PHYSOC MONTHLY

OCTOBER 2021 EDITION

COLOURS

PHYSOC

@thephysicsociety

thephysicsociety.org

CONTENTS

OCTOBER 2021 EDITION

FOREWORD

Dear Reader,

You may have subscribed to PhySoc Monthly because of your love for physics. Maybe it's because of your general adoration for all that is factual and rational, or maybe you have a thirst for knowledge that just needs to be quenched. Either way, we're back with a new team and here to light your way.

In this edition of the newsletter, we will explore the world of colours, so join us on this journey as we take you through skies, oceans and to the other side of the rainbow. Hopefully, just hopefully, you take away more than just a pot of gold from this colourful odyssey.

Warm Regards,
The Physics Society 2021-22

SCATTER, SCATTER: IT DOES MATTER

As a kid (or maybe even now), you may have casually questioned why the sky is blue. You likely received several different explanations: maybe it's because the ocean reflects sunlight back into the sky, or maybe it's because of the water in our atmosphere. But both can't be true, since the sky's still blue in dry places far from the sea, like the desert. So why is it blue?

Before *you* get too scattered, let us explain these:

Refraction: it is the change in speed of a wave entering another medium. For a real world analogy imagine that you are running, then all of a sudden the left half of your body is moving through maple syrup- you can probably tell that the left half of your body will be slowed down but the right half would not. This would cause you to turn to the left, a similar thing happens when a light wave enters a different medium at an angle. The area of the wave that reaches the medium first experiences the change in speed before the other side resulting in it turning. This is covered in greater detail in our third article, Guide to Being a Physicist.

Photons: An elementary particle with zero mass, that is a basic bundle of energy that makes up all electromagnetic waves (like visible light).

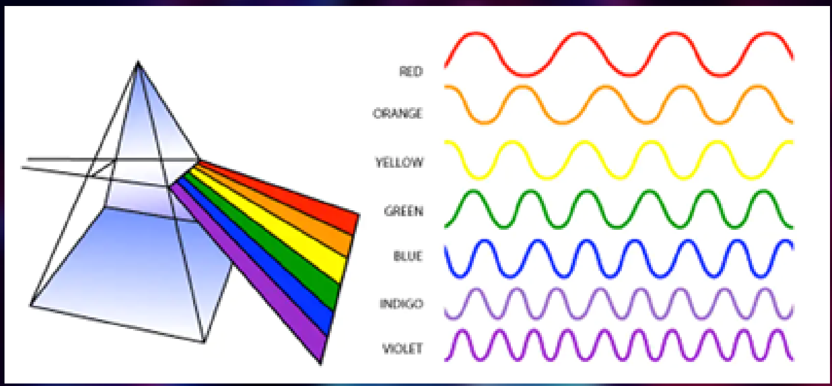
Interference of waves: this is when waves move across each other. This could lead to them cancelling each other out, distorting them or even making them larger.

Turn the light bulbs on!

Before we actually get into the explanation, it's time for some good old recollection. In school, you likely mechanically learned that light is an electromagnetic wave, and that although sunlight looks white, it's actually made up of several different colours.

Another (fairly obvious) property of light is that it usually follows a straight path unless it hits an obstacle. It can then be reflected (sent back), refracted (sped up or slowed down), dispersed, or scattered (like molecules of gas in the atmosphere).

Dispersion is the spreading of white light into its full spectrum of colours Essentially, light passes through a denser medium than air, like glass or water, and slows down- splitting up into its different colours.



