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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 29

Today, I'm going to talk about light.

Light is an electromagnetic phenomenon, and already in the sixteenth century, way before Maxwell, a lot of studies were done of the interaction of light with water and with glass.

And the kind of experiments that were done follows -- say this is air -- I call that medium 1 -- and this is water -- call that medium 2 -- and I have a light beam that strikes this surface.

Light comes in like so -- and I define this angle as the angle of incidence, and I call that theta 1 This is the normal to the surface, and we call that the angle of incidence.

I will see now that some of that light is reflected -- reflected with an L, as in lion -- and some of that light goes into the water, and we call that refracted -- refracted, with an R, as in Richard -- and this angle, we'll call theta 2.

And it was a Dutchman, Willebrord Snellius, who, in the seventeenth century, found three rules that govern the relation between these three light beams.

The first one is that this beam, this beam, and this beam are in one plane.

As you see, that is my plane of the blackboard.

The second thing that he found, that this angle, theta three, which is called the angle of reflection, is the same as the angle of incidence.

That was known before him, of course.

And then the third one, which is the most surprising one, which is called after him, which is called Snell's Law -- although his name was Snellius -- is that the sine of theta 1 divided by the sine of theta 2, if we go from air to water, then that ratio is about 1.3.

If you go from air to glass, it's a little higher, it's like 1.5 or so.

He introduced the idea of index of refraction, which I will call N, as in Nancy -- index of refraction.

For vacuum, the index of refraction, per definition, is 1, but it's very closely the same in air, we always treat it as 1 in air.

And in water, the index of refraction is approximately 1.3, and in glass, depending upon what kind of glass you have, it's about 1.5.

And so we can now amend this law, Snell's Law, by writing here N 2 divided by N 1, N 1 being the index of refraction of the medium where you are, your incident beam -- that's why I put a 1 here -- N 2 being the index of refraction of the medium where you're traveling to.

You're refracted into this medium.

And so you see, indeed, that since water is 1.3, and air is 1, that this ratio for air to water is 1.3.

And this is called Snell's Law.

And it is immediately obvious that if you go from air to water, or you go from air to glass, that angle theta 2 is always smaller than the angle theta 1, because this number is larger than 1.

But if you go from water to air, then the situation is reversed, and that's what I want to address now, that's actually quite interesting.

So now, my medium 1 is now water, and my medium 2 is now air.

And so now, I go from here to here, and so here I have my angle of incidence theta 1 and here I have my angle of reflection, that is the theta 3, and now here, I have my angle theta 2.

And so if I write down, now, Snell's Law, then I get the sine of theta 1 divided by the sine of theta 2 is now N 2 / N 1, but N 2 is 1, divided by 1.3, if we go from air -- from water to air.

And what is so special here is that theta 2 can obviously never be larger than 90 degrees.

And so if you substitute in here, theta 2 is 90 degrees, then you will find that theta 1, then, is about 50 degrees.

And if you apply this equation, and you substitute for theta 1 an angle larger than 50 degrees, you're going to find the sine of theta 2 being larger than 1, which is nonsense.

It cannot happen.

And so nature ignores Snell's Law, and nature says, "Sorry, I can't do it," and what nature now does, if the angle of theta 1 is too large -- in this case, with water, larger than 50 degrees -- this is not there anymore, and all the light is now being reflected off that surface.

And we call that total reflection.

Total reflection.

So total reflection happens when theta 1 is larger than a certain critical angle, and the sine of that critical angle -- for which I write cr -- is N 2 / N 1, but there is a condition.

And the condition is that N 1 must be larger than N 2.

If that's not the case, then there is not total reflection.

And total reflection is actually very interesting, it has practical applications, which I will discuss with you shortly, but I first want to do a demonstration in which I want to show this to you.

I have here, water, and here is air, and I have a laser beam which I can shine in, and I can change this angle theta 1, and slowly increase it, and you will see that when I approach 50 degrees, first of all, you will see that theta 2 increases, increases, increases, and then, when I approach the critical angle and exceed it, then we have 100% reflection.

