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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 30

Earlier in this course, we discussed linear polarization of electromagnetic radiation, and I demonstrate this at 75 megaHertz and at 10 gigaHertz.

Today, I will concentrate exclusively on the polarization of light, which is at a much higher frequency.

The light from the sun or light from light bulbs is not polarized.

So I can ask myself the question, now, what does it mean when light is not polarized?

Let's think of individual light photons as plane waves, with a well-defined direction of polarization.

So each one is linearly polarized.

A beam is coming straight out of the blackboard.

The first photon arrives, it's linearly polarized in this direction.

This second photon arrives, linearly polarized in this direction, so the electric field vector is oscillating like that.

Another photon, another photon, and another photon.

And what you see here, very clearly, that there is no preferred direction which you average over time, and that's what we call -- call unpolarized light.

It was Edwin Land who, in 1938, developed a material that can turn this into linearly polarized light, for which he became very famous, in addition to this demonstration that I showed you last time.

If I take one of Edwin Land's sheets, which will turn light into polarization in this direction, and I first take one photon, for instance, this one.

That one comes in from the blackboard towards you, and so here it is.

Oscillating the E vector like this, E0 is the maximum value of the electric field strength in that plane electromagnetic wave.

And this is the direction of the polarizer that I have through which this photon goes.

I can now make a simple calculation, by projecting this E-vector onto the preferred direction of polarization, and this new E-vector is now down by the cosine of theta, if this angle is theta, this E-vector is now E -- E0 times the cosine of theta.

If you ask me now, whether the light is reduced in intensity, I would have to say, "Yes, of course," because light intensity depends on the Poynting vector, and the pointing vector is always proportional to E0 squared, because the Poynting vector is the cross-product between E and B.

And if E is reduced, B is also reduced.

And so we get a cosine square reduction.

If, now, I average over all incoming photons -- so I take all of these, which represent an unpolarized beam -- so I get not only one like so, but I get one like so, and one like so, and one like so, and one like so -- then clearly, I have to calculate, now, the mean value of cosine square theta.

And the mean value of cosine square theta is one-half, and so if the intensity of the unpolarized beam, unpolarized light was originally I0, once it comes through this polarizer that Edwin Land gave me, then I get one-half I0, but that is now 100% polarized.

And it is 100% polarized in this direction.

And the one-half is the result of the average value of cosine square theta.

If this were the case, it would be an extremely ideal polarizer, we would call this an HN50 polarizer -- they don't exist, it's only in your head -- and the 50 refers to the fact that 50% get through polarized.

In the optics kits that we hand out today that we will need throughout this course, you don't have HN50 polarizers, they don't exist.

I don't quite know what yours is, I didn't measure it, yours may be an HN25 or maybe an HN30, which would then mean that the I0 strength of an unpolarized light of beam would not be half of I0, but maybe only .25, or .3.

But in any case, the light that will come through your linear polarizers will be very closely to 100% polarized.

So what I will do now, I will take unpolarized light, and I will have this light coming straight out of the blackboard perpendicular to you, with strength I0, and here is one of my polarizers, and the light that comes through here is linearly polarized in this direction.

And so we already know that one-half I0 will come through if it is an ideal polarizer, and it is polarized in this direction.

I take a second sheet, an identical one, I put it also in the plane of the blackboard, but I rotate it over an angle theta.

So here is now a second sheet, which has a preferred direction of polarization in -- in this direction, and the angle is rotated over an angle theta.

So between this one and this one is an angle theta.

And so you can now immediately tell what the intensity of the light is that comes through this second polarizer.

It must, of course, be polarized in this direction, because that is the allowed direction polarization for that second sheet -- and the intensity must now be one-half I0, because that's what comes in, and then I have to multiply it by the cosine square of theta.

I don't have to average it now over all angles, because there is only one value of theta between this sheet and this sheet, so this is now the new intensity, and it's all polarized in this direction.

And this law, whereby the light intensity is reduced by the factor cosine square theta, is known as Malus' Law.