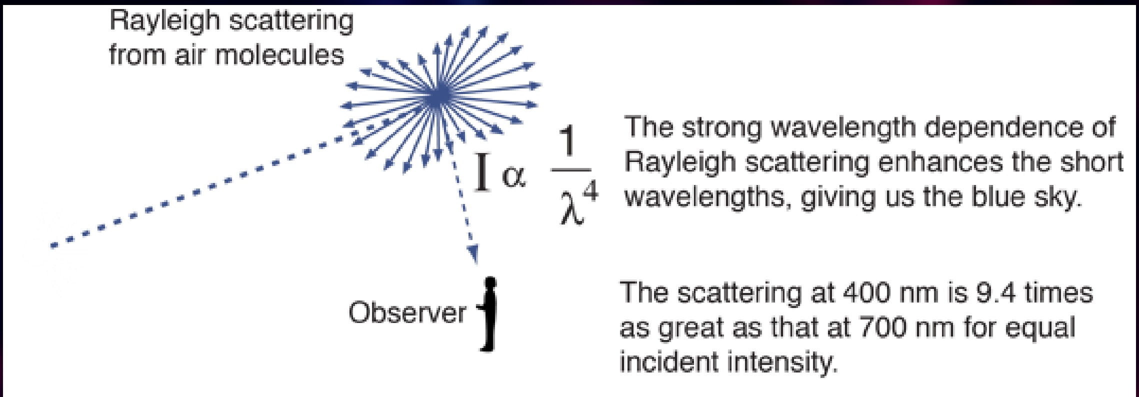
Source: The colours of light - scinight.weebly.com

A blue sky is a-zure thing

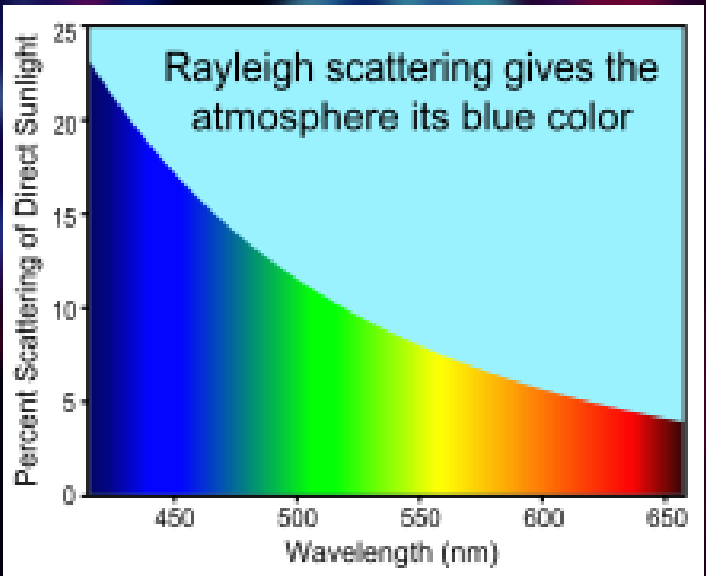
Scattering *occurs when particles or large gas molecules present in the atmosphere interact with and cause the electromagnetic radiation to be redirected from its original path.*

As sunlight reaches our atmosphere, molecules in the air scatter light near the blue end of the spectrum almost 10 times as much as light near the red end of the spectrum. Scientists call this Rayleigh Scattering. But why does the blue scatter more?

Rayleigh scattering, the dominant scattering mechanism in the upper atmosphere, causes shorter wavelengths of energy to be scattered much more than longer wavelengths. This is because shorter wavelengths are closer to the size of the oxygen and nitrogen molecules in the atmosphere, and interact more with them causing more scattering than with longer wavelengths. Blue light has a wavelength of 400nm while red light is 700 nm in wavelength. In addition, the intensity of scattering of light is inversely proportional to the 4th power of the wavelength, leading to blue light getting scattered most.



Source: The colours of light - scinight.weebly.com



Source: Wikipedia

The fact that the sky appears "blue" during the day is because of this phenomenon.

You may ask - why is the sky blue and not purple when violet would scatter more for the same reason? This is due the fact that purple or violet is at the very end of the visible range of light- so close to the edge of the human visible range that most people can’t even see it.

Alright, we’ve talked enough about the fascinating dispersion of light and have hopefully satisfied your curiosity about why the sky looks blue. How about we dive into a deeper explanation of this concept?

If the upper atmosphere’s blue, why aren’t our surroundings too ?

