**Rainbows Presentation**

**Script**

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. Today I show you how to see rainbows in a beautiful way. I’d like to start by asking you some simple questions about rainbows.

1. Is the red part of a rainbow on the inside or outside?
2. What is the radius (in degrees)?

This is a rainbow in the sky; there is a horizon, and it’s a clear perfect circle. A perfect circle has a center somewhere inside. This means you can measure R in terms of how many degrees. The number of degrees is roughly the radius. Without measuring it, is it 10, 20, 30, 40, or 50 degrees?

1. What is the length? Sometimes you see long bows or short ones.
2. How wide is the strip of colors in degrees?
3. Which is the brighter, the outside of bows or the inside of bows?

Perhaps some of you noticed there is a difference of light between outside of the bow and inside of the bow. Maybe you’ve never realized, but there is a difference. Where is the brighter area: inside of the bows or outside of the bows?

1. Where and when can you see a rainbow?  
   What time of the day can you see a rainbow? In the morning? Noon? Afternoon?  
   Where would you see the rainbows? North? West? East? South?
2. Is there a 2nd rainbow? If there are 2 rainbows, we can ask some additional questions.
   1. Where should you look for the 2nd rainbow?
   2. What is the radius of the 2nd rainbow?
   3. What is the length and width of the 2nd rainbow?
   4. What is the color sequence of the 2nd rainbow? Is it red on the inside or outside?

You can answer most of these questions if you have really seen a rainbow. Who knows the answers to these questions? Who knows the answer to 1? Who knows the answers for 2, 3, 4, 5, 6, and 7? Most of you probably don’t know the answers to the questions after 2. This is why I stated that you have looked at rainbows, but you’ve never really seen them. I’m going to help you see them today.

We can see one drop of water on the screen. I put the sun at the horizon. Later I will put it little bit higher in the sky. Lights from the sun hits this raindrop. There is a lot of light, but let’s think about one narrow beam which hits the raindrop point A. This is the angle of incidence. Light hits point A. Some of the light is reflected, and some of the light will go to the into the water. We call this reflection.

Snell’s law tells me this angle r. Snell’s law is as follows: Whatever light goes in there reaches point B, some of the light will come out here, and some will be reflected inside. Then the light reaches point C. Again, there is a transition of water to air, so some of the light will be reflected inside of the water and some of them come out here. As far as the geometry is concerned, this angle is r, this angle is also r, this angle is also r, and this one is also r. And the angle here is what follows from Snell’s law. The light came in like this but comes back like this. So, the direction has changed over the angle delta. The delta angle is easy to calculate in terms of i and r. Let’s calculate the delta angle.

Delta equals 180 degrees plus two i minus four r. Now think about all the possible narrow beams of light that can strike the raindrop. Some of the light beams hit this at an i of 0 degrees, 10 degrees, 20 degrees, 30, 40…and the largest value of i is 90 degrees. So, I can calculate all of the angles of i, which is obviously all of the i's that occur. The sunlight hits the raindrop and all i's are present. You can calculate all angles the of i's. What are the values of r and the delta i's? I’ve taken i to be between 0 and 90 degrees, and all these angles are possible. R follows Snell’s law and delta follows this geometric relationship. In Snell’s law, reflection of water is 1.336. You can calculate i and r and find the delta from the geometric relationship. Let’s fill out the table.

It’s surprising, but there is a minimum value for delta at about 138 degrees. As you can see, the delta starts at 180 degrees when i is 0 and goes to the minimum value of 138 after which it increases again. That means this angle phi here has a maximum value which is very roughly about 42 degrees. This is the key to understanding rainbows.

Imagine now, one raindrop is here. Sunlight comes in at all angles of i, not just one but all angles of i. The raindrop is actual symmetry. The light can come like this: the light can go this way, but can also go this way, this way and this way. So, it’s completely symmetrical. In this whole drawing, you can rotate about this line. Therefore, the phi maximum is 42.4 degrees, and then the lights go back in this direction. The lights come out in the form of a cone. The top half of the angle of the cone is roughly 42 degrees. No lights can go here, because that means the angle of phi would be larger than 42 degrees, and that’s not allowed.