Malus' Law.

If theta were 30 degrees, the light intensity here would be one-half I0 times the cosine square of 30 degrees, which is 0.75.

If theta were 0 degrees, that means that this sheet is in the same direction as this one, if everything were ideal, one-half I0 would get through the second sheet.

If theta is 90 degrees, then nothing will get through, because the cosine of 90 degrees is 0.

We call that crossed polarizers.

If you cross them like this, no light will get through.

Now, before I demonstrate this, I have to be honest with you, because the idea of reducing the energy of individual photons by reducing their electric field strength, as I did, is a cheat.

A light photon has a well-defined energy which depends uniquely on the frequency of the light.

Blue light has a higher frequency than red light, so blue light has a higher energy than red light.

And when you send blue light through a polarizer, the way I did here, it either comes through or it doesn't come through.

But if it does come through, it is still blue light, there is no such thing as a reduction in energy.

Whereas this reduction, by cosine theta, would imply that the energy goes down, and that moo- would imply, then, that there would be a color change, that it would no longer be blue.

And that's not the case.

If you want to treat this properly, you have to do it in a quantum mechanical way.

The interesting thing is that if you use quantum mechanics, you find exactly the same law, you find also Malus' Law.

So the law is OK, even though the derivation is not kosher.

Now, I want you to get out of your envelope one of your green plates, which is a linear polarizer.

This is the kind of plate that you have, you have three in there.

Only take one out.

These two lights shining on me, unpolarized light.

So the light that comes to you now is unpolarized.

I'm now going to hold in front of my face this polarizer.

So the light that comes through is linearly polarized in this direction.

And you are going to play the role of the second polarizer.

Close one eye, put the polarizer in front of your eye, and rotate it.

And you will see a huge difference in light intensity.

If you cross-polarize with me, then you can't see me.

That may make you very happy.

But keep in mind, if you can't see me, then I can't see you, either.

So rotate it around and convince yourself that this light that reaches you is now, indeed, linearly polarized, and when you rotate around your polarimeters -- we call the polarimeters, we call them polarizers -- you can see me either, or you cannot see me at all, and there is anything and everything in between.

Very well.

There is a second way that we can produce 100% linearly polarized light, and we can do that by reflecting unpolarized light off a dielectric.

For instance, water or glass.

None of this follows from Snell's Law, Snell's Law was 250 years before Maxwell, polarization wasn't even known in the days of Snell.

But Maxwell's equations allow you to properly deal with refraction and reflection, including the polarization.

And I will make no attempt to derive this for you in detail, that's really part of 8.03 if you ever take it, but I will present you with some results so that you can at least appreciate the far-reaching consequences of the reflection in which we can produce 100% polarized light.

Suppose I have unpolarized light coming in here, medium 1, index of refraction N1, medium 2, index of refraction N2.

It's coming in at an incident angle of theta 1, it's unpolarized.

Some of it is reflected -- and this angle is also theta 1 as we discussed earlier -- and some of it is refracted into this medium, and this angle we'll call theta 2.

So this light, unpolarized comes in, reflects, and refracts.

If you want to use Maxwell's equations, at the action, where everything is happening right here at the surface between the two, you will have to decompose the incoming light, the electric field vector in two directions.

And one direction is perpendicular to the blackboard, so this is the E-vector, and the other direction is in the blackboard.

You will have to do the same here, and you have to do the same here.

And if you look at this decomposition, then notice that both components -- this component, as well as this component, is perpendicular to the direction of propagation.

That is always a must with traveling electric -- magnetic waves.

You see the same here.

This component and this are both perpendicular to the reflected beam, this component and this are both perpendicular to the refracted beam.

This one, the one perpendicular to the blackboard, we normally give a symbol perpendicular, we call this the incidence plane, the plane through the incident light and the normal to the surface, we call that the incident plane, in this place -- in this case, that is the blackboard.

We call this the perpendicular component, and we call this the parallel component.

