MIT OpenCourseWare
http://ocw.mit.edu

8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 31

All of you have looked at rainbows, but very few of you have ever seen one.

Looking at something is very different from seeing it.

And today I will make you see the rainbow in a way that goes way beyond the beauty that we can all experience, a way that you will always remember.

And I would like to start asking you 15 perhaps simple questions about the rainbow.

The first question then is would any one of you remember if you see a bow whether the red color is outside or whether the -- the red color is inside?

And then I wonder about the radius of the bow.

If this is a bow in the sky, something like this, here is the horizon, it's clearly a perfect circle, and so the perfect circle has somewhere a center.

And so that means there must be a radius R.

You can measure that radius in terms of how many degrees and so what is roughly that radius.

You've never measured it but is it 10 degrees, is it 20, 30, 50, 60?

The length of the bow.

Is there a difference, do you sometimes see a very long bow, sometimes a very short one?

What is the width of the bow?

You see colors here.

How wide is that strip of colors in degrees?

Perhaps some of you have noticed that there is a difference in light intensity between inside the bow and outside the bow.

Maybe you've never seen it, and if there is a difference where is it brighter, inside the bow or outside the bow?

What time of the day would you see bows?

Would you see rainbows in the north, east, south or west?

Is there perhaps a second bow in the sky?

And if there is a second one, where should you look for the second bow?

And if there is a second one what is the color sequence of the second bow?

Is the red on the outside or is the red on the inside?

And then you can ask the same question, what would be the radius of the second bow?

And what would be the width of the second bow?

All these first 12 questions in principle you should have been able to answer if you really have seen a rainbow.

The last three is more difficult.

The question is are the bows polarized?

In what direction are they polarized?

And are they weakly polarized or are they strongly polarized?

Who knows the answer to 12 questions, to the first 12 questions?

Who knows the answer to more than 10?

Who knows the answer to nine?

Eight?

Seven?

Six?

Five?

Four?

Do I see a hand at four?

Good for you.

Five, four, three?

Three, good, that's already good.

Two?

One?

And who knows the answer to zero?

Most of you, right?

I haven't seen a lot of hands though.

All right.

So I've made my point.

You've looked at rainbows but you've really never seen them.

And I'm going to make you see them today.

What you see here on the blackboard is one drop of water.

I put the sun for simplicity at the horizon.

Later I will put it a little bit higher in the sky.

Light from the sun hits this raindrop.

I've only drawn one narrow beam which hits the raindrop right there.

And you see here the angle of incidence, which with Snell's law we call theta 1.

I call it I here because it's nicer for me, more descriptive, it means incidence angle.

Right at that point A some of the light will be reflected and some of the light will go into the water.

We call that refraction.

And Snell's law will tell me this angle R.

Whatever goes in there reaches point B where there is a transition back to air and so some of that light will come out here and some of that light will be reflected inside.

And then when it reaches point C again there is a transition from water to air.

Some of that light will be reflected inside the water.

And some of it will come out.

And as far as the geometry is concerned, if this angle is R, then this angle is also R, this is also R, and this is also R.

And the angle here is I.

That follows from Snell's law, and I'll leave you with that.

Notice that the light came in like this but it comes back like this.

So the direction has changed over the angle delta.

And the angle delta is very easy to calculate in terms of I and R.

Delta is 180 degrees + 2I - 4R.

I want you to check that at home.

The 4 Rs come in here.

One, two, three, four, and the 2 I's come in here and there.

If now I think of all possible narrow beams of light that can strike this raindrop, one that would strike it here would have an I of 0 degrees.

And then here would be 10 degrees and 20 degrees and 30 and 40.

And the largest value for I is when the light strikes here, would be 90 degrees.

And so I can calculate for all these values of I, which obviously all of them occur, sunlight strikes this raindrop, and all these angles for I are present.

So I can calculate now for all these angles of I what the value is for R and then I can calculate what delta is.

R follows from Snell's law and delta follows from this geometric relationship.

And what you will find now very much to your surprise, that there is a minimum value for delta which is about 138 degrees.

