COLOURS

A lesson about light and colours

Prof. Daniela Bosco

What you have to know

- Refraction of light
- Chromatic aberration
- The state of the art in Newton's time

Refraction of light

When a ray of light hits the interface between two media, it changes its direction

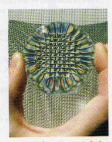
The direction of propagation in the two media is related by Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

n_1 and n_2 are the indices of refraction of the two media

Chromatic aberration

It's a common defect of simple lenses.
Sometimes you see a fringe of colours around an image seen through a lens or a telescope.
Chromatic aberration can be corrected by combining two or more lenses.



▲ Chromatic aberration typical of a simple lens.

A short story of light and colours

Aristotle's theory:

- Light is pure, simple and homogeneus
- Colours are imprisoned inside objects: sunlight hits an object and they spread out
- Colours are formed with white and black light, the two basic colours

There is more……..

A short story of light and colours

The scholastic theory:

Colours are:

- Transitory - an alteration of light
- Permanent – qualities of bodies

The mechanistic theory:

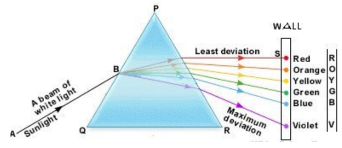
Colours are only transitory – they are due to some alteration of light

There is more……..

1664-1665: Newton at Cambridge

- Newton is about to construct a telescope
- One of the main defects of a refracting telescope is chromatic aberration
- He begins studying colours

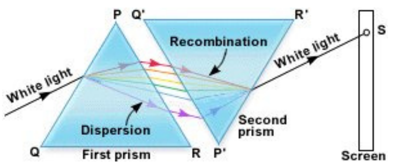
1665-1666: a first experiment



For this distribution of colours Newton coined the term **SPECTRUM**.

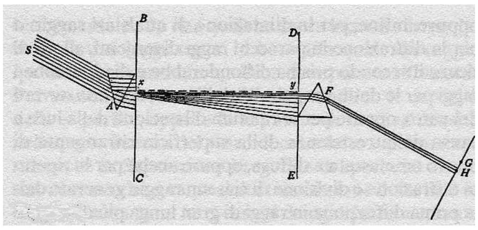
The description of the experiment

1665-1666: a second experiment



The description of the experiment

The *experimentum crucis*



The description of the experiment

Newton's conclusions

- White light is a "Heterogeneous mixture of different refrangible Rays"
- Colours of the spectrum cannot be individually modified.
- Colours are "*Original* and *connate properties*, which in divers Rays are divers. Some Rays are disposed to exhibit a red colour and no other; some a yellow and no other, some a green and no other, and so of the rest".

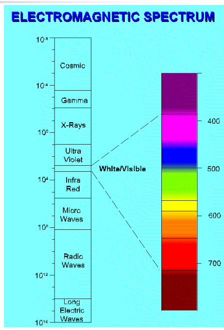
There is more……..

If light is a wave

According to the wave theory, every colour corresponds to a different wavelength of light or to a different frequency:

Range of λ: 700 nm for red light and 400 nm for violet light.

Range of f: $4.3 \cdot 10^{14}$ hz for red light and $7.5 \cdot 10^{14}$ hz for violet light.



The dispersion of light

The index of refraction depends on the frequency of the light: the higher the frequency, the higher the index of refraction.

White light is a mixture of frequencies, so:

Different colours travel in different directions

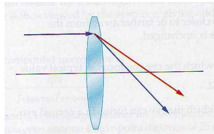
This "spreading out" of light according to colour is:

DISPERSION

The dispersion of light

Dispersion is the cause of chromatic aberration in a simple lens:

Different colours focus at different points.



▲ **FIGURE 27–19 Chromatic aberration in a converging lens**
Chromatic aberration is caused by the fact that blue light bends more than red light as it passes through a lens. As a result, different colors have different focal points.

The reflection telescope

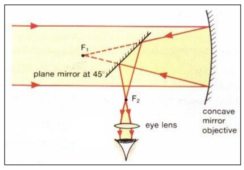
"I should like to inform you that Mr. Isaac Newton, Professor of Mathematics at Cambridge, has invented a new kind of telescope. All I can tell you now is that, when first seen and examined here, it was a telescope about six inches long..."

From a letter to Christiaan Huygens

The reflection telescope

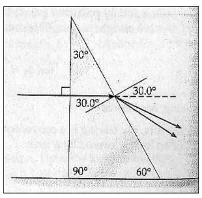
To solve the problem, Newton designed a telescope that used mirrors, rather than lenses, to bring the light to a focus.