And this is, of course, the incident beam.

So this one we call the perpendicular component, this one we call the parallel component, and this is now of the refracted beam.

This is the parallel component, this is the perpendicular component of the reflected beam.

The incident light is not polarized in this sense.

So if you average, then there is no preferred direction of the electric field.

That means, then, that in this representation, the strength of this component and the strength of this component must be exactly equal, because if one were stronger than the other, then it wouldn't be unpolarized, then there would be, on average, a preferred direction.

So this component has the same strength as that component for the incoming light.

What Maxwell's equations now can do for us -- it's a lot of work, you may see it in 8.03 -- it can relate the parallel component in reflection with the parallel component of incidence, the parallel component of refraction with the parallel component of incidence, it gives you two relations, two -- two equations.

It can also relate the perpendicular component of reflection with this perpendicular component, and the perpendicular component in refraction with this component.

So you get four equations.

If this light that comes in is unpolarized, the strength of this component is the same as this one.

In general, you will see, if you apply these four equations, that that's no longer the case here.

They're no longer the same intensity, and they're no longer the same intensity here.

That means this reflected light and the refracted light has now become partially polarized.

I will only give you the relation, one of those four equations.

I will only address today the parallel component of the incident beam, and the parallel component of the reflected beam.

And I don't imagine that any one of you will try to remember that equation.

I don't either, I have to look it up every time that I deal with this.

So E0, which always represents, then, the maximum possible value of the electric field, of the parallel component, of the reflected beam, that's the one that I'm after, I'm going to make polarized light by reflecting, is E0, the parallel component of the incident beam times -- and this depends now on the angle of incidence and on the indices of refraction -- is going to be N1 times the cosine of theta 2 - N2 times the cosine of theta 1.

Believe it or not, all of this follows from Maxwell -- divided by N 1 times the cosine of theta 2 + N2 times the cosine of theta 1.

And if you apply Snell's Law, you can simplify this equation -- in this case it will help us -- and so you get -E0 parallel incidence, and now you get here the tangent of (theta 1 - theta 2) / the tangent (theta 1 + theta 2).

So these two equations are identical.

Though that may not be obvious to you, certainly not obvious to me, either, but if you substitute Snell's Law in here, you can show that these two are the same.

Keep in mind if you're ever interested in the intensity of this light, then you must always remember that the Poynting vector is proportional to E0 squared, so you always have to square these numbers when you're interested in light intensity.

This is just the strength of the E-vector.

There is something very special hidden in this equation, and that is, when theta 1 + theta 2 is 90 degrees, then the downstairs here is infinitely large.

And so that means that the parallel component in reflection is 0.

So E parallel in refection goes to 0.

And if that one goes to 0, there is only this one left which is not 0, and that means the reflected light is now 100% polarized in this direction, because I have killed this component completely.

But it only works if this is met, this condition.

If this condition is met, that theta 1 plus theta 2 is 90 degrees, then it follows from high school math that the sine of theta 2 is then the cosine of theta 1.

That's immediately obvious, right?

You remember the triangle, theta 1 plus theta 2 is 90 degrees, the sine of one angle is the cosine of the other.

And if now, I remember Snell's Law, which says that the sine of theta 1 / the sine of theta 2, if N2 divided by N1 I can replace now, only for this special case, the sine of -- sine theta I can replace by the cosine of theta 1.

And so I get here, now, the tangent of theta 1.

And so if this is the tangent of theta 1, that is under these conditions, then we have met the condition that I was looking for, that I end up with 100% linearly polarized light.

And so this is the secret to getting 100% polarized light.

And this angle is called the Brewster angle.

And so if we, for instance, look at the transition from air to glass, glass has a index of refraction approximately 1.5 -- depends on the kind of glass that you have -- if I go from air to glass, which is what I will do in my demonstration, then the tangent of this angle is N2 / N1, this is glass, so this is 1.5, N1 is 1, then you will find that the Brewster angle, theta Brewster turns out to be about 56 degrees.