That means this angle phi here has a maximum value which is very roughly about 42 degrees.

And I will show you some numbers.

You can download this, by the way, this is on the Web, under lecture supplements.

Here all I have done I've taken I to be from 0 to 90 degrees, all these angles are possible, with Snell's law, using an index of refraction of 1.336, that you see at the bottom, I calculate R and then in the last column using that relationship I calculate delta.

And indeed you see that delta starts at 180 degrees when I is 0.

And then goes to a minimum of roughly 138, after which it increases again.

And this now is crucial, is key to an understanding of the rainbow.

Imagine now that I have one drop of water here.

And sunlight comes in at all angles of I, not just at one, but all angles of I.

Whatever you see here has of course axial symmetry.

It is a spherical drop.

And the light comes in like this.

So light can go this way but it can also go this way.

And it can also go this way and this way, so there's complete axial symmetry, so this whole drawing you can rotate about this line here.

And everything holds then in axial symmetry.

So therefore if phi maximum, if this angle phi maximum is 42 degrees, then the light that will go back in the direction of the sun, the light that goes through the journey A B C and then comes out of the raindrop, that's all I'm talking about, now, I'm not talking about this light that sneaks out here, it is this journey, A, refraction at A, reflection at B, and then coming out at C.

That light comes out in the form of a cone.

And the half -- top angle of the cone must be roughly 42 degrees.

And so I will go -- I'm going to draw that cone for you.

Like so.

And like so.

And you have to think of this as a cone.

It's completely symmetric, axial symmetric, about this line.

And this angle here then is roughly 42 degrees.

No light can go here.

Because that would mean that phi would be larger than 42 degrees and that's not allowed.

Now comes something very important.

The index of refraction of red light for water is about 1.331.

And that translates into an angle for phi max which I can calculate now -- it translates into an angle of phi max which is about 42.4 degrees.

But blue light has a slightly different index of refraction, therefore has a slightly different angle for phi max, and the blue light has an index of refraction of something like 1.343.

Notice I have blue light and I don't use violet light.

Violet is much harder to see with our eyes.

So I always refer to it as blue light.

And that has a value for phi max which is approximately 40.7 degrees.

A different index of refraction means of course that if you know I, that R is slightly different, using Snell's law, so you get slightly different values for R, and so you get slightly different values for delta, so you get a slightly different value for delta minimum, you get a slightly different value for phi max.

What does this mean now?

That means if you look at this cone of light that goes back into the direction of the sun, that the outer edge, the outer surface of that cone, which has the largest possible angle, this angle is now 42.4 degrees, must be red light, because blue light cannot come out in that direction.

Because the maximum angle for blue is 40.7, is not 42.4.

So it's only red light that can come out when the angle -- the half angle of the cone is 42.4 degrees.

And the blue light is not going to make it until this angle here -- I'll put it in here -- is 40.7 degrees.

If you look inside the cone with an half top angle of 40.7 degrees all colors can come back.

All this is saying is that for red light phi maximum is 42.4.

It can also therefore be 40.7.

It can be 30.

It can be 20.

It can be 10.

It can be 0.

Light that comes in here at I=0 reaches point P, comes straight back.

That's allowed.

Phi would be 0 then.

If all the colors can make it back inside this cone that I have given here a blue color, that would mean that your brains will tell you that it is white light.

Because you see red light, you see blue light, you see green light, you see yellow light, and so your brains will tell you that that is white light.

If I had a screen here with a small opening to let the sunlight in and I asked you what would you see on this screen having only one water drop, then you would see the intersection of this cone of light with this screen.

And it would look as follows.

The outer edge, the outer circle, which is the intersection of the cone with your screen, would be red.

And then there would be an inner portion whereby all colors can come back.

So that would be white light.

And then as you go further in from the red, until you reach that white portion, then the last color that will be added is the blue.

And you can already of course sense that all the action about the rainbow occurs here.

And here there is no light.

It's going to be dark because there is no way that phi can be larger than 42.4 degrees.

