is happening including what you do with your mobile phones, this vision principle etc which uses light. So what else?

Biomedical imaging clearly, lot of things you are able to see, parts of the human body like internal parts of human body through optical probes, that is through endoscopy. You are able to do imaging of what is happening inside a body through the endoscopes.

And, of course, even in terms of what is happening in our eye, what is happening, at the surface of our body we are able to image using biomedical imaging. So, we use light for that. What else?

Let us get a little more modern. Let us get more up-to-date. Where else do we use light these days? You have heard of Augmented Reality? So, what is Augmented Reality? It is basically, you have a display that comes in, that mixes 2 different scenarios and it is able to give you extra information than what you normally have with your regular vision.

So that whole thing about Augmented Reality which is actually one of the disruptive technologies that is going around. There are lot of Fortune 500 companies, technology companies, the Microsoft, the Apple, the Google they are all out there, trying to come up with Augmented Reality solutions and certainly there is a lot of development happening in that domain.

And then, of course, you can extend that to things like autonomous driving. So, you have a driverless car. And a simpler version of that could be a robot. So, robotics, the whole thing about robotics, it is able to see the situation or things around it and able to take actions.

So, all of those require light-based technologies. So light certainly plays fairly big role in our everyday lives and it continues to change the way we see things around us and we get things done around us. So, it is so much so that by 2050 there is some prediction that most of the Fortune 500 companies around the world will be having something or the other to do with photonics.

So that is why are here. We are here to understand the properties of light, how to generate light, how to detect light and how to manipulate light, how to make light work for us. So that is what this course is about.

So, let me go down here and start making a few notes. So clearly, we are at course which is Introduction

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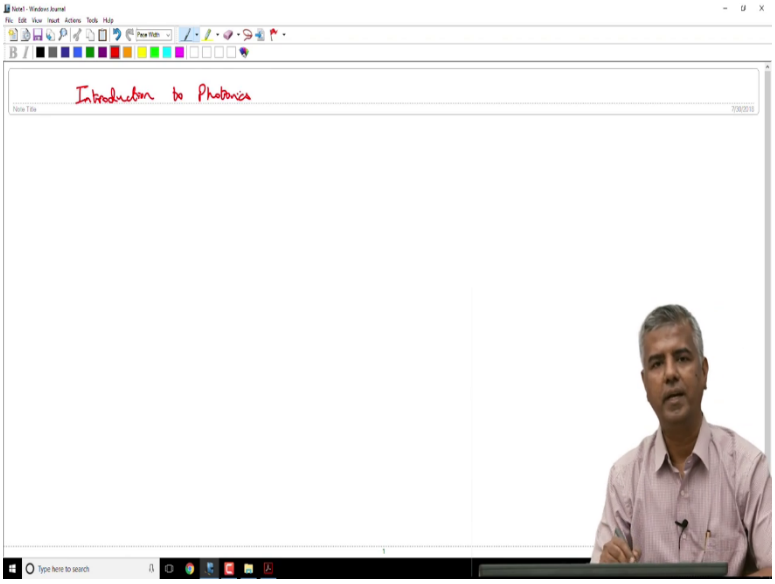

to Photonics and we just started discussing why photonics and we started

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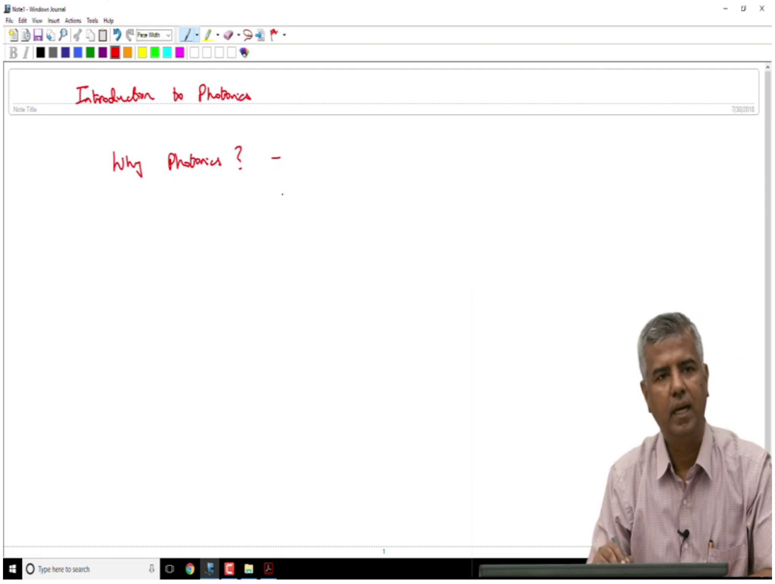

discussing some examples of what is the use of light and we said the whole process of human vision is based on light.

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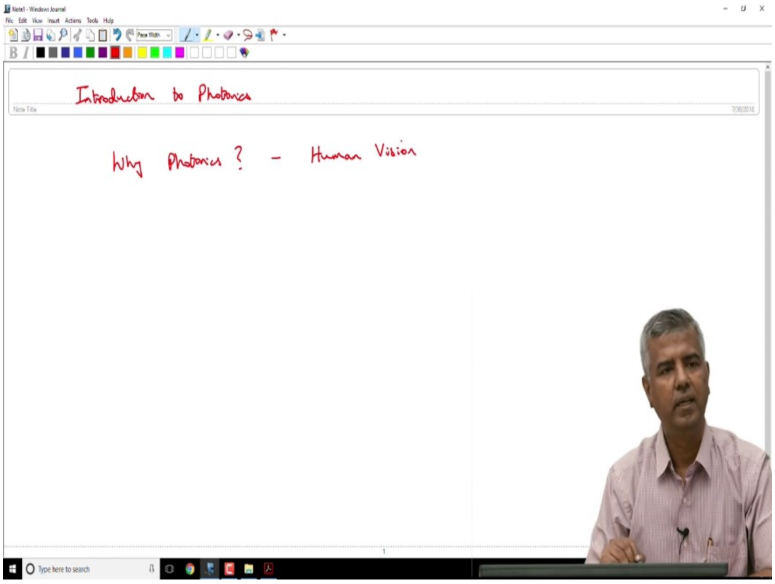

And then you extend to imaging concepts,

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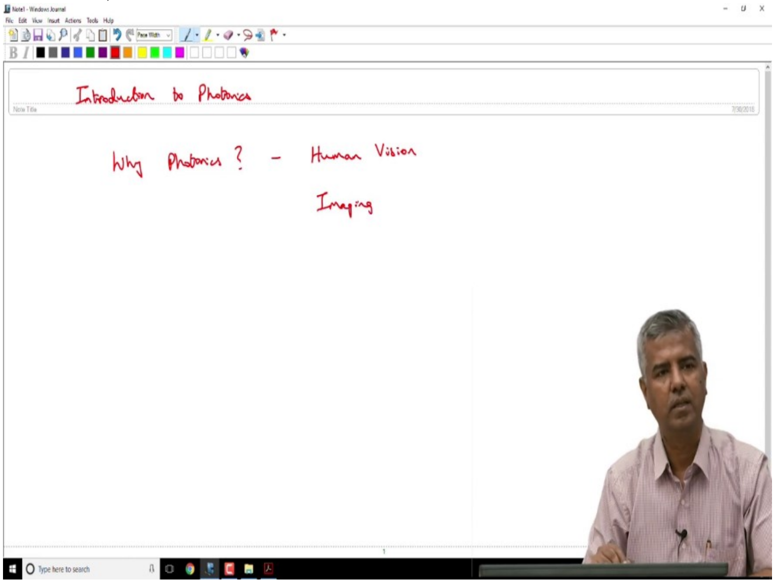

using cameras, using endoscopes you are able to see things around us. Another example of optical communications where

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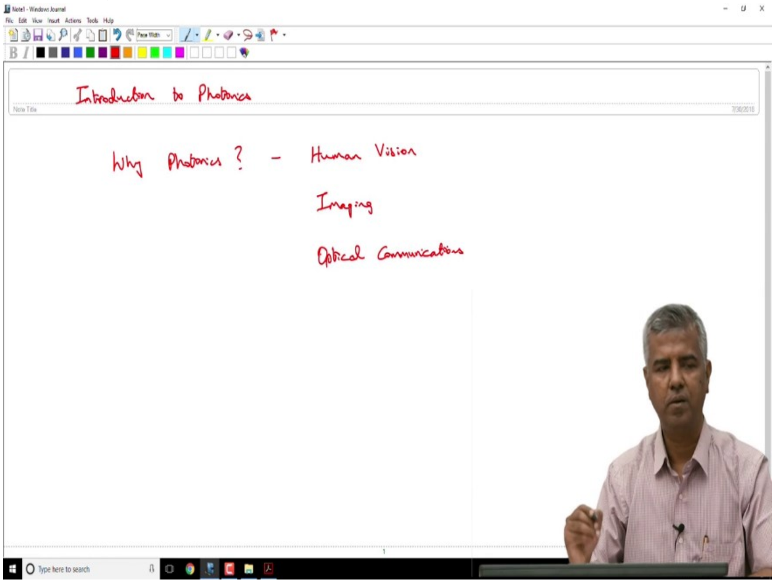

we use light to carry information which has completely revolutionized this whole field of communications.

And then, we can list out things like material processing. So, you take once again your mobile

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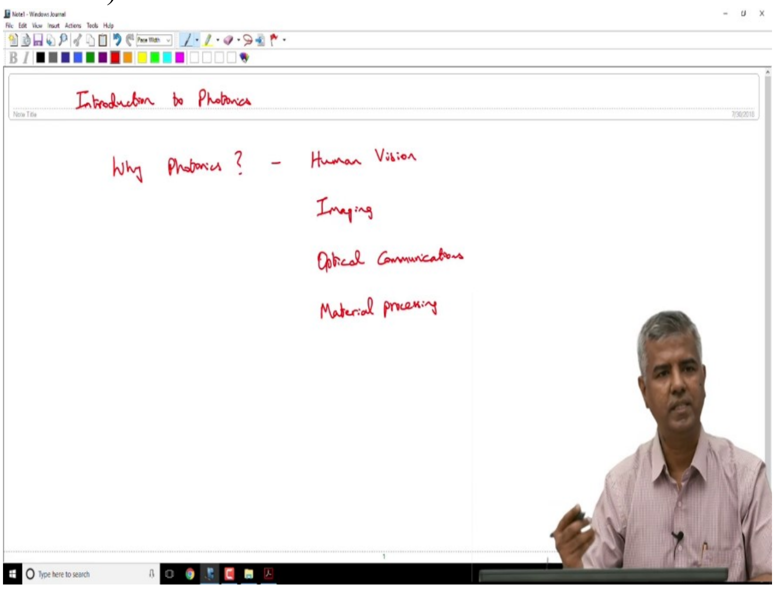

phone as an example. You have different parts of the mobile phone manufactured with such high precision and some of these may involve actually laser-based marking; laser-based cutting and so on. So that is lot of material processing applications for which light is used.

And going forward, things like Augmented Reality

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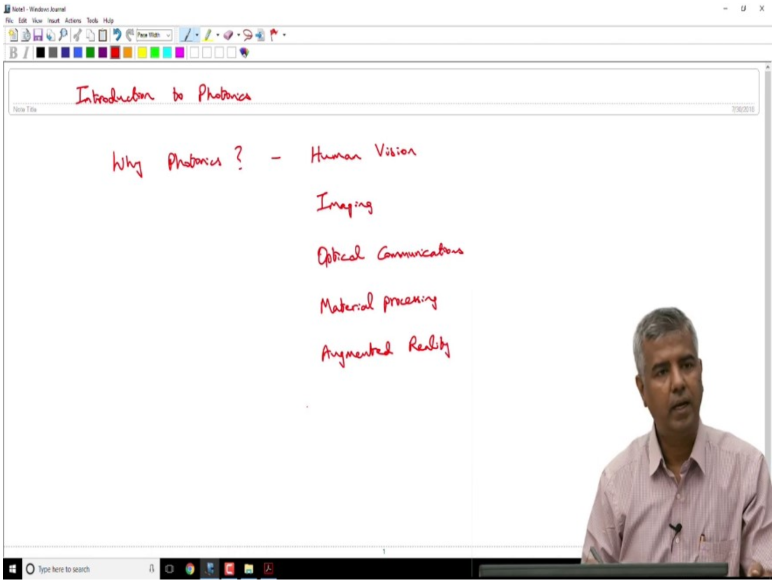

there is something called Gesture Recognition. So, Gesture Recognition is the

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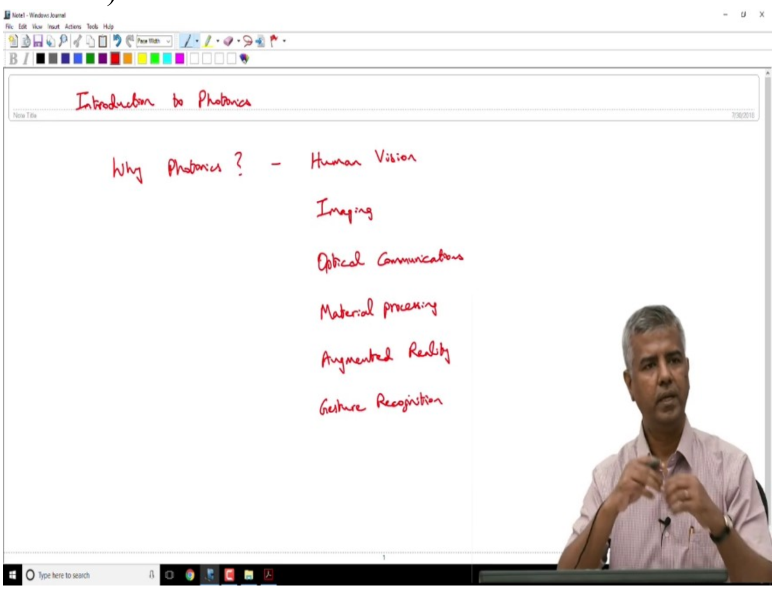

next big thing as far as man-machine interface is concerned.