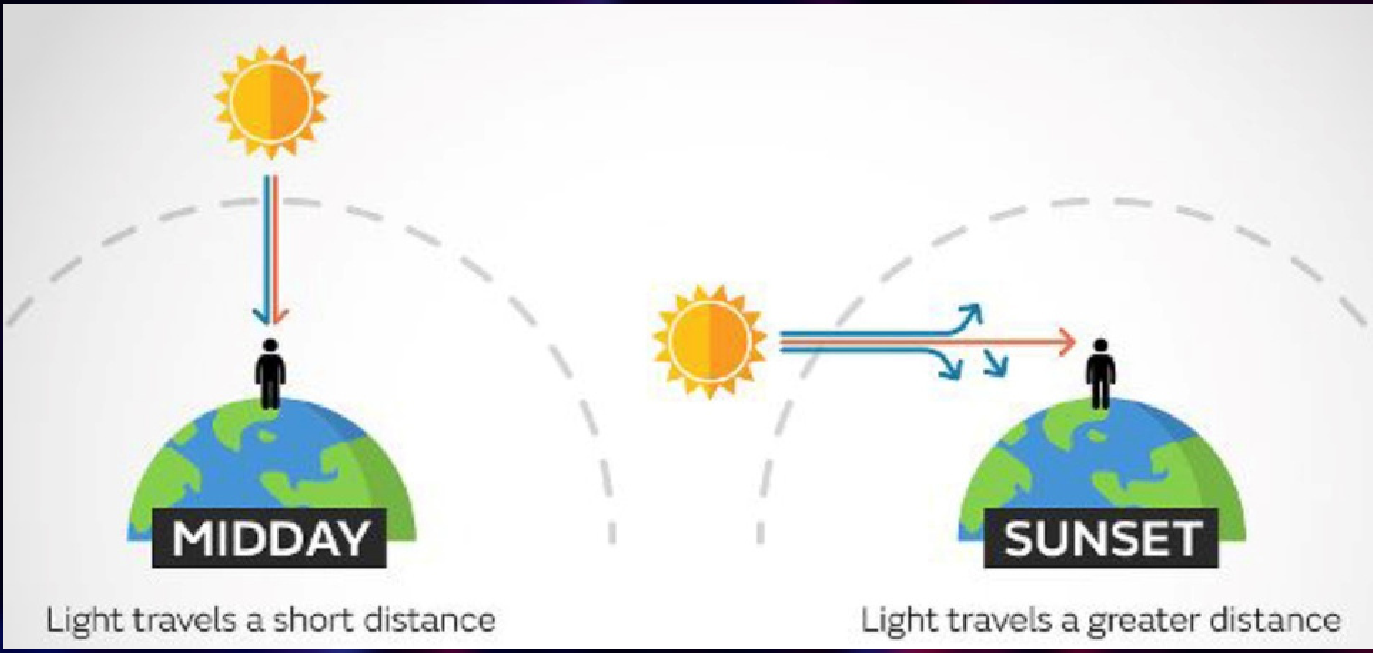
All matter is made up of atoms, that in turn are made up of charged particles called protons, neutrons and electrons. Energy from electromagnetic waves can be absorbed by these electrons. When light interacts with the charges in air molecules, there is a change in electric fields causing the molecules to vibrate at the frequency of the electromagnetic wave, and the vibration of the particle means that it has energy.

The energy absorbed is released by the emission of light. The light gets scattered in all directions and ultimately arrives at your eyes. The sky seems blue because blue light scatters the most, and this happens high up in the sky leading to the sky’s blue color. While blue is scattered the most, the other colours are only scattered a little.

The same logic can also be applied to why the sun seems yellow, the sun is actually pure white but the other colors in the spectrum refract and are therefore lost before they reach our eyes. Yellow on the other hand has a longer wavelength resulting in it refracting less and reaching our eyes.

And then it dawned on me...

As the sun begins to set, the light travels through much more air. This results in the scattering happening far above the surface. Due to this, a lot of the light ends up being scattered out into space. The yellows, oranges and reds that are not scattered as much in the upper atmosphere, makes it to the surface of the earth in greater proportion, making the sky seem yellow as the sun sets.