And if light would appear on the screen outside the red it means that phi would be larger than 42.4 degrees and that's not allowed.

So it's dark here.

It's white light here.

It's red light here.

And as you go further in you will finally see the other colors.

And this really is now the key to the geometry of the -- of the rainbow.

I'm going to put you here, so here you're standing, and let the sun again be near the horizon.

It's always nice when you make a picture.

The easy reference that you have.

You're standing here.

Sunlight is coming in in this direction.

And there is rain here.

If it's also raining here you won't see a rainbow.

Because the sun will not be able to hit these raindrops.

So it's essential that it's raining in the direction away from the sun but that you can still see the sun.

So here are these raindrops.

All right.

You're looking in this direction in the sky.

You're looking up in the sky like so.

And I pick here one raindrop and only one but what I'm telling you holds for all the raindrops in that direction.

What will that raindrop do?

That raindrop will produce a cone of light which goes back in the direction of the sun whereby the edge of the cone is red light and this angle is 42 degrees, 42.4, whatever.

What do you see?

Nothing.

Because there is no light that can come from this raindrop in your direction.

There is no light because that would mean that phi is larger than 42 degrees and that's not allowed.

So you look high up in the sky, you will not see any light coming back from that raindrop.

And think of the whole thing as axial symmetric, right?

Not only there, but there and there you will not see any light.

Now I am looking say at some raindrops which are here.

I pick one.

It holds for any one in that direction.

And so now I draw a line to this point.

This is what I'm looking.

I look in this direction.

I take this raindrop.

I could have picked this raindrop.

I could have picked this one.

Would have made no difference.

What is that raindrop doing?

Well, that raindrop is throwing back at the sun light in the form of a cone and the cone has this angle 42 degrees, 42 degrees.

What do you see now?

Look.

You're looking straight into that cone.

You're nowhere near the edge.

So you see white light.

Because green light comes back at you, red light comes back at you, everything comes back at you.

So you will say ha, I see white light.

Not only there, low on the horizon, but the whole thing is axial symmetric, also there and there.

So you haven't seen a rainbow yet.

But now suppose I ask you to look up in the sky at a very specific angle and we'll make the angle 42.4 degrees.

So you're looking at the sky in the direction somewhere here, I'm not quite sure that I have the angle just right.

So I'm looking in the sky here.

Pick one raindrop.

But you could pick any one, any other other one.

There's nothing special about that one.

So the sunlight comes in like so.

What is that raindrop doing?

Well, it's throwing a cone of light back to the sun.

And it just so happens that you are only looking at the outer surface of the cone where only red light can go because this is the famous angle of 42.4 degrees.

And so you see red light.

And since the whole problem is axial symmetric, you would see red light if you look 42.4 degrees in this direction but also 42 degrees in this direction, away from this direction to the sun.

And so now you see how the bow is being formed by zillions and zillions of small water drops which each of them in their own way contribute to your rainbow.

And we'll now put the sun a little higher in the sky.

So I'll put you here now.

And let's say the sun is now like so.

So, you look at your shadow here on the ground.

The sun is there.

There's your shadow.

Here's your shadow.

Here's your head -- your shadow.

And this is the reference line that we're talking about.

That is this line.

That was this line.

And so where would you see a rainbow?

You have to look now 42 degrees away from that line.

42 degrees away from that line.

That would be red then and a little lower would be your your blue.

And so if I sketch in there the bow, it would be sort of like this and then the blue would be on the inside and here you would have white light and this would then be the red.

It's always relative to this reference line.

This would be roughly -- I call it 42 degrees, but according to my calculation, there it would be be 42.4.

So whenever you know where the sun is, you look at the shadow of your own head and you have to go 42.4 degrees away from that direction from your eye to the shadow.

And so what you're seeing now is that if the sun is low in the horizon then the bow will be high above the horizon and when the sun is rising then the bow goes down and goes down and goes down and by the time that the sun is 42 degrees above the horizon, you're not going to see a rainbow anymore unless the water is right where you are.