We are always trying to work on concepts which can break down this interface between the man-machine and this is the next level wherein just based on some gestures you are able to communicate with the machine and you are able to make the computer understand that you are giving certain commands to do things for us.

So, so we can keep going on in that and some of the more recent developments are

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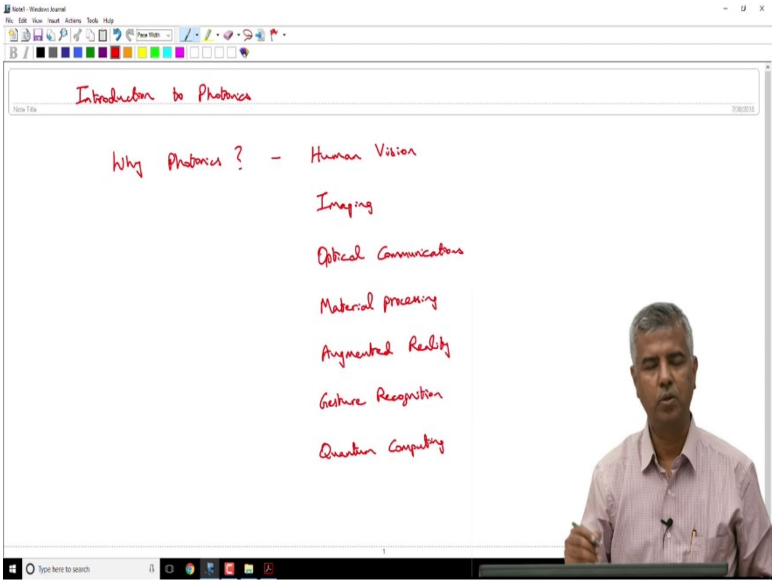

towards going to the next generation of computers based on quantum computing and so on. So, all of these

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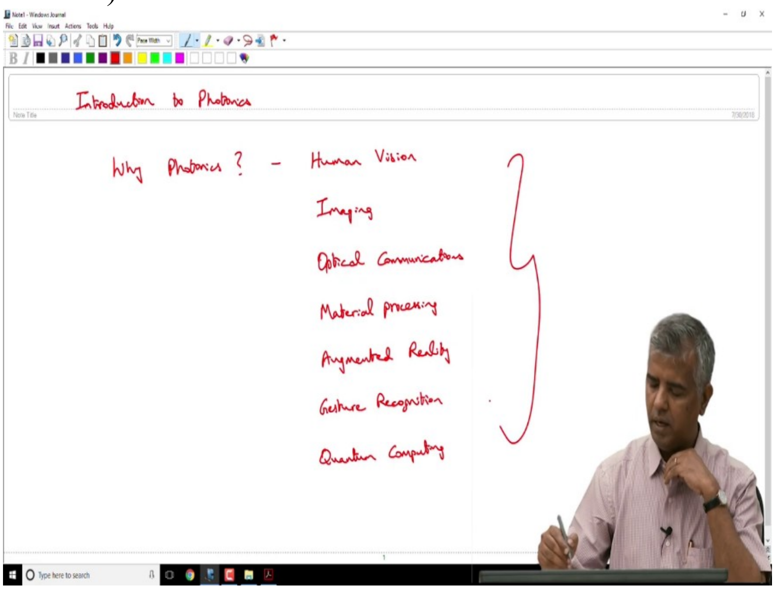

are essentially based on things where we manipulate light. So, from that perspective you can go back

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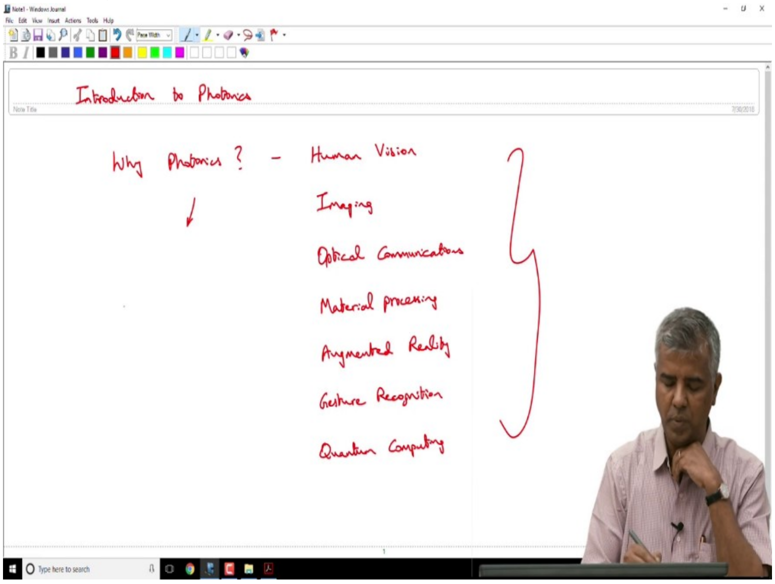

and say, when we what mean by photonics is. Photonics is the science of light.

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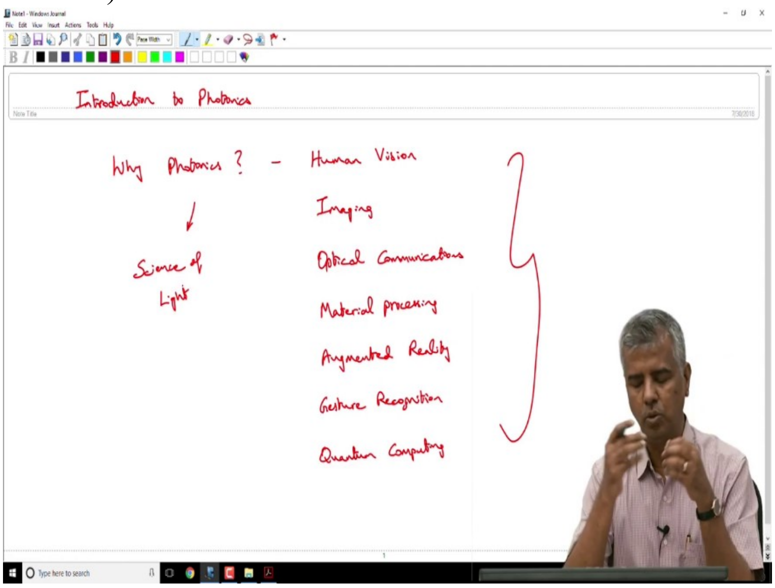

Through understanding this science of light, we can do certain things like what are the properties of light,

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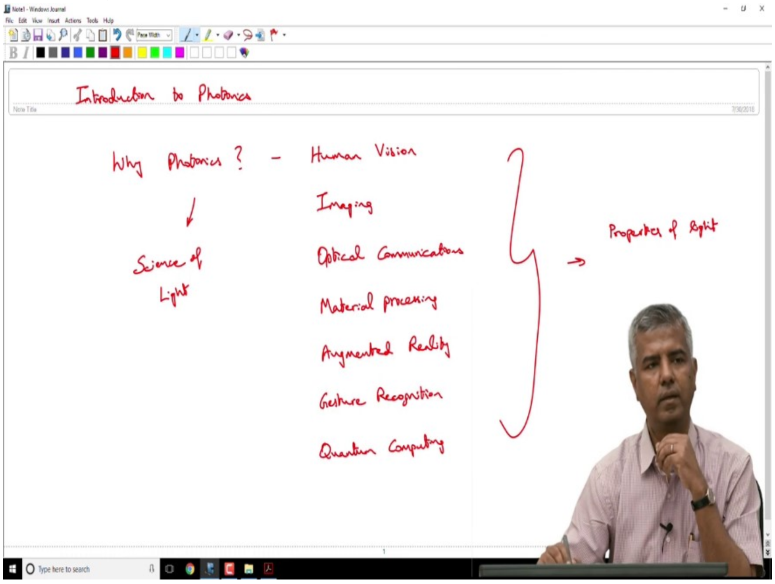

we can try to understand the generation and detection of light

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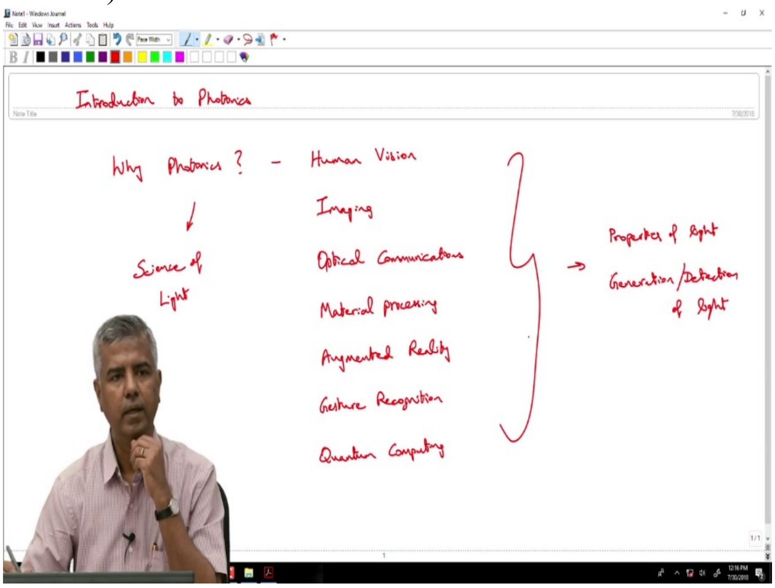

and then probably more importantly, you can look at the manipulation of light.

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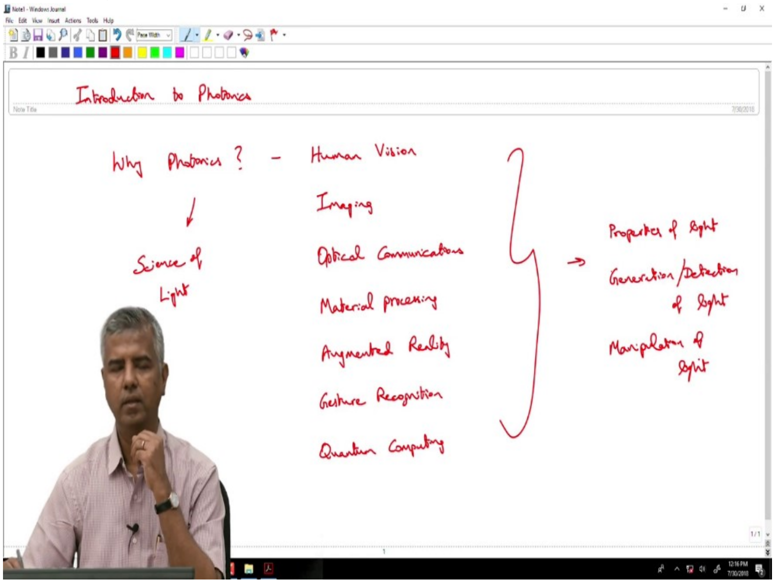

So, what do we mean by manipulation of light? Light has certain properties. So, if you want to describe light, what are the terms that you use to describe light? Wavelength is one characteristic

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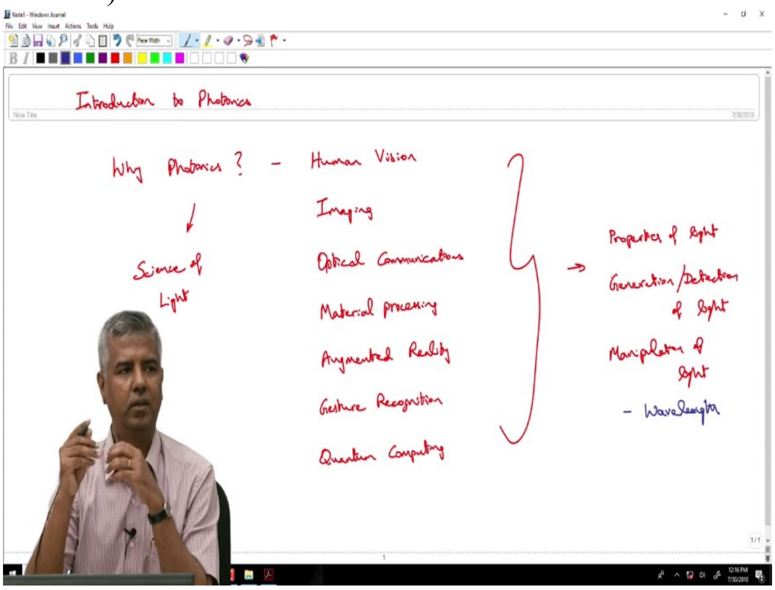

or in other words, in colloquial terms the color of light.

So, I am using different colors here to denote different things and that essentially means that these different colors represent different wavelengths of light.

What else? Intensity. So, you have amplitude of light and of course

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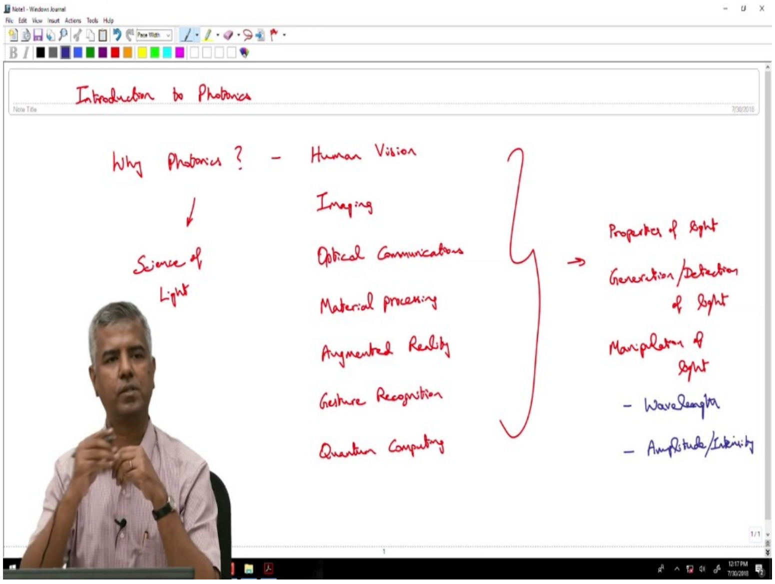

through that, you can look at the intensity of light. What else? Phase, certainly is another property. And another property probably which is not mentioned?