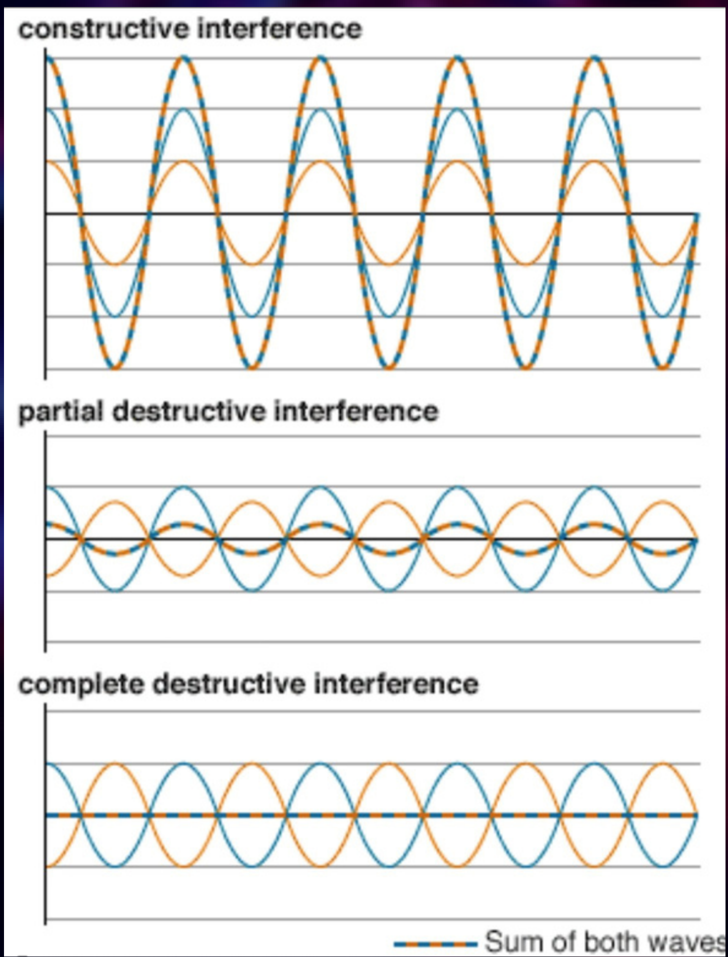


Source: Met Office - Why is the sunset red?

In summary, the Rayleigh effect describes the scattering of light, and explains the result of this phenomenon, which is our bright blue sky. We hope you were able to gain a good understanding of light scattering from our article.

A little bit extra

The interactions between the photons and particles of air create waves of light. Higher up in the atmosphere these interactions occur at a greater distance apart from each other resulting in less interference between the waves. Closer to the ground however, the interacting particles are much closer together. The molecules are only 3 nanometres apart while the wavelengths of visible light are in hundreds. This means that there is a high chance that particles that are radiating light end up around half a wavelength apart. The waves form very close to each other, this increases the likelihood of the waves interacting with each other. This could result in destructive interference ie - waves with exactly opposite amplitudes cancelling each other out. This results in a wave that has no amplitude. This is why Rayleigh scattering doesn't occur close to the surface of the earth.



Source: Constructive interference - britannica.com

***The Grudge* : No, not the movie**

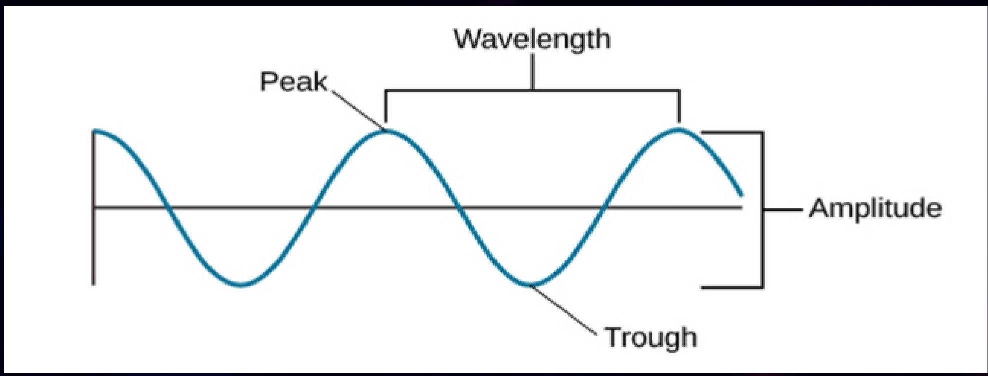
Now that you have understood how the so-called "Lord" Rayleigh figured out why the sky is blue, why don't we debunk another misconception you may have about the colour of the ocean. In reality, the colour of the ocean isn't just blue because it is a reflection of our sky - and it actually took a voyager and his stubbornness to present us with an explanation.