If the water is at a distance, you won't see a rainbow.

So the higher the sun in the sky, the less likely it is that you will ever see a rainbow.

Before I show you some -- some slides and before we're going to answer some of the questions, uh, I want to mention to you that what I went through here is refraction at A, reflection at B -- reflection at B and coming out at C.

You can go through the same geometry and allow for one more reflection at C and then let the light come out, so it would come out at point D and if you did that, you can convince yourself that there is indeed a second rainbow and we call that the secondary.

We call this the primary.

And the secondary has a radius -- this one of course has a radius of 42.4 degrees for the red and the blue would have a smaller radius.

The secondary has a radius for the red of 50.4 degrees.

So in the red, it's 50.4 degrees, and in the blue, it's larger.

So the blue is outside 52.5 degrees.

Is that what it is?

53.5.

The secondary bow is fainter and it is also wider because you see this separation in terms of angle is larger than the separation there.

That's only 1.7 degrees and this is, uh, more than 3 degrees.

And so there is a secondary bow and the secondary bow is only about roughly 10 degrees above the primary.

So if you see your primary at 42 degree angles away from your shadow there and there and there, go another 10 degrees and you should see a second bow.

And you should see the colors reversed.

Red is there on the outside and blue is on the inside.

Red is on the outside and blue is on the inside.

Red is on the outside and blue is on the inside, but here it is reversed.

The secondary bow, the red is on the inside and the blue is on the outside.

So let's answer some questions now.

We'll put the questions back up again and you will see that you can now without any difficulty already answer 12 questions.

The first 12.

Red is outside.

That is non-negotiable, right?

That follows immediately from what we'd talked about, but that's not an issue anymore.

The radius is about 42 degrees and the length of the bow, well that depends on if the sun is high in the sky then the length will be very small because this whole s- arc will then go down and there will only be a little bit left.

It could also be that it's only raining here and it's not raining there.

So depending upon where there is rain and how high the sun is in the sky, that will determine the length of the bow.

The width of the bow, you would think, perhaps naively, that if you subtract the 42 from the forty -- 40.7 from the 42.4 that that would give you the width of the bow which would then be 1.7 degrees in angle.

However, you would overlook then that the sun is not a point, but that the sun in the sky has a dimension of half a degree and each point of the sun, of course, makes its own little rainbow, so you really have to add roughly half a degree.

So, the width of the bow is more like, something like two degrees rather than the 1.7, maybe two -- 2.2 degrees.

It's a little wider than what you would think.

It has to do with the finite size of the sun.

A comparison of the light inside and outside, clearly inside the bow, there must be a lot of white light which you don't see outside the bow -- big difference.

You will see a slide shortly.

The time of the day -- well the sun has to be a little bit low, so you don't expect it at midday and you want rain as well, so late afternoon, early morning would be ideal and you can figure out, uh, in what direction to look.

If it's early morning, the sun rises in the east, you would see the bows in the west and late in the afternoon when the sun is in the west, you would see the bows in the east.

Yes there is a second bow.

It is about 10 degrees higher in the sky than the primary.

And the colors are reversed.

The blue is outside and the red is inside.

And the radius is about 52 degrees.

And the width of the bow is again the difference between these two numbers but you have to add about half a degree.

So you would think on the basis of this that it is more like 3 degrees and you have to add roughly the half a degree, so it's about 3 -- 3.5 degrees.

So let's now look at some slides.

And the first slide that you will see is a -- is a drawing that I made.

Which is meant to repeat some of what I told you.

So you see a person standing there and here you see the direction to the sun.

Your shadow would be this long.

This would be your head of the shadow, here would be your feet.

And if there are water drops here and if there's no interference between the sunlight and the water drops then in this direction 42 degrees you would see this water drop red.

And then the water drops which were here you would see white light from those water drops and maybe from this one you would see red as well as blue.

And if you have water near your feet there's no reason why you can't see the rainbow there either but of course you would have to lead some garden hose to produce water there.

The next slide then.

This is a drawing made by the maestro himself, Newton, who was the first to fully understand the workings of the rainbow.