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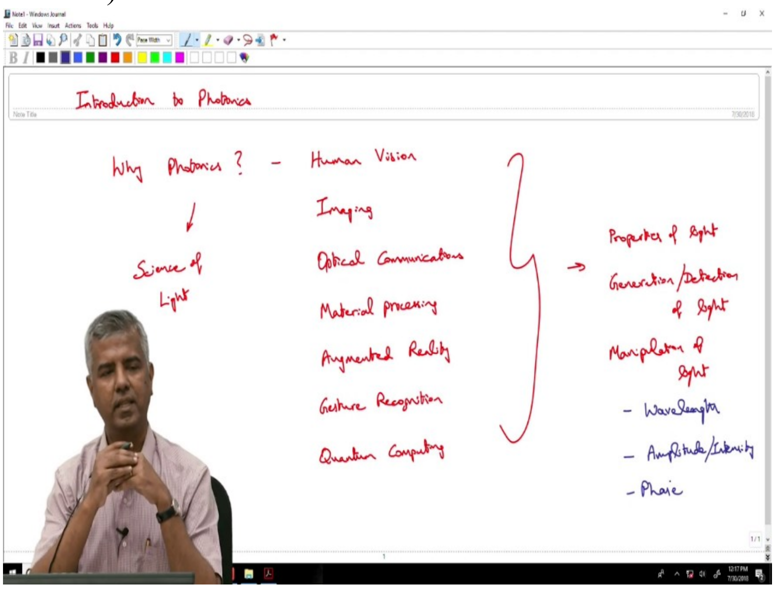

(Professor – student conversation starts)

Student: Polarization

Professor: Polarization, very good.

(Professor – student conversation ends)

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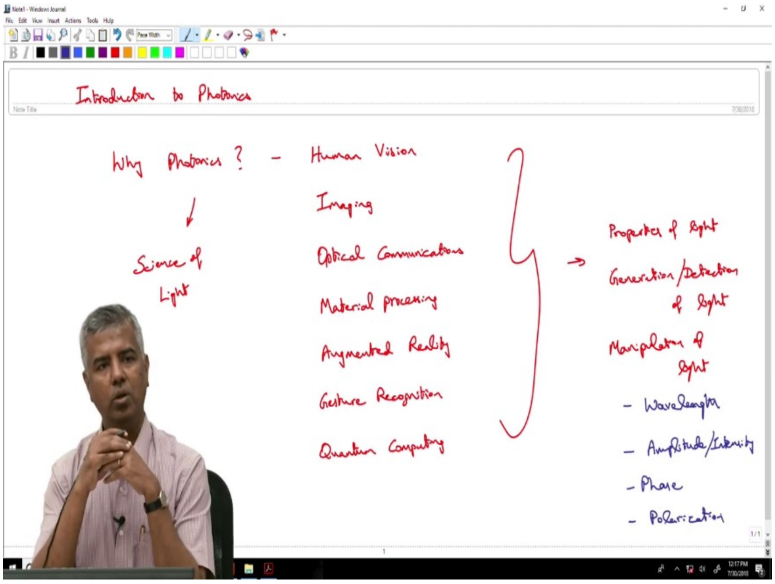

So, we have an opportunity to change certain properties of the light and through that realize certain functionalities. So that is what we are going to be, that is one of the things we are going to be looking at as far as this course is concerned. So, at this point, maybe I should step back and show you the outline of the course, what exactly we are going to be seeing as far as this course is concerned.

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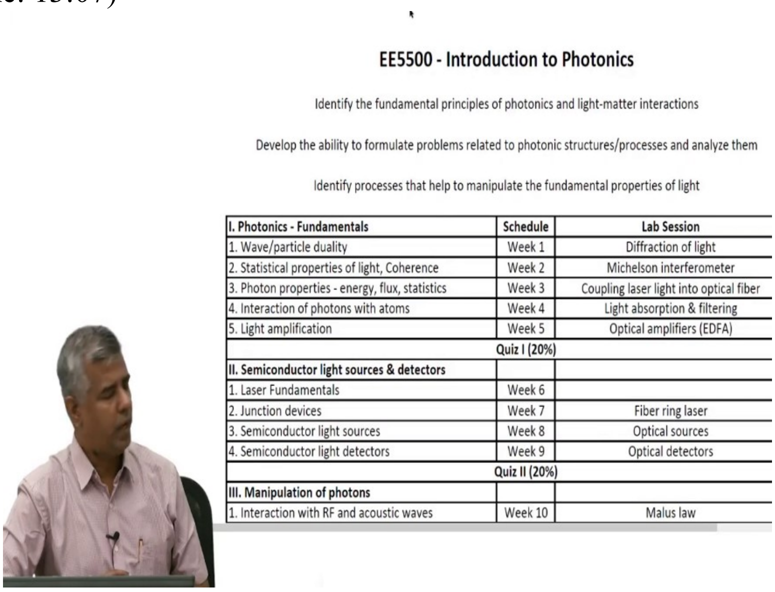

There is a first module which corresponds to understanding the properties of light and when we talk about understanding the properties of light, the first thing that we look at is this important principle called wave-particle duality.

In colloquial terms, you would see that certain people refer to the science of light as optics, and certain other section of people look at it as photonics. Are they different? Not really. Possibly when somebody is talking about optics, what they are looking at properties that are based on the wave nature of light.

And when somebody is talking about photonics, they are talking about physical processes which involve the particle nature of light. So, we are going to go into some of those details and try to appreciate where we can use the wave nature of light and where we need to use the particle nature of light and all that.

So, we will look at some of those to start with. And then we will go into this important discussion, which is probably a fulcrum as far as this course is concerned. Because when we look at the properties of light you start understanding that light is in, in general, random in nature.

In terms of the emission of photons, in terms of detection of photons you start understanding that there is a certain statistics associated with those processes.

And in fact, it is only to explain those statistics, which we try to do in terms of coherence property of light, you start appreciating that. Maybe, it does not help just to treat light as waves. Maybe you need to look at the particle nature of light as well.

So, this topic is really the motivation to look closely at the particle nature of light and so beyond that we are looking at the properties of a photon, the properties, the statistics of the photon and so on.

And then beyond that we are at a position to understand interaction of these photons with atomic systems, with matter. We will start looking into how this absorption and emission processes happen and through that process you come up with this realization that there is something called stimulated light emission.

And if you look at stimulated light emission you start to understand that may be things like light amplification is possible and then once we have realized that we are at a point where we can start making light sources.

So we will jump into understanding the fundamentals of lasers, which is by itself is a complete course. But what we are trying to do is to just look at some of the basic concepts as far as lasers are concerned.

And then the most commonly used light sources are the semiconductor light emitting diodes and some of these light panels are based on semiconductor light emitting diodes, and semiconductor lasers like laser pointer. If I am using a laser pointer, I am using a semiconductor laser typically.

And then we go on to understand light detection. Once we have understood the basics of semiconductor p-n junctions, we can also figure out how light detection can be possible using your semiconductor light detectors. There are photo diodes, what goes into your mobile camera ,for example, all those principles.

And beyond that we will go on to looking at the manipulation of light, so that is our last module. So, we will

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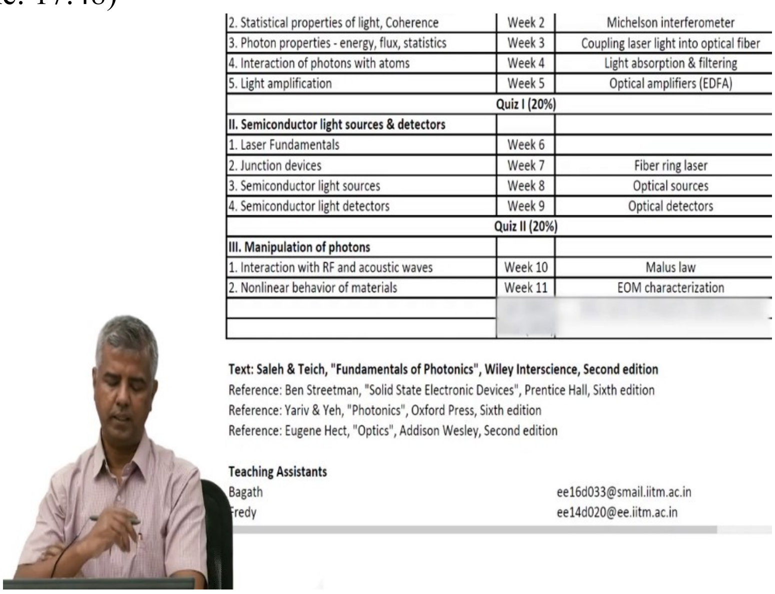

look at how light can interact with RF waves, that is electromagnetic waves, radio frequency electromagnetic waves and acoustic waves.

Can you believe that? You can manipulate light using acoustic waves. How are we able to do that? Those are some of the principles we are going to look at in week 10.

And beyond that we can also look at how to manipulate photons through non-linear properties of material, non-linear response of material. The most part in the course, we are looking at interaction of light with material, as if it is a linear response that we are getting from the material but towards the last portion we will look at what if the material responds non-linearly to the light that is incident on it.

What can we do with that sort of a property? So, this is essentially, I have charted it out as for 11 weeks. It may actually spill over to 12 weeks. But one important aspect of this particular course, the way it starts for you students here is that it is going to be a theory-cum-practical course.

Each week we will actually be doing a laboratory session which is enhancing your understanding on that particular concept that is taught in that week. It is to the point that your laboratory sessions are essentially driving what we are discussing in the theoretical aspects of this course.

And for those of you that are doing this course online, what we will be able to do on a weekly basis, is provide a demonstration of those concepts so that you can follow what is going on, essentially what the students do, the students here do in the laboratory you will be able to do that, you will be able to watch that at least as a in-class demonstration.

The lab sessions, that are defined over here are enhancing those practical aspects that we are going to study as far as this course is concerned. As far as the textbook for this course is concerned, I am going to be closely following this excellent textbook which is written by Saleh and Teich, Fundamentals of Photonics.
Saleh and Teich puts this material in such a way that you can start from appreciating some of the wave properties of light and then go on to appreciating the photon properties of light.

It is nicely structured which is in tune with what I want to teach as far as this course is concerned. So, we are going to adopt that as the textbook and of course there are certain other reference books that are provided which can be helpful in understanding these concepts at a deeper level.

So, we looked at why photonics, why we are, why we are offering this course and then closer to why it makes sense to follow this course. Then we also said essentially what we are doing in this course is dealing with photonics where we are looking at the properties of photons, light in general

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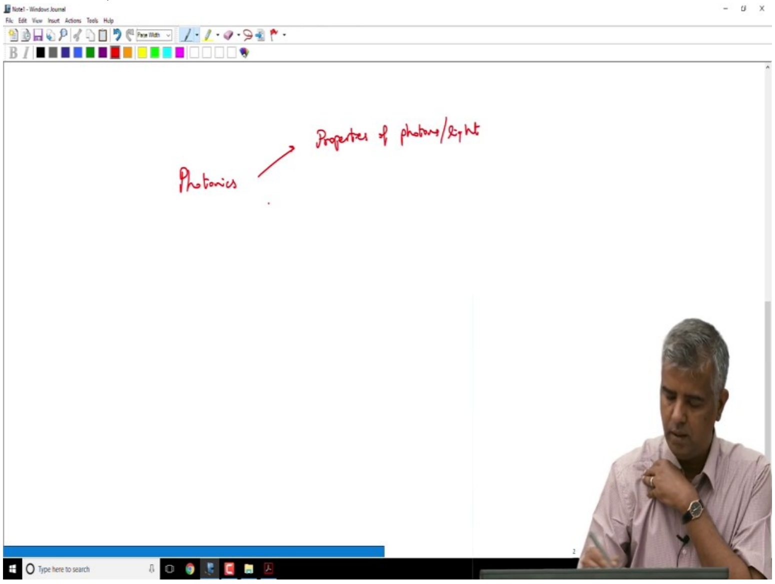

then generation and detection of photons

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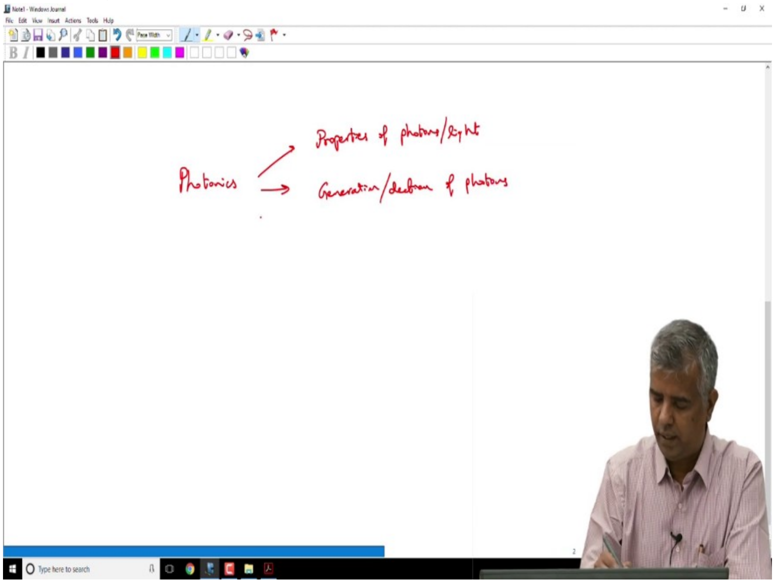

and manipulation of photons.