I can also make linearly polarized light by going from glass to air, by bouncing it off this way.

Then, of course, I have to invert this, and then you will get a Brewster angle which is smaller, which is 34 degrees.

But since I will do it with -- from air to glass, I want you to concentrate on the 56 degree angle.

The way I'm going to do this demonstration, it's right set up here, we have light, a light beam that strikes a piece of plane parallel glass.

That's all it is, there's nothing special about this piece of glass.

So the light comes in like so, and here, I have a piece of glass.

This is the angle of incidence, theta 1.

And so it's going to be reflected in this direction whereby this angle is also theta 1, and something will go in here, that is that angle theta 2, which I don't worry about, because I want you to see that this can become 100% polarized.

As this light comes in, it is unpolarized, this component and this component have equal strength, if theta 1 is 56 degrees or somewhere in that vicinity, this light is now 100% polarized.

And I'm going to project that onto the screen, and I'm going to convince you that it is, indeed, polarized.

You cannot use your own polarizers to see that, because the light in this beam is going to be 100% polarized.

However, once it reflects off the screen, it no longer is, so you cannot use your polarimeter, so I have to use my own polarimeter to show you this.

So if we can turn the light off there, off the overhead -- thank you very much -- I will turn on the -- the light of my light beam, there it is, and I'm going to make it very dark for you so that we can see that very well.

So the light comes in this direction, hits the glass, and the angle of incidence is now about 45 degrees.

I purposely didn't make it 56 yet.

I have here a large sheet of polarizer, one of Edwin Land's polar- polarizers, and I will rotate that in this beam.

You will see that it is partially polarized, not yet 100%, but it's already partially polarized.

So there is already an imbalance between the perpendicular and the parallel component.

So if I hold it in the beam, and I rotate it, you will clearly see now that it is much fainter than -- than it is now.

And now I will go for the 56 angle, 56 degree angle, roughly, and so now, I rotate my polarizer, and now, notice, I can kill that light completely.

100% linearly polarized.

I may not have the angle perfect, but that's OK, you get the idea.

It is very close to totally dark.

Now you see the light, it's polarized in this direction, and now I can kill it.

So that's quite a remarkable thing, that if we reflect light off a dielectric, that we can -- at one angle, and one angle only, which is the Brewster angle, that we can turn it into 100% linearly polarized light.

This does not apply to conductors.

The behavior of conductors is very different from dielectrics such as -- such as water and glass.

You can use Maxwell's equations, of course, to study the reflection of electromagnetic waves off metals, but you get a very different result.

And so never expect to get linearly polarized light which bounces off metals.

I have here, for your pleasure, a metal sphere, and I have a glass sphere, and if you still have your linear polarizers at hand, uh, you can now -- or a little later -- just hold them in front of your eyes, and rotate them around -- of course, you're not seeing light at the Brewster angle, the chances are that some of the light that's reflected off this glass that you can clearly see that it is partially polarized.

You can see a difference in light intensity as you rotate it.

You're not going to see that off this metal.

Now, I come to a third way of polarization.

There is a third way that we can make 100% linear polarized light by the scattering of unpolarized light, and we have to scatter it off very fine particles, preferably a tenth of a micron.

Dust particles would work very well.

Now, the theory of light scattering is extremely complicated, but I will be able to convince you that if I scatter the light over an angle of 90 degrees -- so it comes in like this, and it scatters over an angle of 90 degrees -- that it becomes 100% linearly polarized.

I will stay on the center board.

Suppose I have light coming in like so.

And I have one light photon, I concentrate on one to start with, and it happens to be that that light photon is linearly polarized in this direction, and so the E-vector is oscillating like this.

Later, we're going to add all directions that we want.

I just picked one now.

And here are my fine dust particles, and these dust particles have electrons, and the electric field passes by, and these electrons, which are charged, are going to oscillate in this direction.

They're going to experience an acceleration, which is the force that they experience, divided by their mass, and therefore, that is the charge that they have, times the electric field, divided by their mass.