Let me first turn on the laser so that there's a little bit of light, and I'm going to show it to you there for those of you who are not sitting very close, and that means I have to set the light situation -- OK, so there you see, the light coming in, just the way we had it on the blackboard, this is the way it comes in, in water, this is the reflected part, and this is the one that is refracted into the air.

So that is this one here.

And now I'm going to increase that angle, when I touch the table, the water will start to wiggle a little, and you will probably see that.

.

So I'm going to in -- OK, I decre- I'm going to increase that angle, look how I'm increasing it.

Look, that theta 2 is getting larger, is going to approach the 90 degrees, I increase theta 1, I increase theta 1, look at theta 2, almost 90 degrees, I'm very close to the critical angle now, I'm almost at it right now, and now all the light is being reflected.

100% reflection.

A remarkable phenomenon.

And this has practical applications.

And we're going to show you some of these practical applications, too.

The most important practical application is fiber optics.

If I have a fiber, and it is properly designed -- so this is a fiber -- and some light comes in here, and it hits here -- so this is, say, some plastic, or glass, and this is air -- if this angle of incidence is larger than the critical angle, 100% reflected.

And so nothing comes out in the air, 100% reflected.

Here, again, the critical angle is exceeded, and so 100% is reflected, and you can go through this whole thing for miles on end.

You can put even knots in there, as long as you never exceed the critical angle, that light will propagate, and there will never be any loss of light, and that's why people are very much interested in this.

You can transport even images, as I will show you, through fiber optics.

I have here, uh, fiber optics, which has 4000 fibers in it, 50 microns in diameter each, and we have a laser beam here, and the laser light will come out -- I will show you the laser light shortly there -- and it doesn't matter what I do with the fibers, I can even go 180 degrees and shine them there, as long as, inside the fiber, I always exceed the critical angle.

Uh, oh, I don't want the television any more, so we can turn this off, and let's here have the laser light.

There it is.

Here you see the laser light.

OK, now look at this, this bundle that I have here.

I turn it into an absurd snake, almost like an S.

All the light still comes out.

So it goes all the way through, I'm going to turn it 180 degrees around, turn it to the wall there.

There it is.

So there's an amazing phenomenon that this light doesn't get out in the air, it stays inside the fiber, and that's the idea behind fiber optics.

I have another, uh, application of fiber optics right here which is very similar.

You can send an image through fiber optics.

This is my fiber optics, now, thousands of small fibers.

And I send a message in here, this side, an image, could be a person, could be a text.

And here we have a TV camera.

And we can watch that image, on this side of the fiber appears that image, and this television camera will be able to see that image.

And let's see whether we can show you that message.

OK, I have to do something here again, I think you're going to -- ah, there it is.

So you actually can see the individual fibers, you see them?

How -- how interesting.

Each one, these are individual fibers.

And their diameter is probably not much more than 50 or 100 microns.

Let's see what message there is for you.

Oh man, oh man, exam 3.

You don't want to hear about that, do you?

Well, that depends on what the message says.

Problem -- no.

No.

Problem 1.

Problem 1.

The figure -- oh, oh, oh, oh, below -- oh, I must have -- that's the wrong message, I couldn't possibly meant to give you away the exam, of course, so I apologize for that, that I showed you the wrong message.

But at least it demonstrated to you that you can send an image through fiber optics, even secret messages.

Newton had an interesting explanation for Snell's Law.

Newton was the man of planets.

He was the man of particles, masses, accelerations, F = MA.

And so his explanation came with particles.

He says light, light are particles.

So if this is the surface between, let's say, air and water, Newton argued as follows.

If light comes in, it has a certain speed, V1.

And therefore, it has a horizontal component.

And it has a certain vertical component.

And he says that if this light ends up in water, at the moment that it reaches the surface, it gets an acceleration perpendicular to the surface.

Why?

He didn't tell us.

But he said, it gets an acceleration perpendicular to the surface.

In other words, this horizontal component does not change.

That remains what it was.

But this component changes, this becomes substantially larger, depending upon the index of refraction, of course.

And so the new velocity is now in this direction.

And so you see that, indeed, the angle theta 1 is larger than the angle theta 2.

But Snell's Law immediately follows from this.

The sine of theta 1 -- this angle is theta 1.

So this angle is theta 1.

So that's this velocity divided by this vector.