So,

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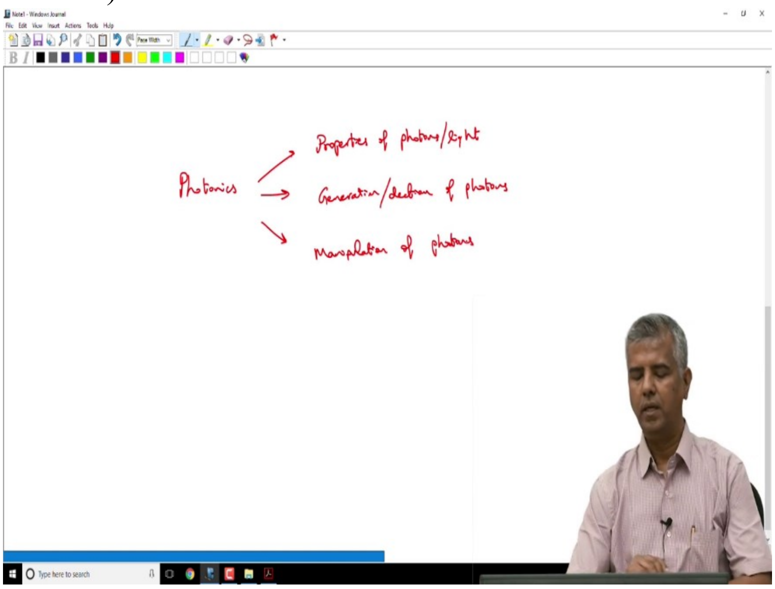

those are the three primary modules that we are going to be studying as far as the course is concerned. And let us first start with understanding the properties of light. And to do that, we will have to step back and take an historical perspective of the science of light, how it came about and it all starts with a simple concept called ray optics.

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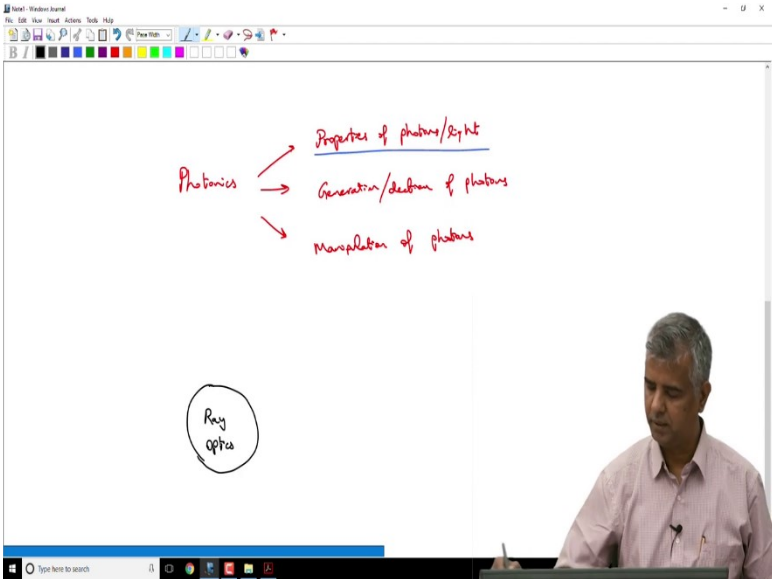

And ray optics is primarily based on this observation by a scientist by name Fermat in the early 1600s.

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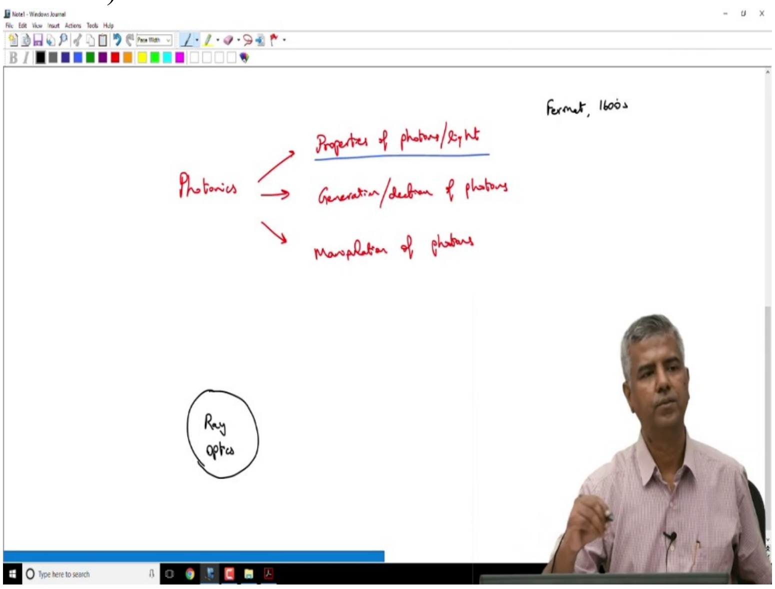

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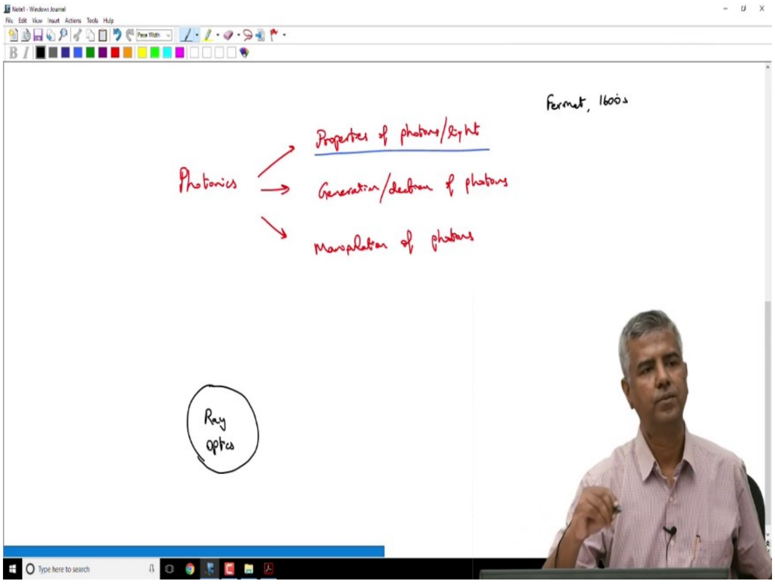

Fermat essentially hypothesized at that time that light travels in path of least time. So, what does that mean?

In a homogenous medium it actually corresponds to saying to light travels in straight lines. If I use the light source over here, I can essentially model this light source as rays of light that are coming and hitting me and from me, bouncing off to you.

So, once you are able to say that light travels in straight paths, you can use rays to represent the propagation of light. And that is the simplest way of explaining how light travels through different media.

Ray optics is a fairly powerful concept as far as understanding properties of light is concerned and that is going to be a starting point of most of the discussions that we do in the early part of the course.

Fermat said light travels in straight lines,

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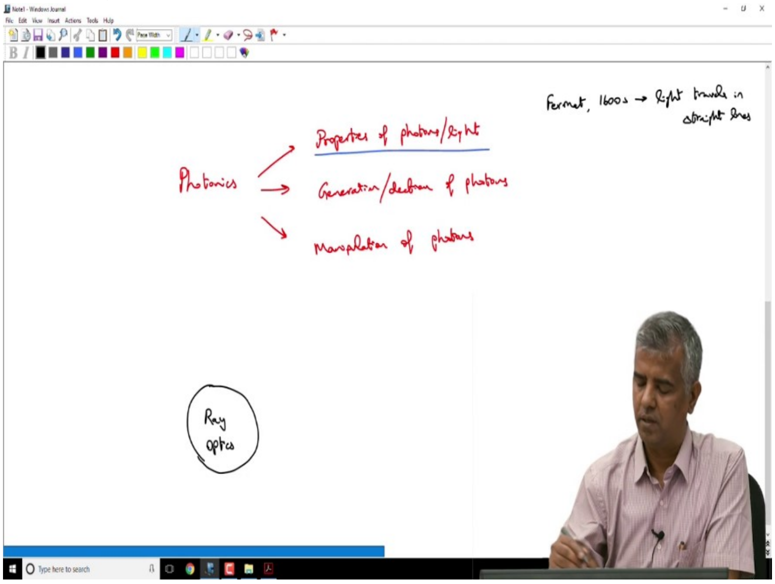

which we are calling as rays. And then this other scientist by name Huygens in the mid 1600s, he came up with the hypothesis that light travels as waves just like sound waves.

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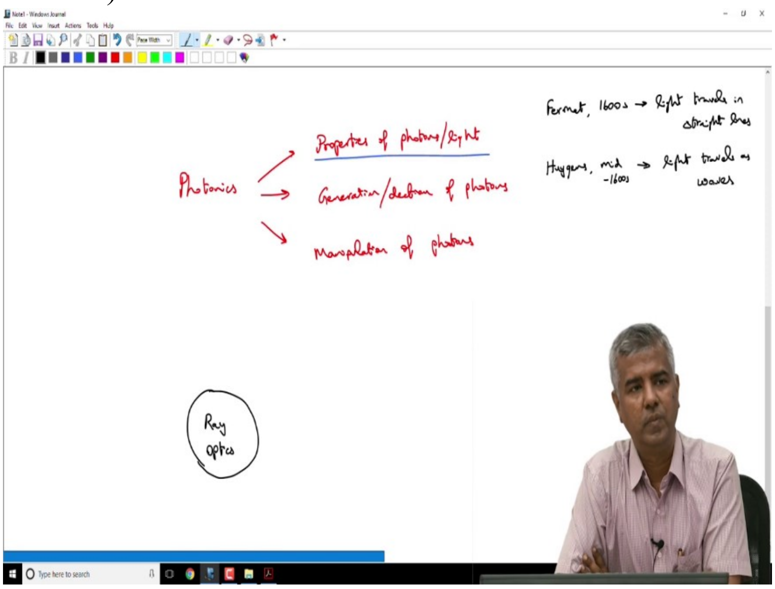

Huygens hypothesized that light also has, demonstrates wave-like property.

So that happens to be superseding what we are seeing in ray optics, so you get into what is called wave optics and what is the important aspect of waves? What are we introducing when we talk about waves?

(Professor – student conversation starts)

Student: 0:26:02.3

Professor: Wavelength

(Professor – student conversation ends)

We start introducing things like wavelength and this whole concept of phase

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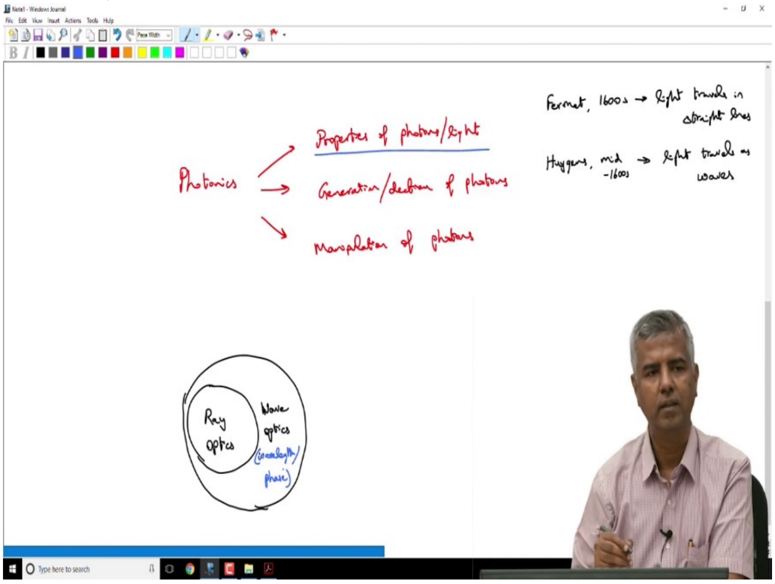

that, that light carries. So that is actually easily explained when you have a wave. So, when you are looking at them as rays, the rays do not represent any particular color nor does it represent any accumulation of its phase as it propagates. It just tells about the direction of light.

But now when we discuss this in terms of waves you start saying, there are these other characteristics that come into picture.

And then came this declaration from Maxwell around the mid 1850s, mid 1800s where he declared that light travels as EM waves, electromagnetic waves.

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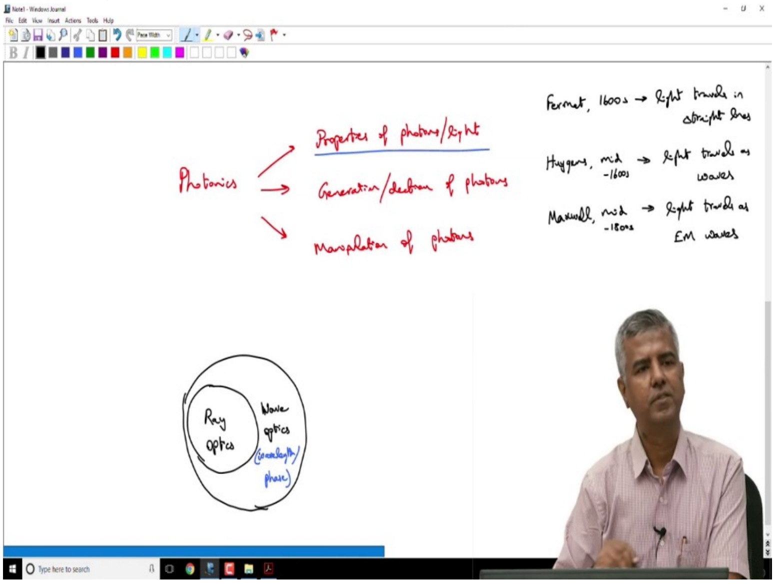

And that actually brought about another study

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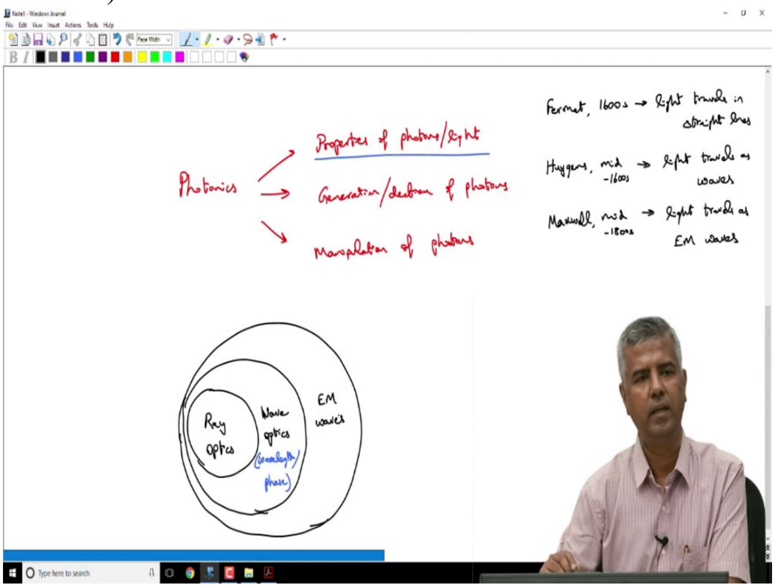

based on modeling light waves as electromagnetic waves.