C.V. Raman was travelling overseas when he noticed the blue iridescence of the Mediterranean and started to wonder: why blue? Aware of Rayleigh's work, but not an acceptor of his explanation, he, like any other physicist, took out a quartz prism that was somehow just lying in his pocket and proceeded to conduct experiments to prove Rayleigh wrong.

Now, as per usual, he ended up receiving a good ol' Nobel Prize for this in 1930, but what was it that he found? The short answer - the aptly named Raman Effect

The Raman effect? More like the trampoline effect

A quick recap before we dive right into it - we know that a wave is the means of transferring energy from here to there without moving any stuff (mass) along with it. How does this happen? Small particles, namely atoms and molecules, are responsible. The wavelength of a wave, on the other hand, is not the length of the wave, as the name suggests, but instead, the distance between a point on one wave and the same point on the corresponding wave, as shown in the diagram. And finally, the frequency of a wave is the number of waves passing through a point in unit time.



Source: Khanacademy.org

Hopefully, after this brief summary of these key terms associated with waves, we're all on the same page. Now, let's see how this can be put to use in understanding the Raman effect.

C.V Raman discovered that, whenever light passes through a transparent medium (through which you can see) like air or water, some of it gets deflected by molecules. At times, this causes a change in the wavelength of light, which we know as the Raman effect.

Confusing? Absolutely. But maybe we can help. To explain this further, let's take an example of a light beam travelling through air. If this light ray collides with a molecule in its path, most of the light would see itself scatter (separate and go in different directions) with the same energy. A small proportion of the light would also bounce back, however, interestingly it would do so with a different amount of energy. Why you may ask? Well, let's just say if the molecule with which it collides is in a good mood, it can 'give' some energy to the light ray, and the opposite if in a bad mood! This particle beam of light can therefore bounce back with more or less energy and frequency than what it previously had (Remember more the energy, the faster the light ray would travel in unit time). And if the frequency changes, the wavelength would also obviously change as the speed of light remains constant, and the medium does not change.

Photons, electrons and the molecule : A Sticky Situation

Zooming in: what exactly happens that causes this energy transfer between the light and molecules?

Light is a stream of small packets of energy called photons, which are elementary particles with zero mass. When these photons collide with the molecules in the medium (let's say the medium is water, in this case), they give their energy to the shared pair of electrons in the water molecules. A quick recap: water molecules are made up of hydrogen and oxygen atoms which are covalently bonded with each other (covalent bonds are formed when electrons are shared between atoms). When the shared pair of electrons between the atoms in the molecule receives this extra energy from the photons, it becomes more excited (physicists refer to this as the electrons moving to a higher energy state) and the vibration of the covalent molecule changes. Following that, the energy is again emitted out by the shared pair of electrons. Usually, the electrons return to their original energy state, and the resulting photon that is emitted has the same energy as before. This is the Rayleigh effect, explored in the previous article. In a minority of cases however, the excited pair of electrons emit either more or less energy than they had originally received. This causes the energy of the emitted photon to be different from that of the originally absorbed photon.

If the photon's energy changes, the light's frequency changes - and its colour changes.

The deeper you go, the bluer it gets-

We've understood now why molecules absorb light, and how some of them scatter light at a different frequency than the original - so how does this relate to the sea being blue?

The molecules of water, due to their unique pickiness and attitude issues, have a tendency to mainly absorb light wavelengths on the orange end of the spectrum (red light)- why so, well that's an explanation we'll cover another day. After absorbing this light, the molecules give some of their energy away to the photons in red light, helping increase the light's frequency. As a result, the light emitted from the water molecules has a lower wavelength and a bluish colour. The resulting blue light from the water then enters our eyes, making the water appear blue.