Now comes something very important. The red light’s index of refraction for water is about 1.331. Let’s translate it to the angle for phi max. In translating phi, the max is about 42.4 degrees. But purple light has a slightly different angle for phi max. The purple light’s index of refraction for water is about 1.343. The phi max is approximately 40.6 degrees. What does this mean?

If you look at this cone of lights that goes back toward the sun, that’s the outer edge, outer surface of the cone. The largest possible angle must be red light because purple light cannot come out in that direction because the maximum angle for purple is 40.6 is not 42.4. So only red light can come out at 42.4 degrees. And the purple light is not going to make it until here, at 40.6 degrees. If you look inside the cone, at less than 40.6 degrees, all colors come back at you, so your brain tells you the color is white light. Since you see the red light, yellow light, and blue light, your brain tells you that’s white light. If I had a screen here, I ask you what you would see on the screen from the one small rain drop. You would see a circle. The outer edge of the circle should be red, and then in the position where all color can come back, it would be white light. Then further and further from the red light up until the white light, the last color would be purple light. As you can see, the rainbow occurs here. And there are no lights because there is no way to go larger than 42 degrees. So now you can see from red color to purple color and there is darkness and there is white.

I’m going to put you here; you are standing here. And let’s have the sun be again near the horizon. You’re standing here, sun light is coming in this direction, and the rain is here. If it’s also raining here, you won’t see a rainbow because the sun will be not able to hit these raindrops. So, the rain is the away from sun, but you can still see the sun. You’re looking in this direction in the sky. And I pick up one raindrop here. What will the raindrop do?

The raindrop will produce a cone of lights which goes back in the direction of the sun. The edge of cone is red light and this angle is 42 degrees. What do you see? Nothing! Because there is no light. Phi is not allowed to be larger than 42 degrees. If you look up higher in the sky, you will not see any light which comes from raindrops. Think of the whole thing as symmetrical. You will see nothing not only there, but also there, there, and there.

Now let’s pick up a raindrop here. This raindrop is sending back a cone of lights to the sun. And the cone has a 42-degree angle on the top half. What do you see now? You are looking straight into the cone not near the edge. Therefor you see only white light. You haven’t seen a rainbow yet. I ask you to look up at a very specific angle, 42.4 degrees. Pick up one raindrop. When the sun light comes like this, the raindrop throws the cone of light back to the sun. You are looking at the outer surface of the cone where only the red light can go because this is the famous angle of 42.4 degrees. So, you see a red light. You see red light not only here, but also anywhere 42.4 degrees away from the horizon.

Now, let’s put the sun here in the sky. You can see your shadow on the ground. This is a reference line that we are talking about. For looking at the rainbow, you look up 42.4 degrees away from that line. The top would be red and the lower would be a purple. If I sketch a rainbow in there, it will be like this. Purple light will be inside, here is white light and here is no light. If the sun is higher in the sky, you can look at your shadow and look up 42.4 degrees away from that direction. That means when the sun is lower in the horizon, the bow will be higher and longer. Then the sun is rising, the bow goes down, further, and further. At the time the sun is at 42.4 degrees you won’t see a rainbow anymore. Unless the raindrop is right where you are.

Let’s get back what I was saying, about raindrops. The sun light comes in at A, are reflected at B and comes out at C. You can do some geometry but one more reflection at C is allowed. Then that light comes out at point D. This is the second bow. We call that a secondary. We call this a primary. The secondary has a radius in the red at about 50.4 degrees and the purple is larger than red light at 53.5 degrees, so purple is outside. The secondary is fainter, higher and wider because the separation of color is bigger than the primary. This is a secondary bow, and it is roughly 10 degrees away from the primary bow. And you will see that the color is reversed. Red is on the inside and purple is on the outside.

Now let’s answer the questions from before. It is not so difficult anymore. (Go back to Q1-7 at the beginning of the slideshow.)