And so as this electric field vector, this electric field component, oscillating with frequencies omega, is passing by these electrons, they themselves are going to oscillate with frequency omega, and this is the force that they will experience.

Uh, this is the acceleration they will experience.

Notice that the electrons will experience a way higher acceleration than the protons, because the protons have a mass which is more than 1800 times larger than the electron.

So whatever follows, it's really the electrons that do the job and not the protons.

So, we have charges that move up and down, and now comes the question which we have discussed earlier, so this is just simply to refresh your memory, if you're here at point P, in what direction will you now see electromagnetic radiation that is produced by charges that are being accelerated?

We discussed that earlier, and we even had a movie about that.

And perhaps you will remember that the electric field, at point P, is now oscillating in this direction.

A spherical wave goes out, if I accelerate charges here.

And the rules about this direction of the electric field are very simple.

E is always perpendicular to the direction of propagation, which is the position vector -- I call this the position vector R -- and the second rule is that A R and E are in one plane, and that happens to be, in this case, the plane of my blackboard.

But of course, that doesn't have to be the plane of the blackboard, because I can choose my point P in space here and these rules still apply.

The incident photon, which in this case, I picked only one, is completely destroyed.

It is absorbed by the dust.

And the electrons which are going to radiate, re-radiate a photon at exactly the same frequency, because if this is oscillating with angular frequency omega, then the acceleration would be with angular frequency omega, and so this E field will have angular frequency omega.

So it really is as if the photon comes in and takes off in a different direction, that's why we call this scattering.

So the frequency remains the same, but the direction changes.

And the probability that that photon will go in this direction or this direction is 0, because you remember that no electromagnetic wave is propagated in the direction of the acceleration, there's a high probability that it goes out in this plane, perpendicular to A, and at this angle theta, the probability is a little lower.

We discussed that earlier.

Now, I'm going to convince you why light that scatters over 90 degrees that comes in like this, and then [wssshhht] comes to you, why that is 100% linearly polarized.

Here is a beam of light.

And this beam of light is unpolarized.

That means, if I look down on this beam, you have individual photons, and I described to those -- maybe a little bit artificially, but I will do that, it was successful with Malus' Law -- I describe to them, individual directions of polarization.

So each photon, on its own, has a uniquely defined direction of polarization.

It is a picture that is not kosher, you really need quantum mechanics to do this right, but on the other hand, the result that you find is probably correct.

You will find the same result if you did it in a quantum mechanical way.

So here, you have these dust particles, and so what is going to happen is, this light comes in, and then [wssshhht], one may be scattered in this direction, [wssshhht], another one in this direction, another one in forward direction.

And you can go in all directions as you please.

I'm now going to look in the plane perpendicular to the blackboard, because in the plane perpendicular to the blackboard, every photon that ends up there is at 90 degrees angles.

It comes in like this, that is 90 degrees, this is 90 degrees, this is also 90 degrees.

And here is that plane.

I just draw a circle, but there is nothing special about the circle.

And so the photons come now straight to you, perpendicular to the blackboard.

That's the picture that I have now in mind.

And let's say you were looking here.

So you were sitting there, so you have to lift this up, so you're really sitting there.

So this is where you are.

And let's take one photon that comes in, which happens to be linearly polarized in this direction.

We pick one photon, but it's unpolarized light because we're going to add so many photons that, on average, there is no preferred direction.

But I pick one to start with.

And now I ask myself the question, if that photon is scattered in your direction, in this direction, how is the E-vector oscillating here?

So this is now the position vector R, and this is the direction A in which the electrons are going to shake, because the photon comes in, with an E field shaking like this, so the electrons are going to shake like this.

And you will immediately conclude that the electric vector here must be oscillating like this.

Why?

Because it has to be perpendicular to R, which it is, and it has to be in the plane of A and R.

There's only one solution, and then this is the correct solution.

Now there is a next photon coming in.