You see here the primary bow and for those of you who are sitting close you can see the direction of the sunlight going in at A, reflects at B, coming out at C.

Which he calls E, but that's a detail.

And here you see then the secondary whereby the light comes in, one reflection, two reflections, and now it comes back at you and that gives you the secondary.

And so this is red and this is blue whereas here this is blue and this is red.

The next slide.

So if the sun is high in the sky, I've done this many times when I was uh watering my garden, you get this for free, you might as well do this, it's great fun, you're standing there, gives you an immense feeling of power, and is completely clear, there's not a -- not a cloud in the sky, there's no rain anywhere, but you spray water around you and you see a beautiful rainbow encircling your feet.

And always what matters is this 42 degree angle relative to the direction from the sun to you and this is where the shadow of my head would be.

Very easy to do and I would recommend that you try that when you get a chance.

The next slide is a painting from the eighth century, Turkey, I see a hand here -- probably makes reference to the Bible, but I think it reads in the Bible I do set my bow in the clouds, it's very nice and very dandy, the fact that the colors are wrong, the sequence of the colors, that's a detail, it's a nice picture, but red has to be on the outside and blue has to be on the inside.

Small detail.

Next slide.

Ah yeah.

A -- a few years ago, actually it's more than a few, when I was first lecturing 8.03 I knew I was going to talk about the rainbow, ideal for 8.03.

And so I wanted to make some rainbows myself in my backyard in Winchester.

And so there is water coming out of a water hose and the sun was behind me and I took this picture and you see indeed all the ingredients that we just discussed.

Notice the red is on the outside and the blue is on the inside.

You see all this white light.

That is that light that comes back from the water drop but if you go here where the angle of phi would be larger than 42 degrees, which is not allowed, you don't see any light coming back at you, so you look straight through and see the forest without any white light.

So you really see already here sky so to speak is bright here and darker there.

I needed help from my daughter.

And the next slide will show you that.

The poor darling was suffering badly.

It was January, it was freezing cold, she was crying.

She was really crying and I felt guilty but I said look, you know I really need these slides for my 8.03 class, it'll only take you about an hour or so, and she still remembers it, I had email exchange with her yesterday and she said dad I was crying, it was an awful thing what you did to me.

But look, but look.

You know, you got to do something, and when you're daughter of a scientist occasionally you have to suffer a little bit.

And so she's holding here the -- the water hose and you see the same thing red outside blue inside, and clearly the white light, you see this is that white light that I discussed with you earlier.

The next slide will show you then a real rainbow -- oh no, this is the um this is the artificial one I made uh over my driveway, if you want to see the secondary, you need a real dark background, because the secondary is quite faint.

And so that's why I did it over my driveway and you see here the primary, red on the outside, blue on the inside, and here you see the colors reversed.

You can also see perhaps that it's a little wider.

But it's always much s- it's much fainter, so it's -- it's hard to tell.

And then the next slide is one that's a wonderful slide made by Doug Johnson in New Mexico, Socorro, it is where the radio telescopes are, the very large array, now look, red on the outside, blue on the inside.

The sky you got to admit is a hell of a lot brighter here than it is there.

And you may never have noticed that, you've -- you've looked at it but you've never seen it and then here you see the secondary, red on the inside, blue on the outside.

There is a phenomenon that we have never discussed in 8.02 yet, it's coming up I think next week.

And that phenomenon we call diffraction.

Snell's law cannot deal with diffraction.

That occurs when water drops are very very small, say, smaller than a tenth of a millimeter.

What you then get over and above the bow you get areas in the bow whereby you get as we call that destructive interference, the waves begin to kill each other and you get dark bands and you can actually see that here.

With a little bit of imagination you see here a dark band.

And when that is the case the water is always extremely small in size and we give this a name, we call this supernumerary bows.

It's not so uncommon.

If the water drops become exceedingly small, let's say, smaller even than 50 microns, then this diffraction phenomenon becomes so important that in addition to the dark bands all the colors are beginning to wash out over each other, and that creates then a white rainbow.