And the sine of theta 2 is this velocity divided by this vector.

But these two velocities are the same.

So you immediately find that this ratio is V2 divided by V1, a great victory for Mr. Newton.

Except there was one problem, maybe, that it means that V2 is larger than V1, and so Newton argued that the speed of light in water is larger than the speed of light -- light in air.

And in glass, of course, it would be even larger.

Now, there was a Dutchman, and the name of Dutchman was Christian Huygens.

H-U-Y-G-E-N-S.

And this gentleman suggested that perhaps light are not particles, that they are waves.

And this guy came up with a genius idea -- which we now know as Huygens' Principle, at least you call it Huygens' Principle, but we don't call it Huygens' Principle.

You see, this sound, U Y, is pronounced in Dutch as [ouwe].

None of you can say [ouwe] unless you're Dutch.

To make it worse, this sound you don't have either in English.

That's a [kkkkhhhh].

None of you can say [kkkkhhhh] unless you're Dutch.

Let alone that you can say the combination, Huygens.

Anyone who comes forward to me after this lecture and who knows how to pronounce the word Huygens, has to be Dutch.

I will be kind to you, and call it, today, Huygens' Principle.

So Huygens came with the following idea.

Here is a source of electromagnetic waves.

And these electromagnetic waves propagate out in a spherical way.

Not unreasonable.

And so you even see here, the wave crests.

And so he defined the surface at the leading part of the wave, where all points are in phase, he called that the wave front.

So this is the wave front.

And he now postulated that each point of the wave front individually oscillates at the same frequency as the source, and produces spherical waves.

We call them secondary waves, often- also called wavelets.

And that the envelope of the wave fronts of the secondary waves is now the new wave front.

So it works as follows.

Each point that you can choose, you can choose as many as you want to, starts to oscillate at the same frequency as the source, and produces, on its own, spherical waves, there they go, and the new wave front is then here.

And this is called Huygens' Principle.

Of course, he doesn't give any explanation of why these points do that.

He hypothesized that.

And this principle can explain Snell's Law in a very easy way.

I want you to read up on that in your book.

And you will see that it is very easy to explain Snell's Law with this principle, except that now, you will conclude that the sine of theta 1 divided by the sine of theta 2 is V 1 divided by V 2, and therefore, Huygens predicted that the speed of light is lower than the speed of light in air, whereas Newton predicted that the speed of light in water would be higher than the speed of light in air.

So the question now was, who was right?

Are lights particles, or are they waves?

Well, the wave-particle idea of light has been a very long-standing issue in physics, and I will show you, I think, next week -- or maybe after the exam -- how Young, in 1801, conclusively demonstrated that light are waves.

So it looked like Huygens was going to be the winner.

On the other hand, I showed you last lecture that light can behave like particles.

Photons, bullets, tomatoes, radiation pressure, that's particles.

Mass, the whole thing, the whole ball of wax.

And so maybe Newton was right, maybe they are particles.

Well, they're both right.

There are times that you can actually interpret what you see best by assuming they're waves, and that there are times that it's much better to assume that they are particles, with mass, like in the case of the radiation pressure.

But of course, the key question now, is, who was right in terms of the speed of light?

Is the light going faster in water, then Newton was right, or is the light going slower in water, then Huygens was right.

Needless to say that the Dutchman was right.

The speed of light in water is lower than the speed of light in air.

When we derived the speed of light in vacuum, we used Maxwell's equations.

And they allowed us to conclude that the speed of light, much to everyone's surprise, depends on epsilon 0 and mu 0 in a very simple way, I will call it for now, V, that was 1 / the square root of epsilon 0 mu 0.

And we call that C.

If you had used Maxwell's equations as they are valid in materials, in dielectrics, and also in materials that have magnetic properties, than it would be exactly the same derivation, but you would have seen a kappa here, the dielectric constant, and you would have seen here the magnetic permeability.

Kappa, if you're not in air, but in glass, and water, is always larger than 1.

So you see in front of you that the speed of light in water is lower than the speed of light in air.

This can also be written as C divided by the square root of kappa divided by kappa M, and we would nowadays, simply write that as C divided by N.