And what could possibly come out of something like this? What do you think you can explain when you are talking about light as electromagnetic waves?

The last property we were talking about, light polarization comes about this. So, all the discussion on polarization is something that is well explained when you consider light as electromagnetic waves.

And it is not until Max Planck around 1885, he hypothesized that light emission as well as absorption is quantized. You can say in certain ways that the modern optics evolved from this hypothesis by Max Planck which essentially gives a much bigger picture and that is this topic of Quantum Optics or some people like to call it as photonics

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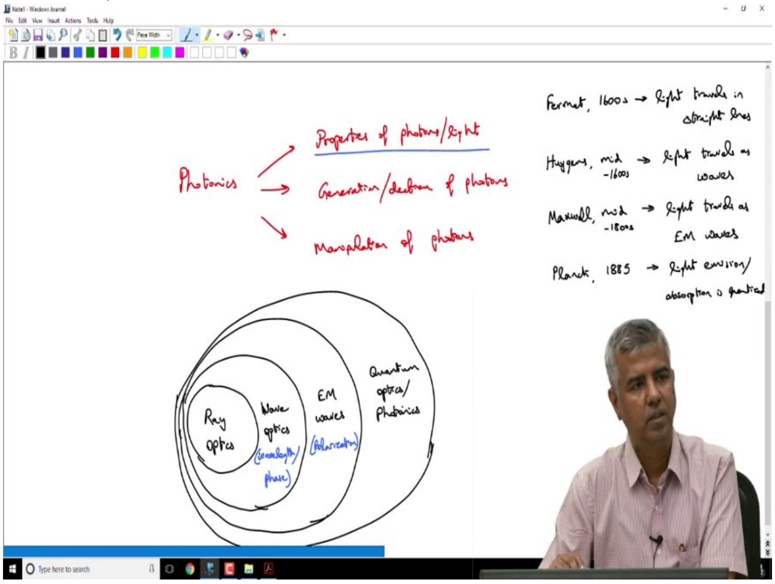

where you start looking at light emission and absorption as quantized and then, of course, the final piece in the puzzle, I think is around 1915 that Einstein declared that light itself comprises of quanta of energy, which was later coined as photons.

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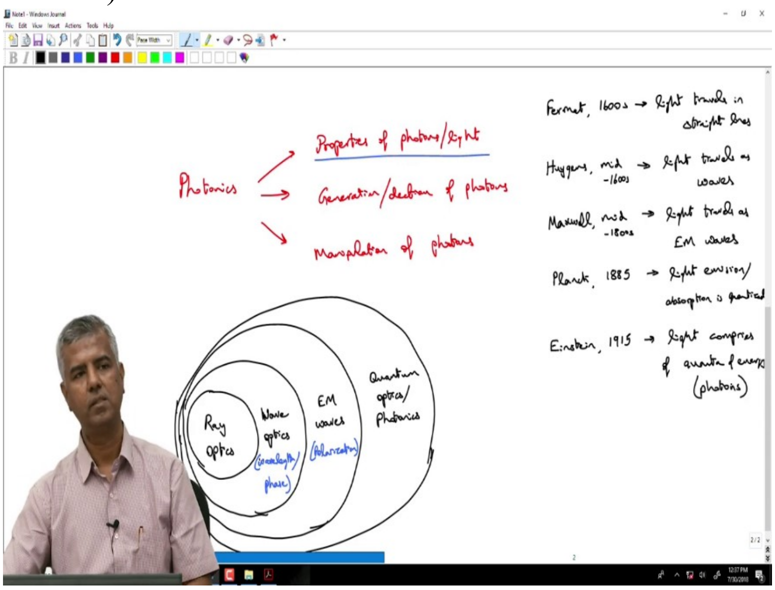

So, all this thing about quantum nature or the particle nature of light, there is lot more discussion and lot more research that was happening beyond that particular point.

This is sort of a brief history of how this field has developed and we are going to try to spend some time trying to understand what if you treat light as ray. What are the kind of problems that you can solve by just treating light in terms of rays of light, that is, propagation of light in terms of rays of light?

And you would be surprised to find that pretty much, more than half, I would say it is a very large proportion of optical systems can be modeled with just simple concept of ray optics. And we are going to try to take some examples of that.

Then we will go on to the subsequent lectures, explaining what are we missing in ray optics and what can we capture in wave optics and then we go on to what are we missing in wave optics that we capture in electromagnetic optics and so on. So that is how we are going to progress going forward.

So, let us just take an example of endoscopy.

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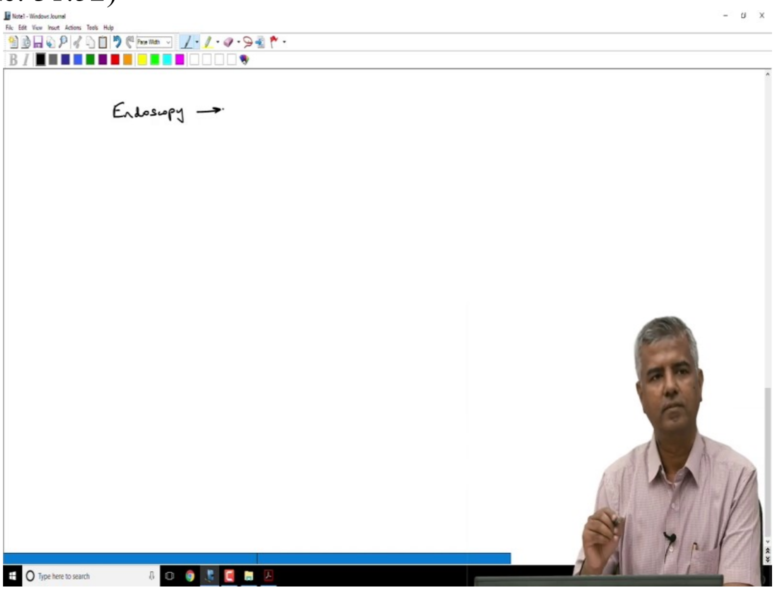

So that is something we were throwing out a little earlier. What is endoscopy? It is about putting an optical probe through your body to see inside parts of your body, things we cannot see from just outside. And that essentially is clearly facilitated by an optical probe.

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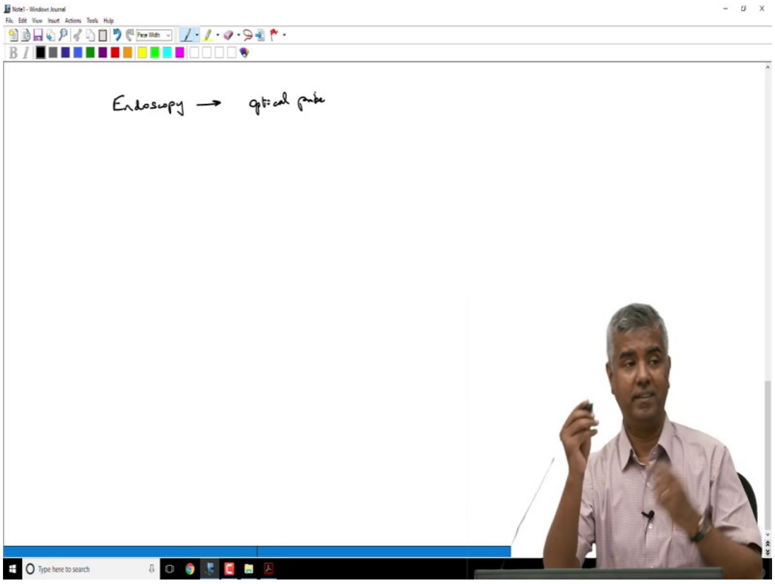

So, let us go ahead and design an endoscope, Ok. Shall we? So, what do we need to design this optical probe? What are the principles that we need to understand? There are two basic principles, one is called law of reflection

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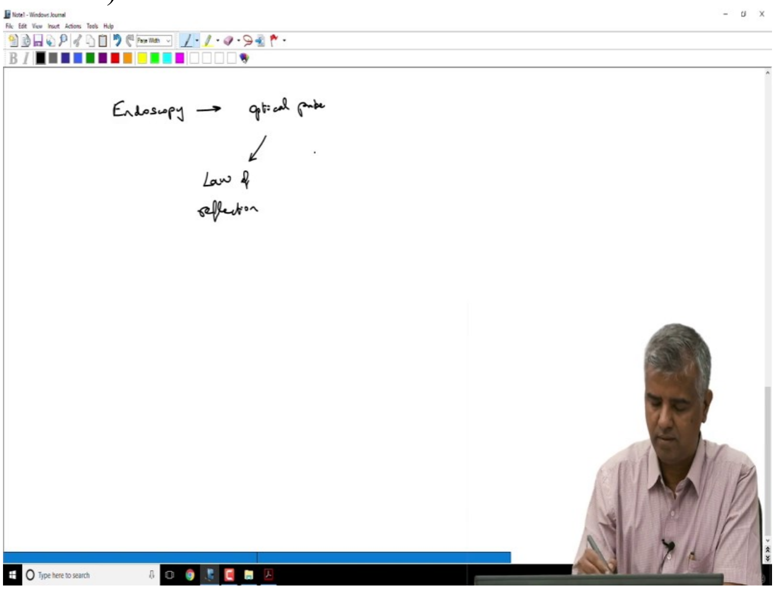

and another is called law of refraction.

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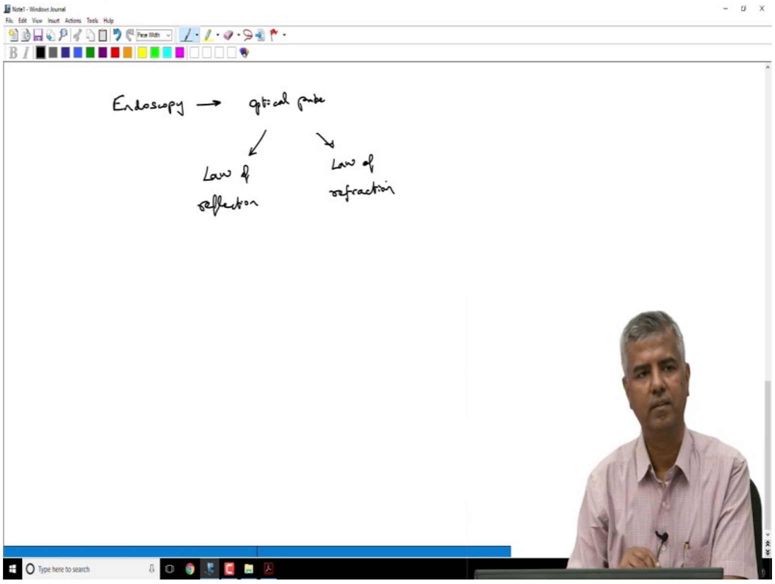

So, what are we dealing with in terms of law of reflection? Basically, say you have reflecting surface over here

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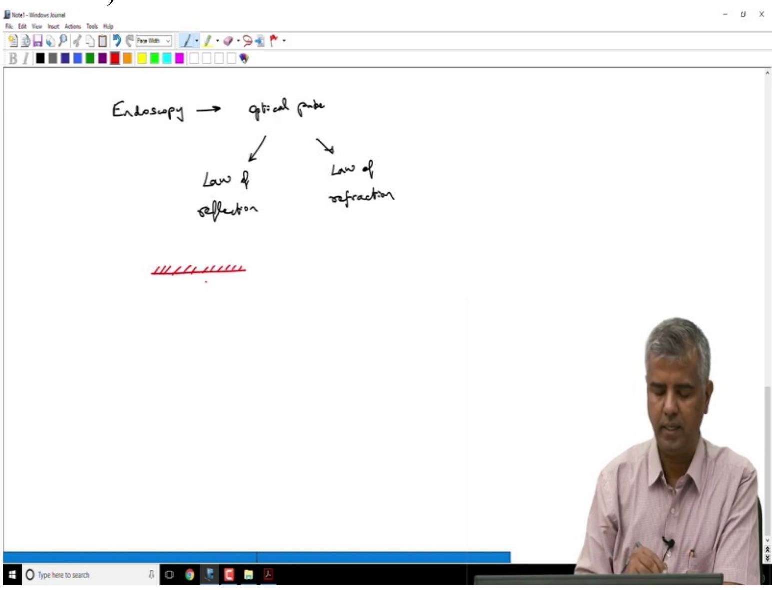

and then if you have a wave that is incident on this, or a light ray that is incident on this surface at an angle let us say,