Plus the dark bands.

And a student of mine who was in my 8.03 lecture sent me years later the next slide when he was -- his name was Carl Wales, this picture he took, it's 340 miles from the North Pole, he was at Fletcher Island at the time, this picture was taken at 2 AM at night in July when the sun is above the horizon.

And so this must be the result of very fine water drops which somehow are there in the atmosphere.

Doesn't look like it's raining but there must have been small water drops.

50 microns or less.

And here you see the white-colored rainbow and you also see beautifully the supernumerary bows, you see the -- the dark bands in there and the next slide is a close-up of that.

So you see here the white rainbow plus the dark bands which is the phenomenon, the result of diffraction.

Now before I will discuss the polarization of the bows, because I still owe you answers to the last three questions, now that I'm at it, I want to show you some phenomenon which are quite common which you may never have seen even though they're quite common and they're rather spectacular.

The first slide that comes now shows you what we call the 22 degree halo.

It's very common around the sun, it's very common around the moon.

The red is inside.

It has nothing to do with water.

It is the result of ice crystals way up in the atmosphere.

You can see it both in the summer as well as in the winter because it's very cold way up there also in the summer.

This is very common.

The reason why you and I don't see it that often, because who wants to look in the direction of the sun.

This angle is only 22 degrees, that's not so far.

But I would advise you to at least keep an eye on the moon.

Because the moon also has this 22 degree halo.

And of course it's much easier to look in the direction of the moon.

That doesn't uh -- any- no problems for your eyes.

This is very common that I see this at least three or four times per month and I always look for it of course.

The next slide shows you both the 22 degree halo as well as the 46 degree halo which is way more -- way way less common, it's very rare to see the 46 degree -- I've seen it only a few times.

It's very rare.

In addition to the 22 degree halo and the 46 degree halo you sometimes see bright spots here.

You see them here and you see them here.

They're really not circles.

They are arcs.

And they have names, they call them sun dogs, mock suns, they have various names.

I've seen this often in in Boston, the 46 degree halo is rare.

All of this as the result by the way of ice crystals.

Ice crystals way up in the earth atmosphere.

And there is a phenomenon that many of you may have seen from an airplane.

Uh if your airplane flies over clouds and you look at the shadow of your airplane onto the cloud you may have noticed colorful rings around the shadow of your airplane.

And the next slide is such an example.

I took this picture several years ago.

You are always right at the center of the circle.

So you can see that I was sitting just behind the wings.

This is the result of diffraction.

Got nothing to do with Snell's law.

It is the result though of very, very fine water drops, but not in the sense of refraction and reflection the way that we discussed it with the rainbow.

This is the result of diffraction.

It's extremely difficult, the explanation of the glory.

And even ten years ago, I read an enormous article about it, I think it was in Scientific American.

Which made an utter attempt to be very quantitative about the explanation, which is not easy.

The radius of this bow, if you want to call it a bow, depends on the size of the water drops.

If the water drops are very small the radius is substantially larger.

So as you fly over clouds you may fly over different clouds with different size of water drops and on a very short time scale will you see the radius of this glory change.

It can be very rapidly.

It could be on a time scale of seconds to minutes.

It's very dramatic.

It's very clear.

And these rings can extend, there's just not one ring, but you can have several rings.

And so this is the result of what we call diffraction.

Now I want to mention to you another phenomenon which is also the result of diffraction.

And that you can see when there is fog.

If you have fog, fog consists of extremely small water drops, just like the ones in clouds.

I mean, fog is a cloud, let's face it.

Then if you for instance had the headlights of a car, you could see your own shadow onto the fog, away from the direction of the car.

And that means you could see then around your head the same kind of stuff that you saw here.

A glory.

We call this a fogbow.

That's just a name.

The Germans have a much better name for that, they call it Heiligenschein.

And heiligen person is someone who is a saint and so you see this around your head, so it is sort of the -- the radiation that you would expect from a saint.

Quite a few years ago I was invited to visit the Soviet Union.