So the index of refraction is really the square root of the product of the dielectric constant and the magnetic permeability.

Now, kappa and kappa of M are very strong functions of frequency.

And that's not so surprising, because at very high frequency, the intrinsic electric and magnetic dipoles, which are being aligned by the alternating external fields, cannot follow quickly enough.

A field wants to drive them in this direction, and it wants to drive them back, and forward, and back, and there's just not enough time to do that.

And so you expect that at high frequencies, the values for kappa are lower than at low frequencies, which is exactly what you see.

In the case of kappa M, that's only important when you deal with ferromagnetic materials, because with paramagnetic and diamagnetic materials, kappa M is always 1 anyhow.

Or very close to 1.

I have chosen water as an example, to show you the dependence of kappa on the frequency.

This is on the Web, so you can download it and make yourself a copy.

And so if you look here -- this is for water -- then, you see there the -- at low frequencies, at 0 Hertz, and even at radio frequencies, at 100 megaHertz -- this is 100 megaHertz, this is, uh, radio -- these are radio waves -- notice that the dielectric constant in water is about 80, and, um, at, um, at visible light -- these are the frequencies of visible light -- it's way lower.

We just discussed that.

The oscillations go too fast, the electric dipoles can't follow it.

And so the index of refraction then, for radio waves, at 100 megaHertz, is roughly 9, and so the speed of those waves in water is 9 times lower than the speed of light in air -- we call it speed of light, but it's the speed, of course, of the radio waves then -- and in the case of visible light, you see that visible light in water, the speed is only 1.3 times lower than what it would be in air, or, of course, in vacuum.

The frequency effect is very noticeable.

If you take red light and blue light, they have different frequencies, and therefore, the index of refraction is different for red light and blue light.

If I take water -- the numbers I'm going to give you are for water -- then the index of refraction for red light in water is 1.331 -- but the index of refraction for blue light in water is 1.343.

And we're going to use these numbers, shortly, to get a deeper understanding of the rainbow that's behind this, of course.

And so you notice that the blue light is 1% slower in water than the red light.

And this phenomenon that you see there, that the speed of electromagnetic radiation depends on the wavelength, depends on the frequency, we call that dispersion.

It is a good thing that sound in air is not dispersive, because -- just imagine that high frequencies would travel faster than low frequencies, just as an example.

Or, or slower, for that matter.

It would mean, then, that if you go to a concert, and you would listen to the violins and the bass, that the violins would reach you first, and then the sound of the bass would reach you later, and the farther you are away from the orchestra, the worse that would be.

If the effect were very strong, here in 26-100, someone sitting in the back row could not even understand my words, because the high frequencies would reach that person at a different time than the low frequencies.

So sound in air is non-dispersive.

But glass and water are dispersive for light, and it's very noticeable.

If I take a piece of glass, and I give it this shape, the shape of a prism, and I shine some light on here, light from these light bulbs, or light from the sun, for that matter, then I can apply Snell's Law here.

I know the angle of incidence, theta 1.

I know the index of refraction -- this is for water, but you can look them up for glass, of course -- and then you will see there is a difference of the index of refraction for red light that there is for blue light.

And so, when you reach this side of the prism, again, you have to apply Snell's Law, and when you do that, you will see that the red light doesn't come out at the same angle that the blue light come out, but the two diverge.

That is the result of the fact that the indices of refraction are different, but also the result of the fact that we have this particular shape, funny shape, namely that this side of the glass is not parallel to this side.

And so if you put a screen here, you will see colors, you can make a spectrum, you can convince yourself that the light from these light bulbs is just not white light, but that it contains many, many colors.

Well, it has to contain many colors, because if I look at that gentleman there, he's wearing a red shirt.

Where do you think that red color is coming from?

It must come from the light bulb, so there must be red light in there.

The woman setting next to him is wearing a green shirt, so there must also be green light in this -- this light.

And the same is true for sunlight.

But the beauty is that, making use of the dispersion, you can decompose the white light into the individual colors, and make a spectrum.

If you take a piece of plane parallel glass, which is window glass, then you're not going to see colors, because, if now I shine light on here, white light from the light bulbs, or from the sun, it is true that it will obviously refract in here.