This phenomenon is clearly seen in large and deep-water bodies such as seas and oceans, but the daily glass of water you drink is probably still stubbornly transparent. That's because shallow water does not have enough water molecules that stand in the way of the light, whereas deep water does. So, the shallow water in your glass is able to absorb less light and the colour change effect is almost negligible – whereas the deep sea, owing to the impeccable teamwork of its humongous team of water molecules, is able to absorb enough light to cause a visible colour change. So what's the lesson we learnt today, children? Teamwork makes the dream (and also the colour scheme) work.

That was over much *blue* soon!

So, folks, that's The Raman Effect. This was the legendary breakthrough discovery that earned CV Raman a sneer against Rayleigh. The Raman Effect has been celebrated for years after its discovery and has given birth to a whole new branch of chemical analysis called Raman Spectroscopy. To conclude, play with prisms more often and then who knows? You may just stumble upon a unique discovery that could earn you a Nobel Prize.

The Dude was Crazy even before the Apple hit him in the Head

Now, how about we mix it up a bit and move away from the colour blue. Let us introduce you to the six other colours, which have been neglected from the articles above, and are entitled to a little attention.

Colour is a property that was assumed to be the mixture of white light and darkness by great minds like Robert Hooke and Aristotle. A colour scale was also created, but, as always, one scientist did not agree with this theory - and his name was Isaac Newton (surprise!). Newton didn't see how Aristotle and Hooke could be right. After all, black and white from a distance looked grey. So, he set out to prove the experts wrong - one of physicists' favorite activities.

After playing around with prisms, he observed that a beam of white light had divided into bands of colour, and here is where the idea of dispersion and refraction was born. Newton had discovered that white light contains other colours. He conducted further experiments known as “Experimentum Crucis” (no, this is not a spell out of Harry Potter), which is a term given to what scientists call a ‘crucial experiment’. Once again proving his hypothesis right, Newton became the first man to understand the mechanisms of the rainbow. So let’s follow the journey of a rainbow and learn more about this very colourful aspect of physics.

Here, Wannabe Physicists - Let us Introduce You to Your Favourite Toy

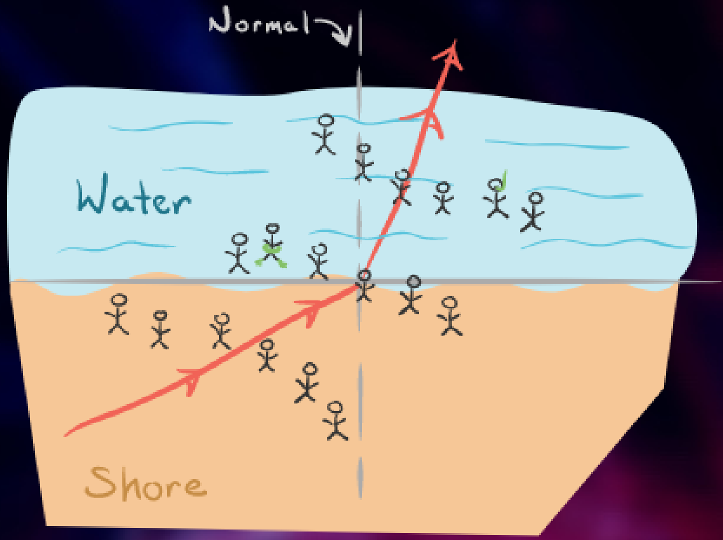
We've all heard of the old-fashioned prism experiment where a single white beam of light entering a prism emerges metamorphosed into multiple colours in an astounding mini-rainbow. Yes, our teachers have grilled that concept into our heads way too many times (in less flowery language) but what's never been explored much is the fundamental reason for this phenomenon. Surprisingly (or maybe not, its physics), the reason is a lot deeper than 'different refractions of different wavelengths of light' - so let's dive right in!

For starters, light always travels in a straight path, but bends when it changes medium. For example, a light ray would bend when it goes from air to water, or from glass to air - that's easy - it's refraction. Now, zooming in, what exactly causes our ever so straight-forward light ray to steer from its ever-so-straight path? To answer that, we'll have to know (and contemplate) two things:
a) the speed of light is different in different mediums
b) it bends only when it approaches the new medium at an angle other than 90 degrees.