And the next photon -- I will give it color, just to distinguish the two -- happens to be oscillating in this direction.

And I ask myself the question, if that photon is scattered in your direction, in what direction is the E-field oscillating?

And you'll come to exactly the same conclusion, in this direction.

Why?

Because it has to be perpendicular to R, which it is, and it has to be in the plane of A and R, and that's the only solution.

A little later, there is another photon that comes in.

How is that electric field being observed here?

Of course, in this direction.

And so, no matter how they come in, unpolarized light, you will always see that if the photon is scattered over 90 degrees, you will always see it polarized in this direction, and therefore, you have created linearly polarized light.

So if you watch here, that is at 90 degrees angle -- or if you watch here at 90 degrees angles -- but of course, it's a whole plane -- then you end up with 100% linearly polarized light.

If you go through the same exercise, say, at an angle here, of 45 degrees, and you look here, it's only partially polarized.

Indeed, if you rotate in front of your eye the polarimeter, you will see clearly light intensity changes.

But not 100% polarized.

You couldn't turn it into darkness.

And if you look from above -- and you may want to go through that exercise for yourself, you will see that the light remains completely unpolarized.

So it is only the 90 degree angle that is very special.

And that's what I'm going to demonstrate to you.

But before I demonstrate this, there is something that I have to tell you, that I cannot hide from you, I wish I could, but I can't.

It's not something that is my goal during this lecture, it has nothing to do with polarization.

But that's the fact, that the probability, when you scatter light off very small particles, a tenth of a micron or so, dust particles, that the probability of scattering is way higher for blue light than it is for red light.

The shorter the wavelength, the higher the probability.

If you ever take 8.03, you're going to see a derivation of that, a quantitative derivation.

Blue light has a 10 times higher probability to be scattered than red light.

And so whenever I'm going to do my scatter experiments on very fine particles, you will see that that light is going to be bluish.

You can't miss that.

Now, if the particles off which I scatter are larger than a tenth of a micron, say 1 micron, this effect of color on probability of scattering is highly reduced, and if I scatter off very large particles -- 10 microns or so -- then there is no dependence any more at all.

And in this lies the secret why the sky is blue -- I will get back to that later today -- the reason why cigarette smoke can be blue, if the smoke particles are very small, and it's the reason why clouds are white.

Because the sunlight hits the clouds, the light scatters, but the water drops in the clouds are not 0.1 microns, but they are much larger, they are more like 10 microns and up, and so there is no preferred wavelength that scatters, and so the clouds look white.

And so the first demonstration that I want to do is very much like what you see here.

I'm going to send unpolarized light up here, straight up.

We have bright spotlights there, and the light goes straight up.

In here, I'm going to put very small dust particles.

And I have decided to do that smoke, simply cigarette smoke.

So I'm going to hold cigarette smoke in these beams, and the light that will come to you, no matter where you sit, must have scattered closely over 90 degrees, right?

It comes up like this, but if you see it, almost for everyone in the audience, 90 degree angle scattering.

So with your linear polarizers, you will be able to see that that light is polarized, and it's going to be polarized in this direction, which is the direction that I have here.

So that's the first thing I'm going to do with this demonstration.

And so I need cigarettes, and I need smoke.

As much as I hate this.

[laughter].

OK.

That should do.

[laughter].

OK.

So, you need a lot of light, and this light comes, presumably from here -- yes, there it is.

Ah, ready for this?

OK, so have your polarizers ready.

I want you to see two things.

Number one, that the light is bluish, and number two, that it is polarized.

Take your time for that.

If you don't see it as blue, then the reason for that is that at low-light intensities, your eyes are not very sensitive for color any more.

It looks quite bluish to me, though.

Now I want to do something in addition.

I mentioned that if the particles grow in size, that the scattering is no longer preferred in the blue.

And I can demonstrate that.

I can kill two birds with one stone.

What I can do is I can hold the smoke in my lungs for a while, and when I do that, the the water vapor in my lungs will precipitate on these dust particles, and they will form small water drops.