Light from the object being viewed is collected by the **concave primary mirror** and reflected to a smaller, **secondary plane mirror** (sometimes called the "**flat**"). The flat is inclined at 45 degrees to the axis of the telescope and reflects light to an **eye lens** which forms an image



Exercise

A Flint-glass prism is made in the shape of a 30° - 60° - 90° triangle, as shown in the diagram. Red and violet light are incident on the prism at right angles to its vertical side. Given that the index of refraction of flint glass is 1.66 for red light and 1.70 for violet light, find the angle each ray makes with the horizontal when it emerges from the prism.



The colours of objects

Why objects have different colours?

Objects reflect one sort of light in greater quantity than another.

The sentence above is red because a red pigment absorbs the major part of the other colours and reflects principally red.

The colours of objects

- Colour is not a property of bodies.
- Colour depends on the way in which a body absorbs the various coloured rays.
- A body, appearing normally red, when illuminated with blue light appears dark.

There is more……..

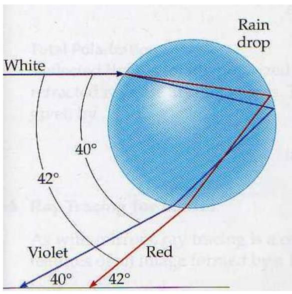
Something about rainbows

A rainbow is caused by the dispersion of light in droplets of rain.

When sunlight enters a drop, it is separated into its coloured components.

▲ A rainbow over Isaac Newton's child-hood home in the manor house of Woolsthorpe, near Grantham, Lincolnshire, England. (Note the apple tree near the right side of the house.)

Dispersion in a rain drop



The final direction of light is quite opposite to its incident direction.

Violet light changes its direction by 320°.

Red light changes its direction by 318°.

The description of the phenomenon

Why is the sky blue?

The atmosphere is a mixture of molecules of nitrogen (78%), oxygen (21%), argon, water vapour and small dust particles.

All these particles have different dimensions.

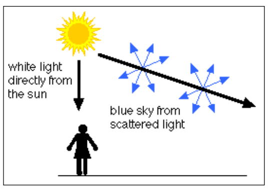
The energy of a wave's incident can be diffused in all directions by obstacles of small dimension placed along the path of light.

Why is the sky blue?

Gas molecules are smaller than the wavelength of visible light.

The smaller the wavelength is in respect to the dimension of the obstacle, the more the light is diffused by the obstacle.

Light with a smaller wavelength, that of blue, will be diffused much more than those of a greater wavelength.



The description of the phenomenon 1 2

A first experiment

Newton made a hole in a shutter to obtain a small shaft of light and placed a glass prism in front of the window, when the beam passed trough the prism he saw on the opposite wall a large coloured oblong stain.

In order to know why the stain was oblong and not circular and from where these colours originated, Newton passed light through glass of diverse thickness, changed the dimensions of the hole in the shutter and finally even placed the prism outside the window.

No variation of the experimental conditions had any effect on the spectrum.

To verify if the spectrum was due to some imperfection or irregularity of the glass he set a new experiment.

A second experiment

Newton passed coloured rays coming out from the first prism through another identical upside-down prism.

The second prism, placed close to the first one, reassembled the colours.

A mark of white light appeared on the wall as if the beam hadn't passed through the prisms.

The *experimentum crucis*

Newton took two boards, placed one of them close behind the prism A at the window and the other at about 12 feet.

Through a small hole in the board BC he selected a given colour to pass through a hole in the board DE to another prism F which refracted the coloured rays on the wall.

A further refraction was the only effect that the second prism had on the monochromatic beam. The selected beam remained the same colour and its angle of refraction was constant.

About rainbows

by The National Center of Atmospheric Research

What is a rainbow?
Author Donald Ahrens in his text *Meteorology Today* describes a rainbow as "one of the most spectacular light shows observed on earth". Indeed the traditional rainbow is sunlight spread out into its spectrum of colors and diverted to the eye of the observer by water droplets. The "bow" part of the word describes the fact that the rainbow is a group of nearly circular arcs of color all having a common center.

Where is the sun when you see a rainbow?
This is a good question to start thinking about the physical process that gives rise to a rainbow. Most people have never noticed that the sun is always behind you when you face a rainbow, and that the center of the circular arc of the rainbow is in the direction opposite to that of the sun. The rain, of course, is in the direction of the rainbow.

What makes the colors in the rainbow?
The traditional description of the rainbow is that it is made up of seven colors - red, orange, yellow, green, blue, indigo, and violet. Actually, the rainbow is a whole continuum of colors from red to violet and even beyond the colors that the eye can see.
The colors of the rainbow arise from two basic facts:
Sunlight is made up of the whole range of colors that the eye can detect. The range of sunlight colors, *when combined*, looks white to the eye. This property of sunlight was first demonstrated by Sir Isaac Newton in 1666.
Light of different colors is refracted by different amounts when it passes from one medium (air, for example) into another (water or glass, for example).