And they took me to the Caucasus, to show me the six-meter telescope which was at the time the largest telescope on earth.

And I went there for a few days.

And I noticed much to my surprise that every night at five o'clock there would be fog coming out of the valley overtaking the telescope so you could make no observations at night, but that was a detail, and what I realized is that the fog was coming up, the sun was there, that was the west, and the valley was at the east, and so I said to myself my goodness if only at the right moment of time I am there, then the sun is my light beam, and my shadow will fall onto this wall of fog coming towards me, this is my chance to make a wonderful picture of this Heiligenschein.

And I'll show you that I succeeded.

I will first show you a picture of this bizarre observatory.

This is the six-meter telescope in the Caucasus.

And this is indeed, you could every night around 5:30, really like a wall, the fog will just coming towards you overtake you.

You can see the timing of my picture was extremely crucial.

If you wait a little bit too long then the fog overtakes you and then the sun would obviously not be effective anymore.

I wouldn't see my shadow on the fog.

So I only had a small time window, maybe 30 seconds, maybe one minute.

But I succeeded and you will see w- Saint Walter coming up.

There is Saint Walter.

You can see here my arm and you can see here my camera.

The camera must be exactly at the center of the glory.

And that's where it is.

I have the camera right here and here you see the rest of my body, isn't that terrific?

This can be used as proof sooner or later.

OK.

Back to our last three questions.

The last three questions deal with the polarization of the bow.

Are the bows polarized?

And the answer is yes, they are enormously polarized.

Why are they polarized?

You can answer that question.

But I will answer it for you.

The light that contributes to the rainbow is the light whereby the minimum angle for delta is about 138 degrees and if you go back to that first transparency you will see that that's the case when the angle of incidence is about 60 degrees.

You can download that again.

And that means that the angle of refraction is about 40 degrees.

40 degrees is very close to the Brewster angle.

The Brewster angle, if you go from water to air, you -- medium where you are is water and you bounce it off this medium, so you go from water to air, the tangent of the Brewster angle is N2 / N1.

N2 is where you're going.

That's air.

So this is 1.

N1 is where you are.

That's the water.

Let's just call that the index of refraction 1.33.

If you calculate now what the Brewster angle is you will find that the Brewster angle, theta Brewster is about 37 degrees.

That is only 3 degrees different from this angle, which is the crucial one, which contributes to the rainbow.

So you're only 3 degrees away from the Brewster angle.

So what happens as this light comes in -- and I will make a, a separate drawing.

So as this light comes in, here it's practically unpolarized, and you should remember the meaning of the parallel and the perpendicular component, the way I discussed that with you earlier.

But right here , you're so close to the Brewster angle that almost everything that reflects is now polarized in this direction perpendicular to the blackboard and so what comes out here is also polarized perpendicular to the blackboard.

And that would mean, then, that if you really think through what that means, that direction of the polarization, it means that the bow is polarized here in this direction, here in this direction, here in this direction, and so on.

and so if you take your linear polarizers, you can hold them like this and you can actually see that the bow is polarized.

And if you put your linear polarizers at 90 degrees angles, then you can kill the rainbow.

It's very highly polarized, it's nearly 100%, because of the fact that the Brewster angle is so very close to the 40 degrees.

43:11 I like to go to Plum Island, which is one hour's drive north of here.

hear Ipswich.

It's a beautiful beach, and you have the ocean in the east and the sun, late afternoon, in the west.

And then the waves come in and the waves splash up water.

And I always look for the rainbow.

I look at my shadow, the sun is there, look at my shadow, go 42 degrees away from the shadow, wherever there is splashing water, -- wsht -- for a split second you see the rainbow.

Red outside, blue inside, just for a split second.

Because then there's no water anymore.

Because you have to wait for a second, water splashes up -- wsht -- rainbow, gone.

And so few years ago I took my friend Bill Predorski to the beach, and I saw the rainbow.

I mean, I always look for the rainbow, right, it's clear.

And I pointed it out to Bill, I didn't make a big deal out of it because he's a physicist, so he knows that stuff.