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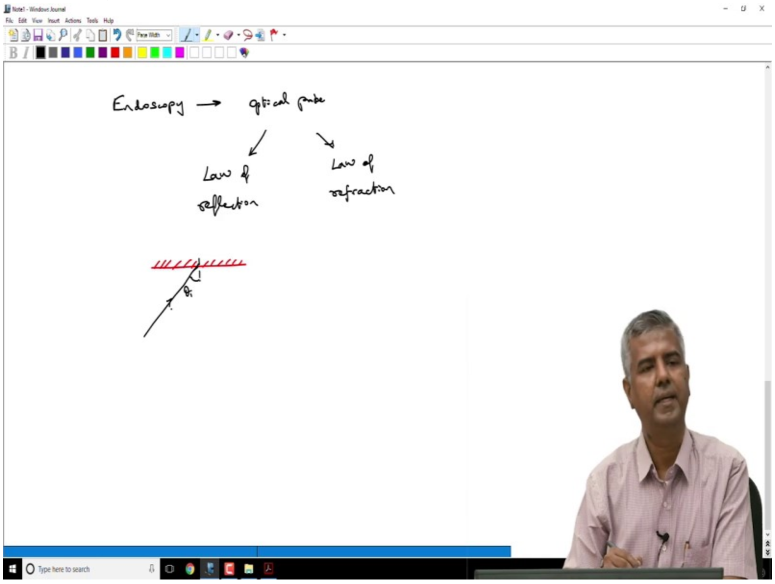

θ_i. It is going to get reflected

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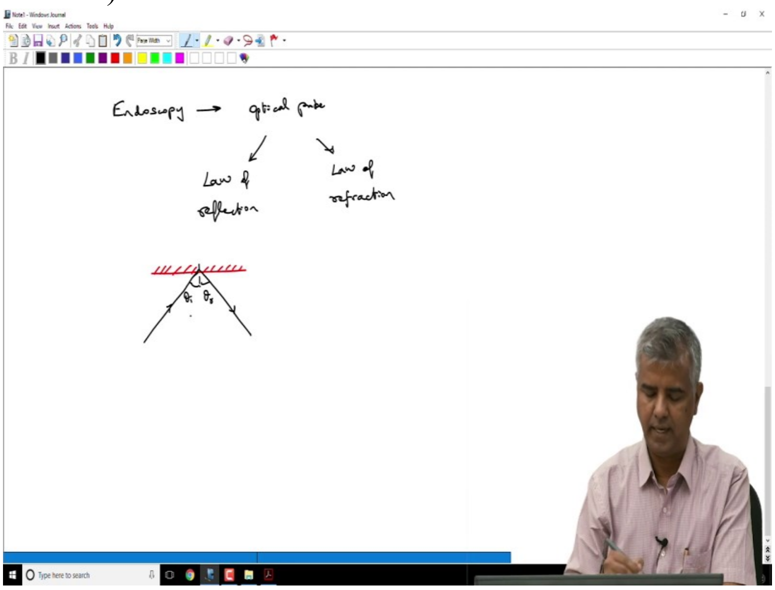

at an angle θ_r.

Now it can be proved that this is the path of least time.

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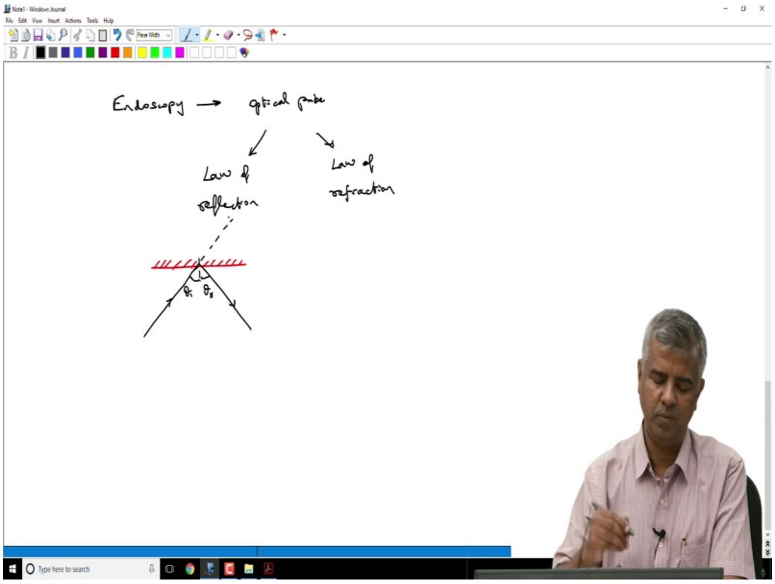

If you start from Fermat's principles, it is just a couple of steps that you can use, one of the key clues in that is that, what if the light had gone straight down? You look at that and then you fold it back and then you can prove that $\theta_r = \theta_i$.

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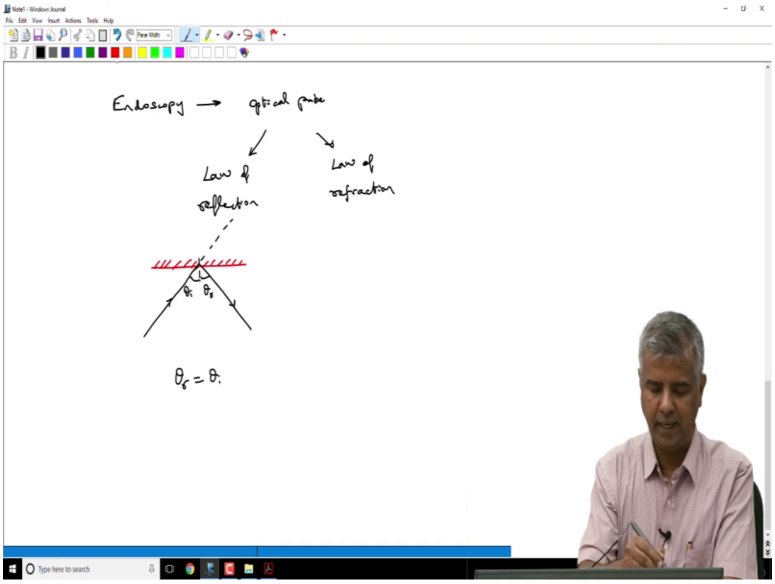

That is the angle of reflection is equal to the angle of incidence.

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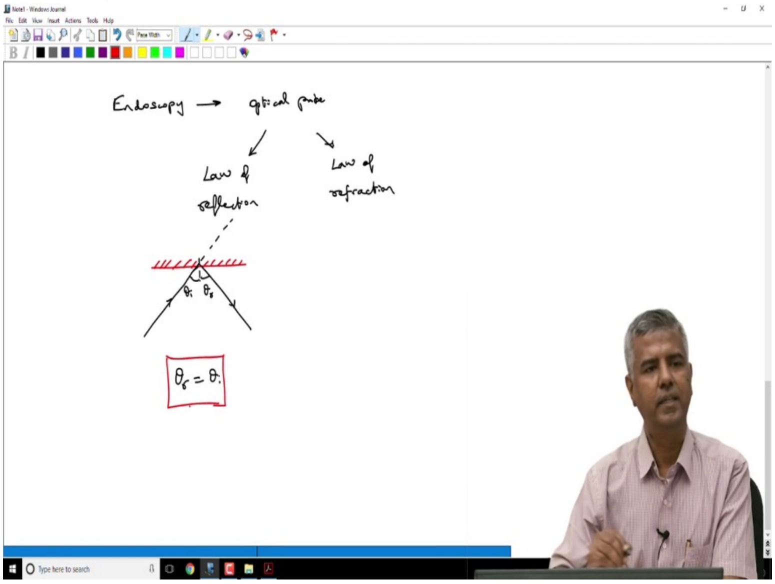

This is once again something that you would have studied in high school physics. You are all very familiar with it.

The other thing you may be very familiar with is this law of refraction where we say, you have an interface between two materials. And in optics, what do we use to characterize different material? Yes, refractive index.

So, let us say this is n_1

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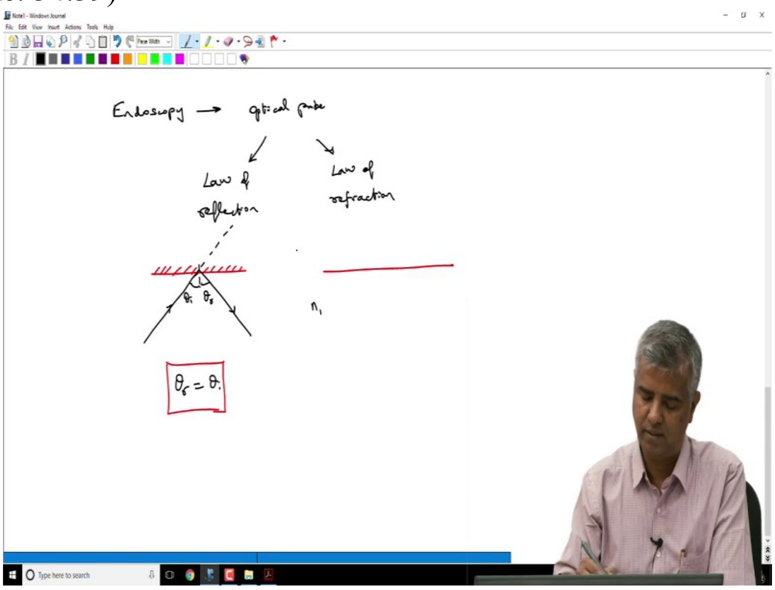

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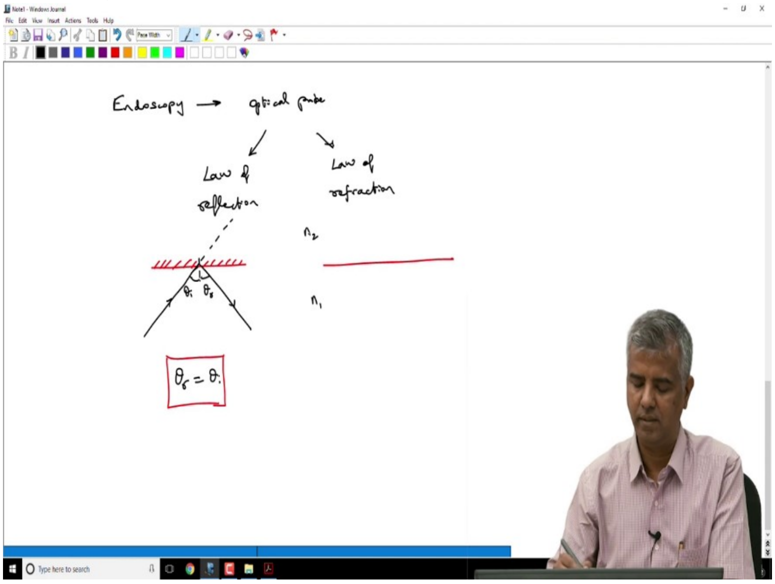

and this is n_2 and this is the normal

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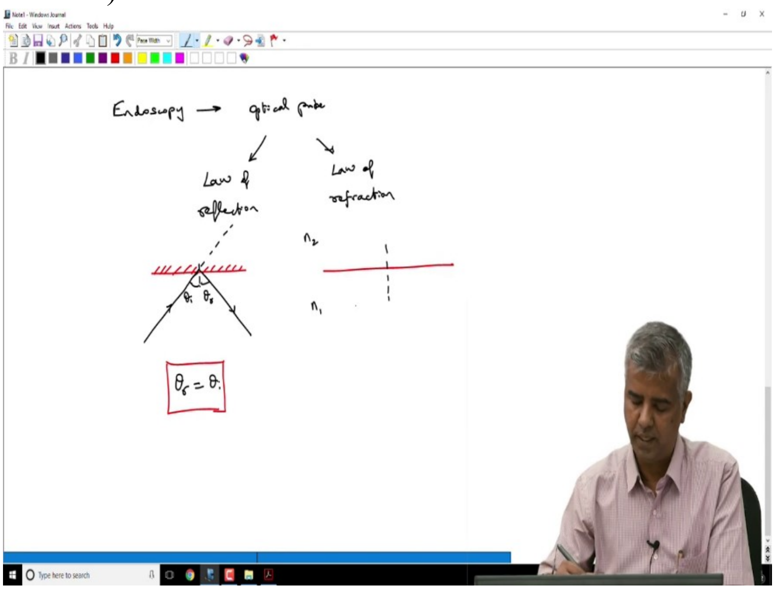

over here and then if I have a light ray

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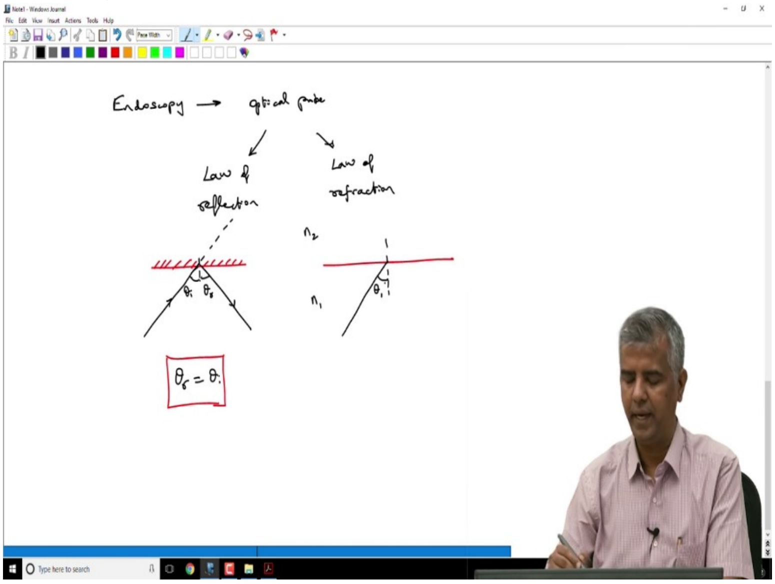

coming in with an angle θ_1 in this case part of the light may be reflected but the other part of the light is going into this second medium with