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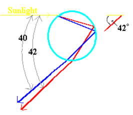


About rainbows

Descartes and Willebrord Snell had determined how a ray of light is bent, or refracted, as it traverses regions of different densities, such as air and water. When the light paths through a raindrop are traced for red and blue light, one finds that the angle of deviation is different for the two colors because blue light is bent or refracted more than is the red light. This implies that when we see a rainbow and its band of colors we are looking at light refracted and reflected from *different raindrops*, some viewed at an angle of 42 degrees; some, at an angle of 40 degrees, and some in between. This is illustrated in this drawing, adapted from Johnson's *Physical Meteorology*. This rainbow of two colors would have a width of almost 2 degrees (about four times larger than the angular size as the full moon). Note that even though blue light is refracted more than red light in a single drop, we see the blue light on the inner part of the arc because we are looking along a different line of sight that has a smaller angle (40 degrees) for the blue.

What makes a double rainbow?
Sometimes we see two rainbows at once, what causes this? We have followed the path of a ray of sunlight as it enters and is reflected inside the raindrop. But not all of the energy of the ray escapes the raindrop after it is reflected once. A part of the ray is reflected again and travels along inside the drop to emerge from the drop. The rainbow we normally see is called the **primary** rainbow and is produced by one internal reflection; the **secondary** rainbow arises from two internal reflections and the rays exit the drop at an angle of 50 degrees° rather than the 42°degrees for the red primary bow. Blue light emerges at an even larger angle of 53 degrees°. his effect produces a secondary rainbow that has its colors reversed compared to the primary, as illustrated in the drawing, adapted from the Science Universe Series *Sight, Light, and Color*.
It is possible for light to be reflected more than twice within a raindrop, and one can calculate where the higher order rainbows might be seen; but these are never seen in normal circumstances.

previous

Aristot. 17° cent

The theory before Newton

Sunlight has been considered simple, pure and homogenous for two thousand years. In literary and religious language, light is compared with purity and simplicity, while sunlight is often identified with God himself (remember the role of light in Dante's Paradise).
Aristotle considers colours as a form of light which is imprisoned inside objects; sunlight is necessary to make them visible: this means that colours become visible to the human eye when a sun ray hits an object. Red, yellow, blue ….. are formed when white and black (the two basic colours) mix. According to Aristotle's theory white is at the beginning of the chromatic scale, black is at the end, the other colours are in the middle.
What really matters is luminosity, the brilliance of light: the more you move towards black the more the colour becomes dark. The most important concepts in this theory are, in conclusion, luminosity and darkness. This means that white and black are the only basic colours, while the others are the result of a mixture.
Between the 13th and the 17th century there is a development of the theory: colours are divided in transitory (as they appear in a rainbow) and in real colours which are permanent, the first ones are an alteration of light, the second ones are qualities of bodies that light can only reveal.
But in the 17th century the mechanistic philosophers deny such division: colour, like taste, is not a quality of bodies such as geometrical quantity, shape and motion; only the last ones arouse our sensations.
Galilei says: "Che nei corpi esterni, per eccitare in noi i sapori, gli odori e i suoni si richeggia altro che grandezze, figure e moltitudini e movimenti tardi o veloci, io non lo credo; e stimo che, tolti via gli orecchi, le lingue e i nasi, restino bene le figure, i numeri e i moti, ma non già gli odori, né i sapori, né i suoni, li quali fuor dell'animale vivente non credo sieno altro che nomi".
The Mechanists, refusing the idea that colours are inherent qualities of bodies, accept the theory affirming that colours are always due to some alterations of white light: so all colours are transient, according to the scholastic philosophers.