But when you apply Snell's Law again, here, then it will come out -- all the colors will come out in the same direction.

So the red light comes out here, and the blue light comes out in the same direction.

And your brains are very special.

If your brains see all colors coming from one direction, they say, "I see white light.

Look at the light bulb.

You say, "Ah, that's white light." But look at this gentleman, you say, "Hey, it's red, it must come from that light bulb.

So your brains are special in the sense that they think that the combination of many colors is white.

And I can show that to you in a -- in a rather convincing way.

You see here a disk.

And I would assume that you see colors on that disk.

If not, you have a problem.

And I can fool your brains.

What I can do, I can rotate that disk so fast that your brains get so mixed up that they're going to say to you, "Yes, that's white light." So let me first give you some ideal light on that disk, and I'm going to spin it up a little.

So you agree with me, right?

You still see colors, yes?

Still see colors, right?

OK.

You still see colors, right?

Yes.

Haha, haha.

Hahahaha.

This is white as it can be for me.

Not too surprising, right?

The same situation when I look at the light bulb.

All these colors are processed by my brains in such a way that they think, or they -- well, they actually make you see white light.

It's as real as you can have it.

And so this raises the subject of the illusion of colors, which is what I want to discuss with you for the remaining part of this lecture.

If you ask a physicist, "When do you see certain colors?

When to we see red?

When do we see blue or green?" Then chances are, that he would give you a standard answer, and he would say, "Well, that depends on, uh, on the wavelength in air.

If you tell me what wavelength you're on, then I will tell you what colors you will see." And I have here a transparency which makes the connection between wavelength and these colors.

It's also on the web, so you can also download this.

And so if the wavelength of light in air is about in this range -- 1 angstrom is 10 to the -10 meters -- yes, you will probably say that's red light.

When the wavelengths get shorter, in this range, you would say, "Yes, that's green light." And when the wavelengths get even shorter, you would say, "Yes, that's blue light." And you can't see any wavelength shorter than this, you're getting to the ultraviolet here, and you can't see any wavelength longer than this, that's infrared, and our eyes are not sensitive for those wavelengths.

So this is all nice and dandy, but we still have the problem of the -- the effect that if you mix all the colors together, like the rotating disk, and like looking at the light bulb, that our brains still tell us that we are seeing white light.

So maybe matters are not really as simple as we think.

And this scheme about colors has been worked out in quite some detail already in the seventeenth and in the eighteenth century, when it was discovered that there was such a thing as primary colors.

Maxwell did some research on that, and Helmholtz, even the poet Goethe did work on this.

They discovered that there are primary colors, and when you mix light -- we call this additive mixing -- the three primary colors are green, violet, and red, and when you mix paint, the three primary colors are yellow, blue, and red.

And the idea behind this is that if you mix the -- the three primary colors in the right proportion, then you can make many colors.

I want to show you a color triangle, which is the recipe, tells you how you have to mix these colors, and in order to do that, I'm going to make it dark, but not all the way dark.

So here you see the color triangle, and the color triangle has in the three colors -- the three corners, the colors red -- one primary color -- and then here it has violet, and then up there it has green.

And now, I'll tell you how this recipe has to be used.

So I'm going to draw here a color triangle and we have red here and we have green there, and we have here, violet.

And if you look at this color triangle, you see all the colors that you can imagine.

Sort of.

You see yellow, and you see here purple, and you see orange, you even see white.

So how do we make these colors, now?

Well, suppose I want to make this color here.

So that's this color, say.

Then you draw three lines -- one, two, three -- from the three corners, and this is the amount of red that you have to put in, and this is the amount of green that you have to put in in the light, and this is the amount of violet light.

And if you do that, in that ratio, you would get the color which is here.

If you want to make very nice yellow -- oh, let's see, let's make some very nice yellow, which is all the way here, at the edge -- you don't need any violet, you can do that exclusively with green and with red, so let's go to this point here, which is yellow, it would mean, then, that I have to put in this much red, and I have to put in this much green.

And if I add more and more red, I go along this line, then I end up here and I get orange.

So I could make orange here by simply increasing the amount of red -- oh, this should not be violet, right?

Ooh-ooh, ooh-ooh, this is green.