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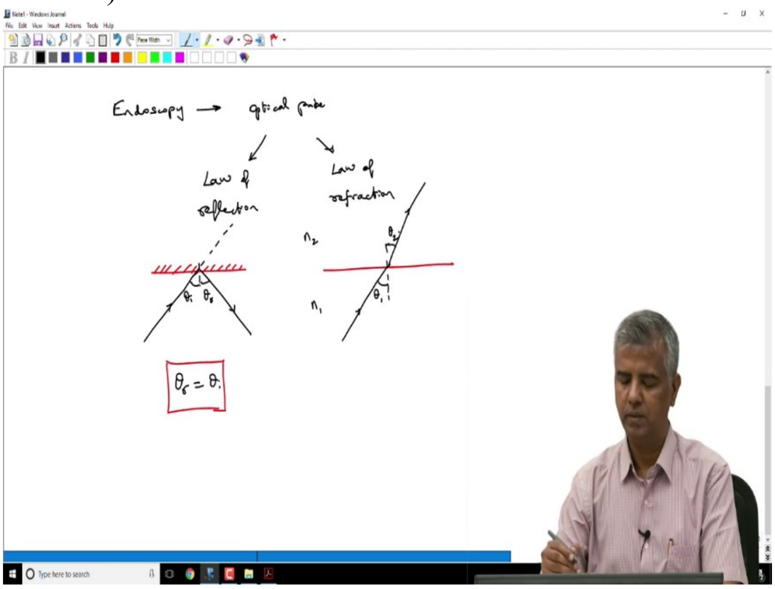

angle θ_2 and then we have this famous law

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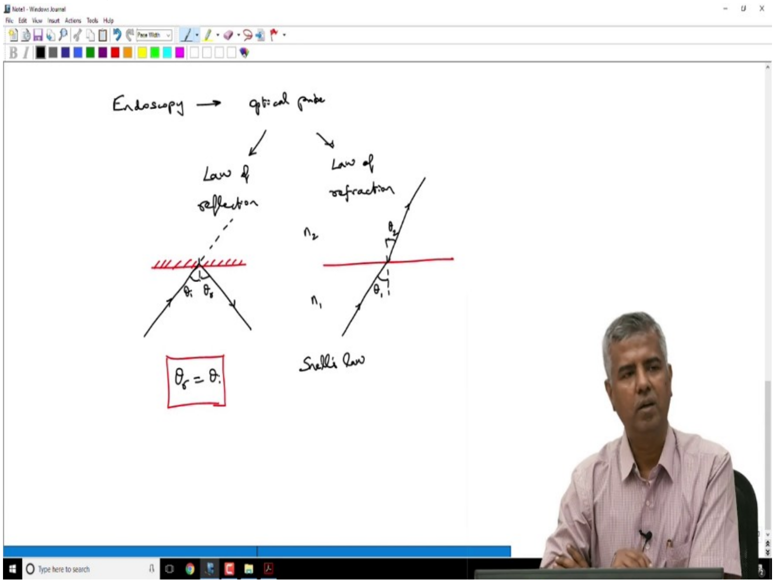

known as Snell's law which says $n_1 \sin\theta_1 = n_2 \sin\theta_2$.

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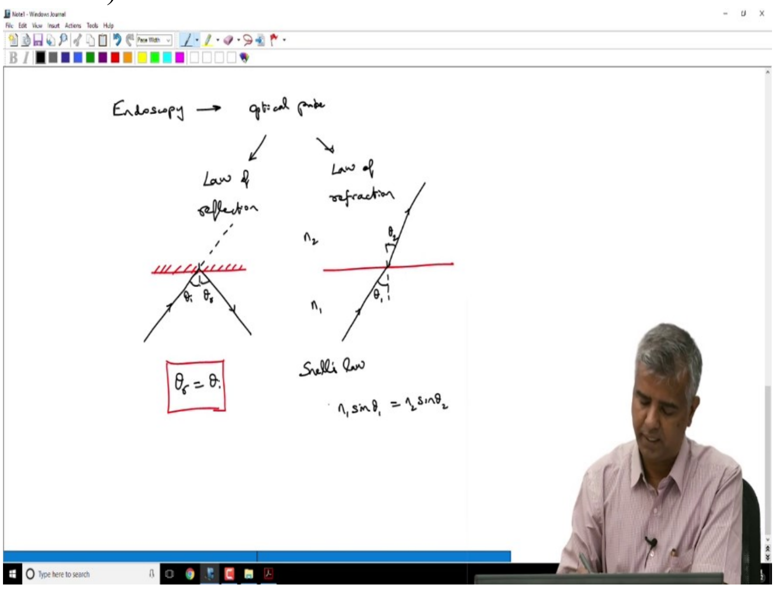

So, this is also something that you are very familiar with and of course,

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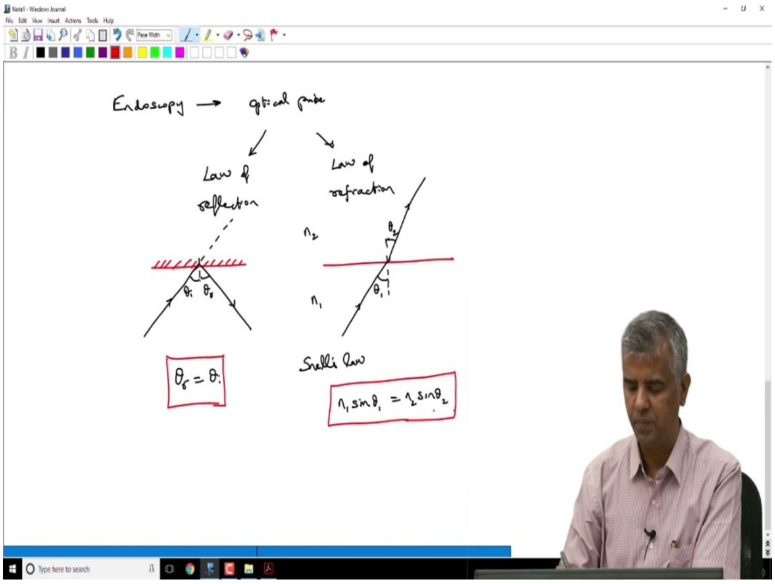

it is not too difficult to prove this, just from geometric perspective, but it is more easily probably proven from the electromagnetic perspective considering the boundary condition between the two media and all that. So, but let us just take this for granted and move on.

Now if you say you have this Snell's law and if you consider a specific condition where $n_1 > n_2$

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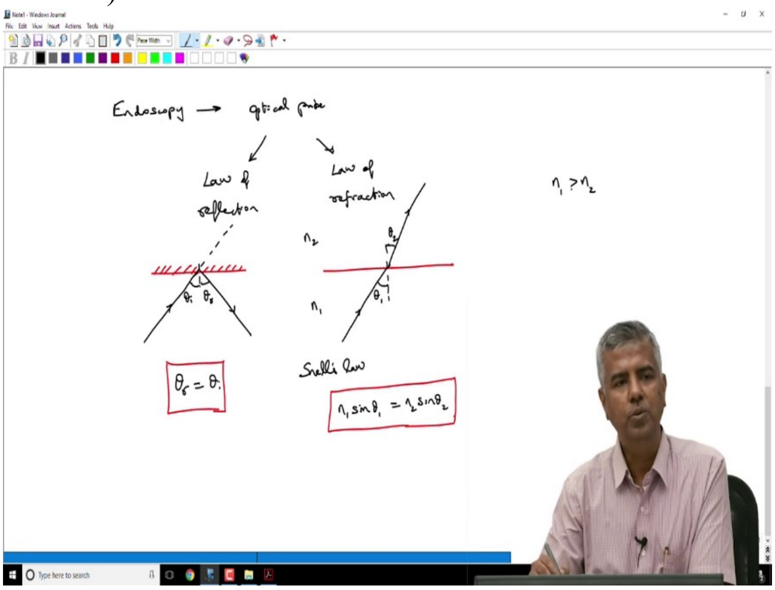

This is already going to imply that if you have to plug it in Snell's law, it says that $\theta_2 > \theta_1$

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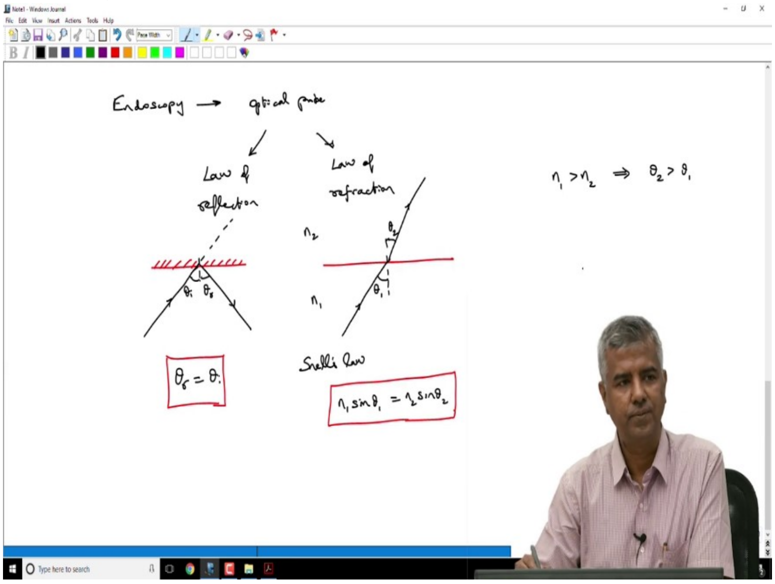

And it is only as a matter of some other value of $\theta_1 = \theta_c$ where θ_2 becomes $\frac{\pi}{2}$

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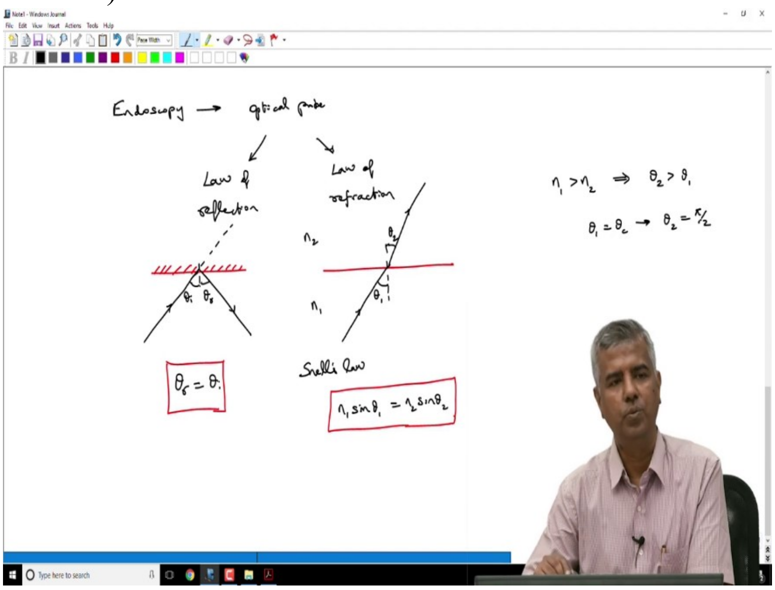

So, as you keep increasing θ_1 it gets to a certain angle where, which you can label as θ_c at which $\theta_2 = \frac{\pi}{2}$.

Now if you write the Snell's law at that particular point it basically says

$$n_1 \sin\theta_c = n_2 \sin\left(\frac{\pi}{2}\right)$$

$$= n_2$$

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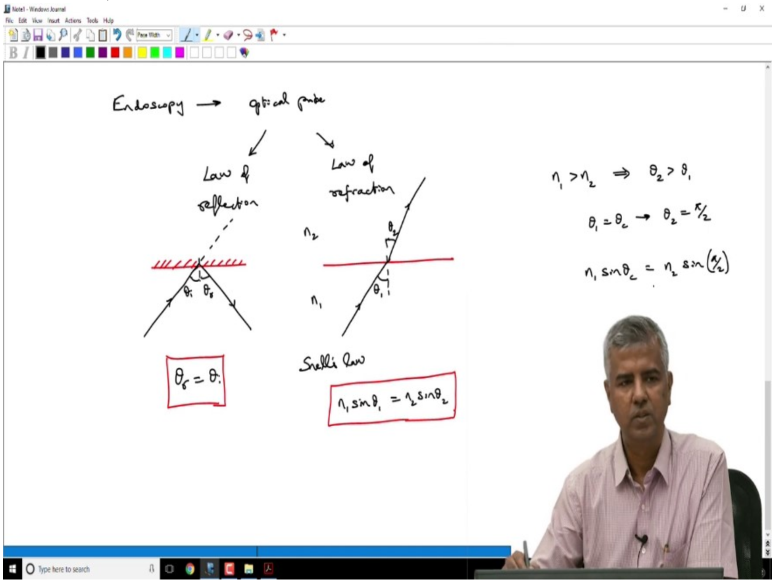

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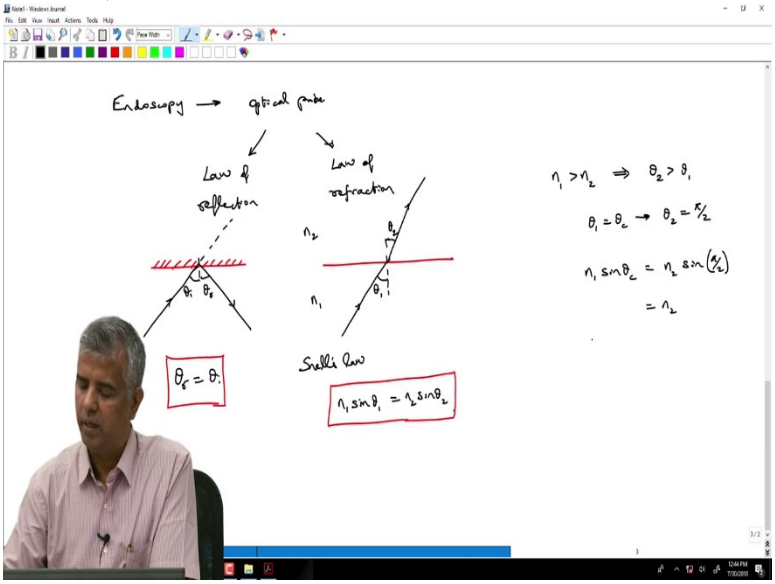

If you define this angle θ_c,

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

So that is fairly simple proof of what critical angle is.