And so I said to Bill, "Look, 42 degrees away from your shadow, you see?

Wsht, wsht." He looked at it, he said, "I see nothing." He looked at it again, wsht, beautiful rainbow, Bill - nothing.

I got extraordinarily annoyed with Bill, I said, "Man, look at it, the rainbow is as crystal clear as you can have it, what is wrong with you?" He says, "I don't think there's anything wrong with me.

He says, "Maybe there's something wrong with you." Yeah, just imagine.

And then I looked at Bill, and I remembered what he looked like.

He looked like this.

[puts on sunglasses] And then I said to myself, ah, I understand why he doesn't see the rainbow.

He is wearing polarized sunglasses and the polarization of the sunglasses is in this direction.

So every time that I saw this beautiful rainbow here, psht, he had his glasses in this direction, he killed the rainbow.

So I said, "Bill, would you please take your glasses off?" He took the glasses off and he said, "There's nothing wrong with you, I see the rainbow." So whenever you want to see the rainbow at the beach make sure you don't wear your polarized sunglasses.

45:23 Now, I will demonstrate to you the rainbow, and what I will do is use one drop of water.

This is exactly what we discussed earlier.

One drop of water, light goes onto the drop, comes back, and here is that drop of water.

And here is the light, I'm going to blind you.

You see this water drop, you've seen it, I'm going to put this to make sure that your eyes don't get blinded.

And this light will come in your direction and in this water drop all these things are going to happen.

All these angles of I occur, and so light will come in this direction.

And I will project it on the screen.

And what will you see?

You will see white, that's the inside, you will see red on the outside.

And that that light that comes out near the edge is very strongly polarized, I will show that to you.

You can't see that with your polarimeters because once it hits the screen and comes back to you it loses the direction of polarization so you cannot use your personal polarizers.

So I will lower the screen.

I will also make it dark and give you 30 seconds for your eyes to adjust to the light.

Because as you can imagine, I've only one drop of water and don't expect too much, you can't do much with one drop of water.

And what you're looking at is really not the rainbow itself of course.

The angle of 42 degrees is only as measured from this one water drop, not from where you are sitting.

If you are sitting very far in the audience, the bow looks smaller than when you're close, because you only see the intersection of that cone with my screen.

47:16 But it has all the ingredients of the rainbow, and with a little bit of imagination, you may be thinking that you see the rainbow, and that would be fine with me.

So we'll make it dark, so that your eyes will adjust.

We'll give it a few seconds for your eyes to adjust.

In the meantime, I can find my polarizer, it's here.

And there it is.

There it is.

Would you agree that it's darker here than there?

You understand now why that is.

Would you agree that you see the red outside and that you see the blue inside?

And you understand now why that is.

And this light near the edge here is highly polarized.

And the direction is also clear -- it is polarized tangentially to the bow, polarized in this direction here, polarized in this direction here.

I have here a polarimeter and I hold it now in the beam to allow the light through, and now I rotate it 90 degrees and I can kill the light.

You see how highly polarized it is.

If I go here, I hold it parallel to the direction of the electric field so the light go through now, and now I rotate it 90 degrees and I can kill that light.

Almost to 100%.

I can kill it here, and I can kill it here provided I hold it at 90 degrees relative to the tangent.

Now the next time that you're going to see a rainbow you will look at that rainbow in a very, very different way.

For one thing, you will check that the red is outside, you will make sure that it's bright inside the bow, that it's dark outside, you will look for the secondary, you will convince yourself that the color sequence of the secondary is different from the primary.

This is a contagious disease which you cannot resist anymore.

Your life will never be the same.

And I'll be very proud of you if from now on you will always carry a linear polarizer with you and I gave you three, so you'd better, so that every time that you see a rainbow, you can be absolutely sure that the bows are indeed polarized and because of your knowledge you will be able to see way more than just the beauty of the bows that everyone else can see.

Your knowledge will add something very, very special and maybe you'll be thinking of me.

Thank you, see you Friday.