Oh, you should have yelled at me.

So this is green and so if I want to make orange here, then I simply have to give it more red and less green.

And if you go to an extreme, and you want to make white light, and you go bingo, right there in the middle, well, then, you have to give it this much red, this much green, and this much violet.

And that's the idea that we just saw, you mix all the colors, and we mix up your brains as well, and your brains then say, "Gee, ah, that is white light." So the idea behind the three primary color theory is that our eye cells, the cells that we have in the retina, respond differently to the three primary colors, and that color sensation, which is, of course what the brains are telling you, those are the messages that are being sent to the brains, and they are processed here, that they are the result of the mixing of these three responses.

And the theory is quite successful.

I'm going to try to make for you the color yellow by mixing these three colors, green and violet.

And if I want to make yellow, then we already argued, all I need is green, and I need red, I don't even need violet.

And I'm going to do that with a -- with this nice little box here -- I will raise the screen because we don't need the screen any more, and I don't think I need the, uh, the slide any more, um, John.

And this box, this box has three lights in there.

Red, green, violet.

And I can change the intensities.

Yes, I can show you, I can make the -- the red less strong, and I can do the same with the green, I can make it less strong.

And I can do the same with the violet.

And so if I want to make, for instance, that yellow, then I can do that with green and red alone, and I have to give it a lot of green, and a little bit of red.

So a little bit of red, and a lot of green.

Adjust it a little.

Hmm, I see yellow, don't you?

Who sees yellow?

OK.

So we make it a little orange, then we have to give it a little bit more red -- yes, I give it a little bit more red -- oh, it becomes orange.

See, so I'm marching, now, here, give it a little bit more red, and you make it orange.

And what I can even do, I can give them all three the maximum strength, and I can turn it to white.

So we will fool the brains again, all these colors, like the rotating disk, like the light from the sun, like the light from the lights here.

I think I see white light.

Your color TV is based on this principle.

You have three electron guns in your color TV.

And there are three different chemicals on the screen of your television.

And these chemicals are in the form of very small dots.

And if electrons hit one of these dots, they become violet, and the other chemicals become green, and the other chemicals become red.

And so the whole idea is, now, that each beam hits its own chemical dot, that's the way they arrange things.

And by mixing the various intensities, you can mix the intensities with three primary colors, and you can see all colors on television.

It works very well.

Of course, if you haven't adjusted your television properly, you may have noticed that sometimes faces are reddish, or faces are greenish.

Well, that's a matter of just adjusting those three guns appropriately, and then you can be very successful, and it's very impressive.

This, uh, three-color scheme works quite nicely.

So, in many cases, the three primary color theory is quite satisfactory.

But there are cases where it fails bitterly.

And those are the ones that I want to discuss for the remaining 10 minutes and 40 seconds.

Already, in the nineteenth century, it was known that there were problems with the three-color theory.

Mr. Benham, in 1895, invented a top which is named after him, it's called the Benham top.

I have one in my office on my table.

It is a top that has just black lines on it, no colors.

You rotate it, and you see colors.

And we copied that top for you, and we have that here, this is a copy, it's a large copy, the top is only this small that I have.

This is a Benham top.

I hope you will agree with me that this is black and white.

Any one of you see colors, let me know now.

I will ask you to leave, then.

OK, so no one sees colors.

Good.

So now, I'm going to rotate that for you, and you will be surprised, what you're going to see.

So there is the Benham top, and I'm going to rotate it somewhere in the ballpark of about 7 Hertz, 5 to 7 Hertz, let's take a look.

Black and white.

Hey, [unintelligible], what am I seeing?

I'm seeing colors.

Not very bright, but I am seeing colors.

I see some rusty brown, right there in the middle, and then I see something of a grayish-green, maybe, and dark blue further out.

Who sees colors?

Who doesn't?

Oh, you're color-blind, then.

That happens.

Well, you see colors, just with black and white rotating.

And, to make it even worse, I can reverse the disk.

I first have to stop it, otherwise we burn out the motor -- and I can reverse, and remember, the rusty brown was in the center.

And now we're going to rotate it the other way around.

And look again what you see.

You're now seeing the rusty brown near the edge.

You see the colors reversed.