And when I puff that out, you will see a distinct difference in color between what you see now, and the smoke that comes out of my lungs when the particles are ten microns and even larger.

You will see, then, that the light is whitish.

So this is -- this comes extra, over and above, it comes for free.

In order to make you see the difference, shortly before I puff out the smoke in here, I will again show you this smoke as it is now, so you can compare the colors, and you will see that there is a difference.

Even though this doesn't -- this may not look very bluish to you, for reasons that I mentioned, in darkness, you don't have a very good sensitive for color.

So I'm going to hold this smoke now -- as much as I hate it, this is one of the worst demonstrations that I have to do -- I hold it in my lungs for a while.

I see a huge difference, but I'm very close.

The second puff [huh] [whew] was very white compared to the first one.

So we were able to catch two birds with one stone here.

The sky is blue because of this phenomenon.

Here, you are standing innocently on the Earth.

And sunlight is coming in, onto the Earth's atmosphere.

The sun is there.

Sunlight comes in, and the light scatters.

And the light that reaches you, that scatters off these extremely fine dust particles, and it also scatters off the air molecules themselves.

There are thermal fluctuations that go on all the time, which causes density fluctuations in the air, and they are sufficient to act as scatterers.

And so if light from here comes to you, the chances are that it is blue, because it has a higher probability than red.

And this is also likely to be blue.

And so when you look at the sky, the sky looks blue, that's the reason, it has to do with this strong preference for color to be scattered when it is blue light.

If you look in the direction of the sky at an angle of 90 degrees to the direction of the sun, the sky is also linearly polarized for the reasons that we now understand, because there is scattering over 90 degrees.

And so when the sun is out there, there is always a whole plane, great circle in the sky, which is 90 degrees away from the sun.

So when you come out with your linear polarizes, as soon as the weather clears, look at the sky, at the blue sky, and look 90 degrees away from the sun, and you will see that the sky is very strongly polarized.

If you look at angles different from 90 degrees, it's partially polarized.

But not as strongly polarized as it is at 90 degrees.

So this explains, in a very natural way, why the sun, when it rises, and why the sun, when it sets, why the sun is red.

Because if the sun rises or the sun sets, the sun is near the horizon.

So now the sunlight comes in like this.

Imagine how much atmosphere it has to travel through, how many scattering particles it will encounter on the way.

And so, right here there is scattering.

That is blue light, that is blue light, that is blue light, that is blue light, that has a higher probability, that is blue light.

So what do you think is left over for you?

There isn't very much left over.

What is left over, the blue is gone, the green is gone, so if there's anything left over, it is red.

And it is that red light that you see.

That's why the sun looks red when it sets, and it looks red when it rises, the same is true for planets, and bright stars, and the moon.

When they're just above the horizon, they look very reddish.

And if there happens to be a cloud here in the sky, well, the cloud will also see that red light, so you get a red cloud.

And that's exactly what you see at sunset, all these clouds turn red.

And so that is, again, the consequence of the fact that the probability for light scattering of blue light is 10 times larger, roughly, that the scattering for red light.

So it explains both the blue skies and the reason why the sky -- why the sunrise and the sunsets are -- are red.

I can show you two slides, whereby you do see this phenomenon, that light that scatters to you becomes bluish.

We can see it in astronomy, and the first slide is a picture of the Pleiades, called the Seven Sisters, very hot stars, they are surrounded by very small, fine dust, and the light that reaches you is not only polarized -- which you cannot see, of course, on the slide -- but it's also bluish.

And so let's take a look at that first.

So here you see the Pleiades, it's called the Seven Sisters -- some people think there are only seven stars in there, but there are hundreds -- and you see here these very bright stars, and here you see the dust surrounding these stars, and this is distinctly blue.

That's the fact, the fact that short wavelengths have a higher probability to be scattered than long wavelengths.

So the blue has a higher probability than the red.

And the next slide shows you a man on the moon.