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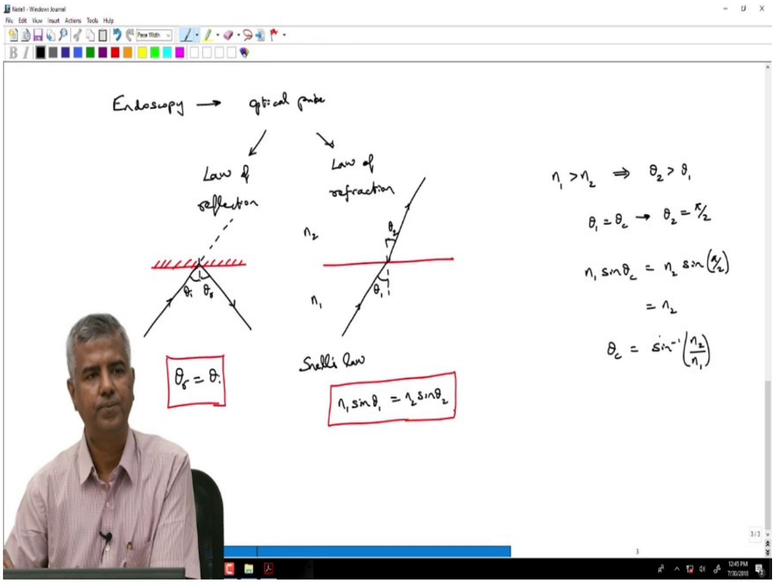

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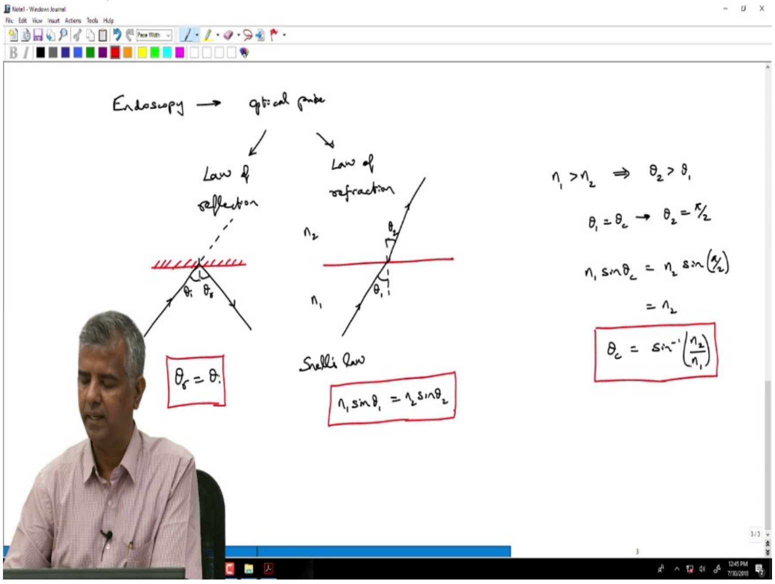

And what happens beyond that critical angle? If $\theta_1 > \theta_c$, total internal reflection occurs.

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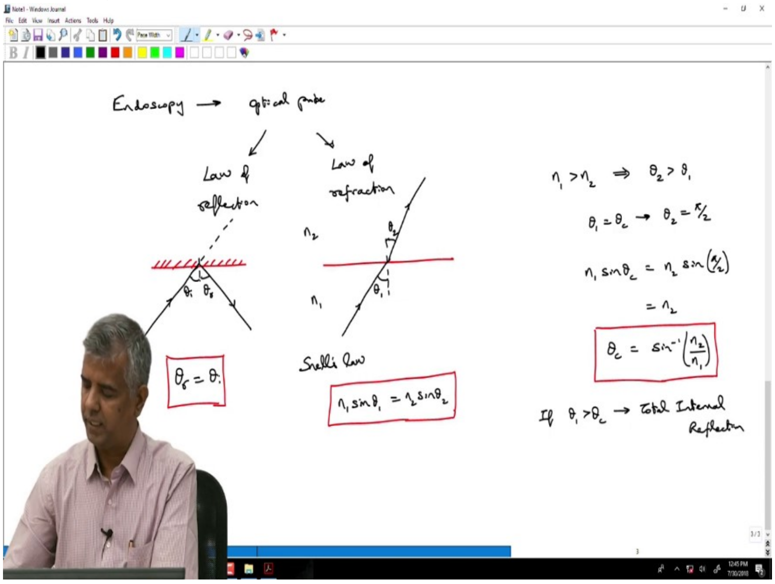

It says that in the same case that we were drawing over here, if you have your interface here, if $n_1 > n_2$ and $\theta_1 > \theta_c$,

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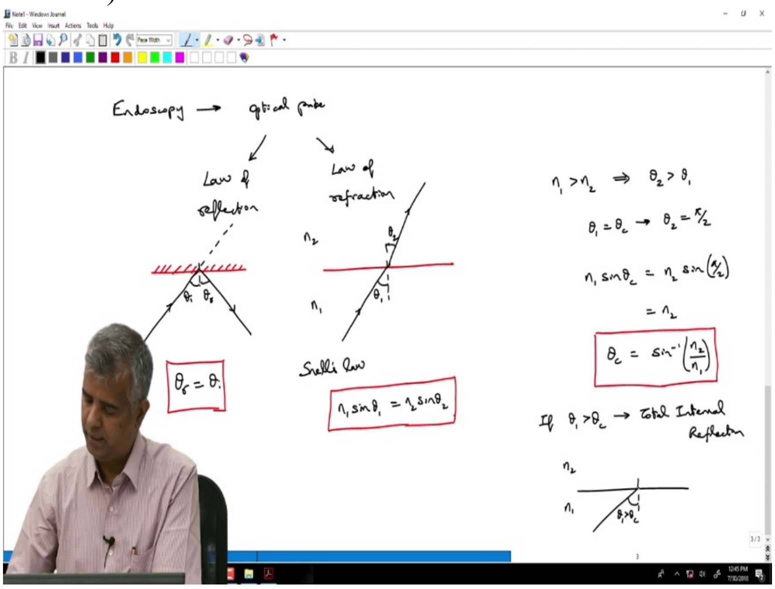

then all the light that is incident on this interface is going to get reflected.

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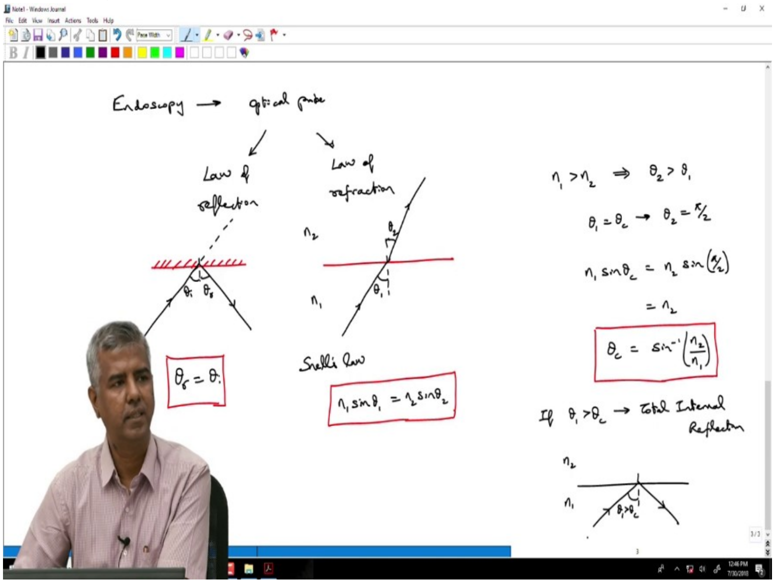

So, you have total internal reflection and if you project this forward and say what if we have one more interface over here which is bounded by n_2.

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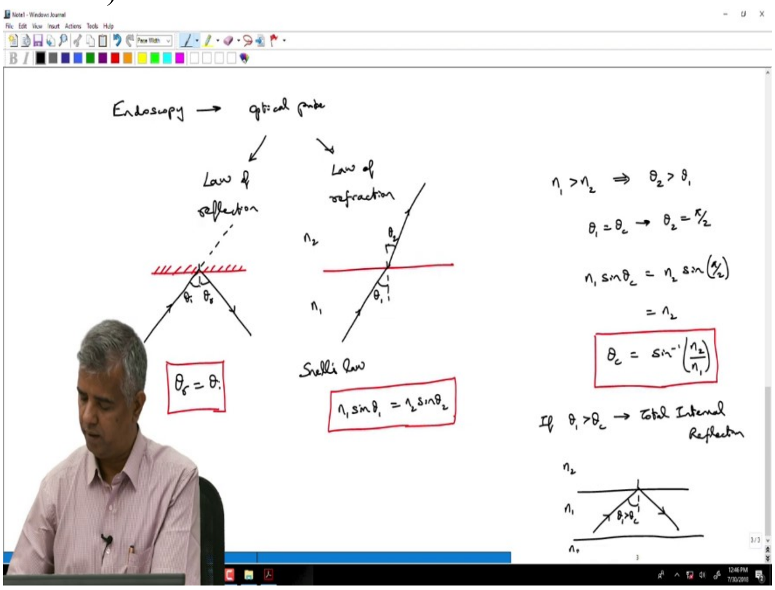

Then if this is θ_1 and these two interfaces are parallel, then this angle of incidence is also

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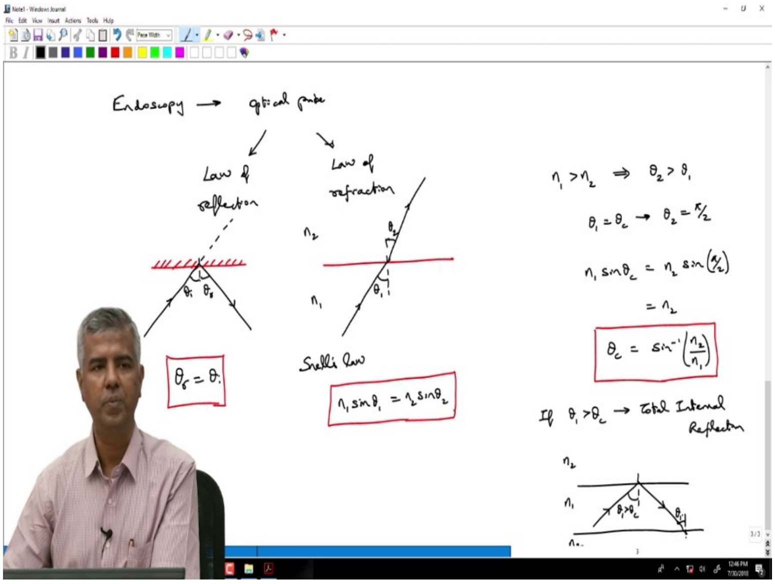

going to be the same angle θ_1.

So, you would have reflection

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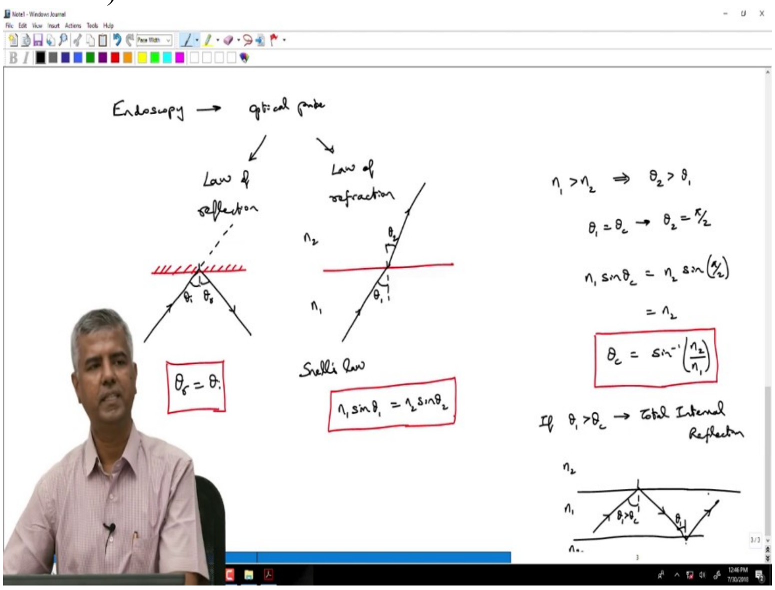

happening over here as well. So essentially, if you manage to get this angle right, when you are launching light into this structure, then it can be confined within that structure and it can propagate over certain distance as long as these two interfaces are parallel to each other.

So that is essentially the underlying principle in endoscopy. You are launching light into this structure and through this process of total internal reflection it is going to carry all that information to the other end. Now, of course, there is a limit to what angles it can gather and to examine, that limit you need to understand what is happening at this interface at the launch side.

But we do not have time to discuss that right now. So, let us stop here and let us continue in the next session how we can define what is the cone of light rays that we can capture within this wave guide as far as an endoscope is concerned.

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And I would also want you to think about this. This is leading on to the next topic that we are going to discuss.

You can do this experiment. Take

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your thumb and index finger, any other finger that you like and look through this. And when you look

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through this with them far apart, you can clearly see what is going on the other side.

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And then you take it closer, closer, closer and to the point where you are touching the other finger. Then obviously you are not seeing anything through that.

But just retract a little bit. Just before you touch that other finger, you will actually see that you are not well or you won't be able to see through, just before you touch that other finger. You can try that now or at home or in your room wherever, But I want you to come back the next session and I want you to tell me what is happening.

Why you are not able to see the light even though there is a gap between the two fingers? That will be the motivation for what we are going to do next.

Thank you.