The speed of light is different in different mediums because in an optically denser medium, i.e., a medium with particles more closely packed together, the wavelength of the travelling ray of light reduces while its frequency remains the same.

However, the light ray bends because when it approaches the new medium at an angle, one side of the light ray enters the new medium and slows down first, whereas the other side of the light ray is still at its old speed in the old medium.

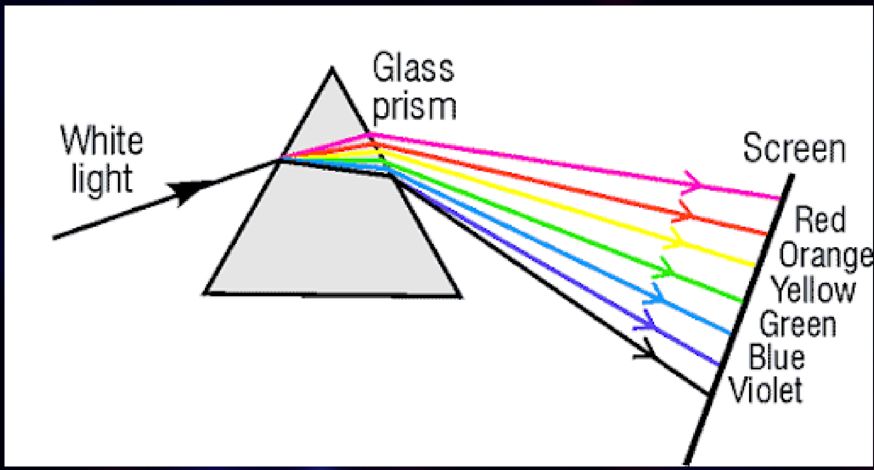
To understand this better, let's imagine a car driving at an angle from a concrete road onto grass. The car's right wheels hit the grass first and slow down, whereas the left wheels are still travelling at their original fast speed in the concrete. This imbalance in speed on both sides of the car will cause the car to turn towards the right (inwards, towards the normal). Now apply this concept to refraction, and you'll be able to figure out yourself when a light ray would bend towards the normal or away from it.



In this case the shore is the rarer medium while the water is the denser medium and the red line represents the light ray

Source: khanacademy.org

As mentioned earlier, white light contains all colours - and since the wavelength and frequency of each colour is unique, white light divides into bands of colour upon refraction, as each colour bends at a different angle. The reason you can't see this 'dispersion' of colours in a rectangular glass block per se, is because the face at which the white light enters is parallel to the face at which it leaves - so the dispersed bands of colour inside the rectangular glass block 'join back' into white light upon exiting the block. On the other hand, in a triangular prism, the face (note: here, a 'face' is being used to refer to a surface that constitutes a change in medium) at which the white light enters and the face at which it leaves are not parallel: hence, the white light splits or 'disperses' even more when it gets refracted by two different faces at different angles, and there results our band of colours.



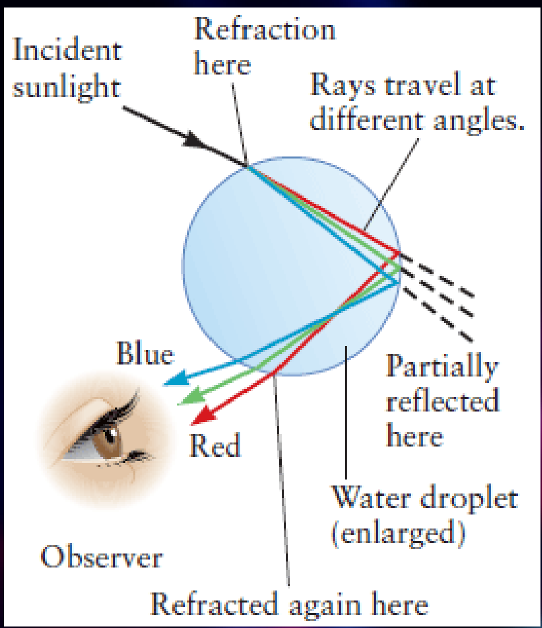
Source: ICSE class 10 past paper

Water is the New Black - sorry, we meant prism

So, now that you have understood what refraction and dispersion are, let's apply it to the formation of rainbows.