And this person is walking on the moon, but as he walks on the moon, he produces dust, by just walking, very fine dust particles that come from the soil that he brings up.

And what he is doing, he is creating around himself sort of a blue atmosphere, a blue sky, because the sunlight comes from the right, and so the light that you see that comes in your direction has been scattered, of course.

Because there is no air on the moon, so that can only be the dust that he has produced, and you see that that dust is blue.

It would probably also be strongly polarized, because if it changes 90 degrees angle, then, of course, it would also be strongly polarized.

Now I want to do a demonstration, the last one, which catches more than two birds with one stone, it's going to kill three.

I have here a bucket with thiosulfate.

And we have light coming from this side which we s- shine through that bucket.

And we're going to put a little bit of sulfuric acid in there, and when we do that, sulfur will precipitate, small particles of sulfur.

These small particles of sulfur will become the scatterers, and so this light, which is unpolarized white light, will begin to scatter.

And you're going to see it.

If you're sitting at right angles, then you will see that that light is linearly polarized, you can enjoy that.

If you're sitting there, you're not so well off, because then the light is not at 90 degrees.

But you will see it partially polarized.

If you're sitting there, it's not at 90 degrees either, you will see it partially polarized.

But you will also see it blue, because the probability that blue light scatters is higher than red light.

So you're going to see, slowly in front of your eye, a blue sky is going to develop.

It's going to be polarized in the vertical direction for those people who are sitting at right angles, partially polarized for the rest of the audience, and then we're going to look at the light that remains after the light had penetrated the atmosphere.

After the blue light is slowly exhausted.

All right.

I will also take a polarizer with me, so I can also show you, then, the polarization.

Let me first put that sulfuric acid in.

I will do that now, so that I know that I -- OK.

So very slowly am I creating, now, my own atmosphere.

And I'm going to make it completely dark.

And so you see white light, keep an eye on the -- on the bucket, the bucket cannot be seen by all of us so well, depending upon where you sit in the audience, but I can already begin to see that it turned slightly bluish.

Of course, I have -- I'm very close.

I admit I'm very close, which is very good.

It's slightly bluish, more and more sulfur is going to precipitate as time goes on, we have to be patient.

Oh, boy, it's bluish.

I will show you that it's polarized.

I will rotate in front of it a polarimeter, and you see, there's a distinct polarization of this light, if it comes out at 90 degrees.

More and more sulfur is precipitating, and look at the sun -- if you think of this as the sun.

The sun is, um, is getting a little yellowish, it's not so white any more.

And you wonder why.

Well, you should be able to answer that, now.

Because the light that is scattered in the atmosphere -- I call this the atmosphere -- is blue.

It has a higher probability than red.

And so what is left over in the direction that you see on the screen there is the remaining light.

And the more blue leaves, and the more green leaves, the redder the sun is going to be.

And if we're going to be a little bit more patient -- and we certainly have the time for that -- you're going to see the sun getting pretty -- pretty bloody red.

So keep an eye on it, also have your linear polarizers, and try to see that the light that comes to you from the atmosphere -- if you are at 90 degree angles, I will once more do it with my polarizers -- that that's strongly polarized.

Oh, boy, look at the sun.

We're getting close, we're getting close.

Whew.

Imagine you're now on the beach, very romantic, and there is the sun, you're with a friend, you don't have your polari- well, from now on, you should always have your polarizer with you, of course.

You can really impress your friend, believe me.

For one thing, you can point out that the sky at 90 degree angles from the sun is nearly 100% polarized.

You can even tell your friend why the sky is blue.

And as you experience this romantic sunset, you can also explain why the sun is getting red, because all that blue light -- and the green light -- gets out first, and this is, then, what is left over.

And the sun is really beautiful now, I already feel these butterflies in my stomach, and ants in my pants, this is sunset all right?

[sniffles] This is very, very nice sunset.

Oh, man.

What a beautiful sunset.

Yes, indeed, indeed! We are approaching sunset! OK, see you Wednesday.