A lot of research, uh, was done in this area.

But a complete neurophysiological explanation is still not available yet, although there are several very successful models that can predict what our brains will see.

And when your color cells are stimulated with flicker light, there are phase delays between the incident -- incident light, and the response, the messages that are sent to your brains, which are currents of course.

And the phase delay is different for different colors.

So what we're going here, we're fooling the brains, we're sending flicker light to the brains with different phase delays, the phase delays in the center are different from the phase delays further out.

And so the brains, then, process that in the usual way, and they say, "Well, I'm sorry, but you're going to see colors." And that's what you're seeing.

The most fabulous example of where the three-color theory fails -- or at least, is very incomplete -- is the work done by Edwin Land in the early fifties.

Edwin Land, very famous man, he was the inventor of the Polaroid film.

He pioneered color theories, and became very famous for a particular demonstration that I will do for you here.

He gave me two slides, I got them personally from Edwin Land.

And these two slides that I'm going to show you are black and white slides.

That is non-negotiable.

I'm going to show them to you, they are as black and white as this disk.

He took one of those slides by taking a photograph of something, and what that something is, you're going to see very shortly.

And the other black and white slide, he also took -- again, black and white film -- but he put a red filter in front of his camera.

But believe me, it is a black and white slide.

So you're going to see black and white slides.

And then I'm going to do something special with those slides, and therefore, I'd rather go there now, and, um, explain things to you as they come along.

And so I have to make it very dark -- oh, the screen has to come down, of course, we're going to need the screen, because we're going to see slides.

So two black and white slides.

So the first black and white slide is this one.

I hope we will all agree that this is a black and white slide.

And the second black and white slide is of the same scene.

This, by the way, was taken through a red filter.

But it is black and white.

The next one was not taken through a red filter, but, I hope we all agree, is black and white.

If I put a red filter in front of this black and white slide, you see exactly what you would have predicted, namely that, yes, it's like looking through a red piece of glass, the whole world turns a little reddish.

Very boring.

Although some kids like that.

So this is what you're going to see.

I can do the same with the other one, this is the one that Edwin Land photographed through a red filter.

If I put a red filter in front of it, you're going to see what you expect, reddish, pinkish colors.

OK.

What do you think you're going to see if we project one black and white slide on top of the other black and white slide?

Well, let's face it.

Let's be down-to-earth.

Black and white plus black and white will remain black and white, and that's what you see now.

One is now on top of the other.

You may not notice that, but I will take one away, and add it again.

Black and white plus black and white gives black and white.

Now, I'm going to ask you to sit very firm in your chairs, because you're going to fall off your chairs if you're not careful.

I'm now going to put in front of the slide that Edwin Land took through a red filter, I'm going to put that red filter in front of my projector, only through that slide.

The other one remains as it was.

And there we go.

And now what do you see?

You see colors.

Is this a miracle?

Well, maybe it is.

I see yellow here, I see green here, I see some dark blue.

Who also sees colors?

Just say yes.

[Chorus of yeses].

Who doesn't?

Good for you.

Isn't this amazing?

Two black and white slides.

That's all you're seeing and then you see this silly red filter, which normally would give you only a little bit of pinkish, reddish light.

But when you put one on top of the other, something bizarre is happening in your brains.

Your brains are so incredibly mixed up that they really think you're seeing yellow there.

And they really make you think that you're seeing green there.

A reasonable question now, is to ask, if we took a picture of this, you take your camera with color film, what will you see?

Will you see colors, or will it be black and white?

Yes, you will see colors, but the colors will be different from the way that you and I perceive them right now.

So now you can ask yourself the question, well, "What are now the real colors?

The ones that you and I see, or the ones that our picture will record?" Well, I think that's a meaningless question.

There is no such thing as right or wrong in these matters.

Our brains are very complicated, and whatever they show us, that's the real thing for us.

Reality is very relative.

And if you're color-blind, which quite a few people in my audience must be -- just a matter of statistics -- then they have a different reality altogether.

Reality is only in the mind of the beholder, and it all depends on how your brains are processing messages.

The message that I'm giving you for this weekend is, have a good time, but by all means, start working on your exam 3, which certainly is not an illusion.