These multicoloured arcs are made when sunlight refracts and reflects off water droplets in the sky. Light entering the water droplet is first refracted and then reflected, and this process continues again and again, sort of like when a ping pong ball bounces off of walls and changes direction many times in a row. The rainbow gains its arc shape depending on the degree at which the light bends after refracting. The more the light bends, the smaller the arc and vice versa. Finally, how does the rainbow show all its different colours? The answer to this is dispersion: as explained earlier, the sunlight hits the water droplet and reflects back and refracts in many different angles, producing the different colours in a rainbow.

What's even more cool is that rainbows are not actually arcs, but full circles! The reason they appear to be in the form of an arc shape is because viewers on the ground are only able to see light reflected above the horizon (the line at which the earths' surface and sky meet) and since horizons can differ from person to person, no two people see the same rainbow! The only time people actually see a circular rainbow is when they are above it. So if you're ever in a plane and happen to come across a circular rainbow, now you know why the shape is different.



A diagram representing how light refracts and reflects in a water droplet

Source: Who likes rainbows? -sites.psu.edu (Penn State University)

Investigating a Rainbow certainly wasn't a White Colour Job

Finally, we have reached the end of the rainbow, but instead of finding a pot of gold, we hope you have found some 'golden' knowledge! But most certainly, the most golden of this golden knowledge was probably that to be a physicist wannabe, you've got to love prisms.

FURTHER READING

- **Sixty Symbols YouTube channel -** What causes rare rainbow arcs?
- **Earthsky.org -** I saw an upside-down rainbow. What is it?
- **HowStuffWorks.com -** "If Rainbows Are Circular, Why Do We Only See Arches?"
- **Thermo Scientific Spectroscopy & Materials Analysis YouTube channel -** Raman Basics
- **Bruker Corporation YouTube channel -** Raman for beginners
- **OpenMind BBVA -** John Tyndall, the Man who Explained Why the Sky is Blue

GLOSSARY

- **Photons -** A type of elementary particle with zero mass.
- **Spectroscopy -** The study of the chemical composition of substances by using electromagnetic waves of different frequencies.
- **Raman Spectroscopy -** A chemical analysis technique that provides information about chemical structure and molecular interactions based upon the interaction of light with a material.
- **Wave interference -** A phenomenon where two waves travelling in the same medium overlap, resulting in a wave of larger or smaller amplitude.

GLOSSARY

- **Constructive Interference -** This is a type of interference where the maxima of two waves add together to form the amplitude of the resulting wave.
- **Medium -** A substance through which a wave propagates
- **Rarer medium -** A substance that is less dense relative to another substance
- **Dispersion -** The splitting of white light into its seven constituent colours

BIBLIOGRAPHY

- **National Oceanic and Atmospheric Administration - SciJinks**: https://scijinks.gov/rainbow/
- **National Geographic - Rainbow**: https://www.nationalgeographic.org/encyclopedia/rainbow/
- **Royal Meteorological Society, MetMatters Rainbows - How Are They Formed**:https://www.rmets.org/metmatters/rainbows-how-are-they-formed
- **Chandra.Harvard - Somewhere Over The Rainbow**: https://chandra.harvard.edu/edu/stop/rainbow_guide.pdf
- **Brittanica.com - Raman effect**: https://www.britannica.com/science/Raman-effect
- **ScienceDirect - RamanEffect**: https://www.sciencedirect.com/topics/engineering/raman-effect

BIBLIOGRAPHY

- **ThePrint Youtube channel - What is the Raman effect that won physicist C.V. Raman a Nobel Prize?**: https://www.youtube.com/watch?v=UWrjBbUQJdA
- **The science asylum - how does Rayleigh scattering actually work?** (**the blue sky**): https://youtu.be/4HBuHX4-VU8
- **Hyperphysics scattering**: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html#c2
- **Britannica.com - Rayleigh scattering**: https://www.britannica.com/science/Rayleigh-scattering
- **The Hindu - Water Colours**: https://www.thehindu.com/sci-tech/science/water-colours/article2937811.ece