Newton

Color from **Project Physics Course**
The importance humans have always attributed to color is shown by the great variety and quality of the colored substances used in paintings and ceramics even from prehistoric times. However, before Newton no scientific theory of color had been developed and all the generally accepted ideas had been advanced by artists-scientists, like Leonardo da Vinci, who had elaborated from the basis of their practical experience.
Unfortunately, what one learns preparing colors could rarely be applied to light. Formerly it was thought that the light of the sun was "pure light" and color originated from the addition of impurities to this pure light, for example when passing through glass.
Newton became interested in color when, still a student at Cambridge University, he was about to construct an astronomical telescope. This instrument had the defect of forming images surrounded by an annoying iridescent halo. It was perhaps in the attempt to eliminate this particular defect that Newton undertook a systematic study of color.
In 1672, at the age of 29, Newton published a theory on the nature of color in the review "Philosophical Transactions" of the Royal Society of London. This theory was the first scientific writing he published. He wrote:
"[…] in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena* of *Colours*. And in order thereto having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my Prisme at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby […]"
The shaft of 'white' sunlight originating from the circular aperture passed into the prism and formed a lengthened stain of colored light on the opposite wall, violet on one extreme, red on the other with continuous gradations of color in the middle. For this distribution of colors Newton coined the term spectrum.
Newton asked himself from where these colors originated and why the image was oblong instead of circular. Trying to answer this questions, Newton passed light through glass of diverse thickness, changed the dimensions of the hole in the shutters and finally even placed the prism outside the window. However, no variation of the experimental conditions had any effect on the spectrum. To verify if the spectrum was due to some imperfection or irregularity of the glass, he passed colored rays outgoing from a first prism through another identical, but upside-down. If it had been irregularity of the glass to produce the enlargement of the luminous shaft, then this should have increased even more passing through the second prism. Instead, the second prism, if put in an appropriate position, reassembled the colors forming the mark of white light as if the ray hadn't even passed through the prism. Continuing the elimination, Newton was convinced of what he had probably suspected from the beginning: white light is made up of colors. It's not then the prism that in some way creates or adds the colors, they always exist but are mixed in such a way that it's not possible to distinguish one from the other.
When light passes through a prism, each of the component colors is refracted according to a diverse angle so that the shaft enlarges itself forming a spectrum.

next

Newton colour

Color from **Project Physics Course**

To obtain a further verification of his hypothesis, Newton made a small hole in the screen on which the spectrum formed, in a way that isolated the light of only one color making it pass through a second prism. He observed that a further refraction was the only effect that the second prism had on the monochromatic shaft, that is after the first prism had separated the colors that make up white light, the second prism couldn't any longer change the color of a single ray. Reassuming his observations, Newton wrote:

"Colours are not *Qualifications of Light*, derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed,) but *Original* and *connate properties*, which in divers Rays are divers. Some Rays are disposed to exhibit a red colour and no other; some a yellow and no other, some a green and no other, and so of the rest. Nor are there only Rays proper and particular to the more eminent colours, but even to all their intermediate gradations."

The colors of objects. Up to this point Newton had spoken only of the colors of rays of light, but in a following paragraph of his work he raised a very important question: why do objects have different colors? Why is the sky blue, the grass green, the colors of paint yellow or red? Newton proposed a very simple explanation:

"[…]the Colours of all natural Bodies have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty then another".

In other words, a red pigment appears such because when white light falls on it the pigment absorbs the major part of the rays of the other colors of the spectrum and reflects principally red, which we observe with our eyes.

According to the theory of Newton, color is not a typical property of an object, but depends on the way in which an object absorbs the various colored rays that hit it. Newton justified this hypothesis taking note that an object could appear a different color when the type of light that illuminates it changes. For example consider a pigment that reflects much more red light than green or blue. When it's illuminated with white light, it reflects principally the red component and then appears of this color. But if it's illuminated with blue light, the pigment will reflect it in only a tiny quantity, not being the red component, and therefore will appear dark and vaguely blue. Newton wrote:

"And this I have experimented in a dark Room by illuminating those bodies with uncompounded light of divers colours. For by that means any body may be made to appear of any colour. They have there no appropriate colour, but ever appear of the colour of the light cast upon them, but yet with this difference, that they are most brisk and vivid in the light of their own day-light-colour.".

Reactions to the theory of Newton. Newton's theory of color initially met with violent opposition. Other English scientists, especially Robert Hooke, objected that it was not necessary to postulate the existence of different types of light for every color, but would be more simple to suppose that diverse colors are produced from 'pure' white light, modified during some physical process, for example a distortion of the front of a wave.

Newton realized the errors of Hooke's theory but shrunk from public disputes, in fact he waited until the death of Hooke, in 1703, to publish his book *Opticks* (1704) in which he examined all the properties of light. While from a purely scientific point of view *Principia* was of major importance, *Opticks* notably influenced the literary world.

previous next

colour

Color from **Project Physics Course**

The poets who celebrated the discoveries of their best scientists had many confused ideas about the significance of Newton's theory of gravity, since they couldn't understand the technical details. But his theory of color stimulated the fantasy of poets remarkably, as in the case of the poem *To the Memory of Sir Isaac Newton* of James Thomson (1727):

"[…] First the flaming red
Sprung vivid forth; the tawny orange next;
And next delicious yellow; by whose side
Fell the kind beams of all-refreshing green.
Then the pure blue, that swells autumnal skies
Ethereal played; and then, of sadder hue,
Emerg'd the deepen'd indigo, as when
The heavy-skirted evening droops with frost;
While the last gleamings of refracted light
Died in the fainting violet away."

The principal representatives of the romantic literary movement of the 18th century and the German 'nature philosophers' didn't have such a good opinion of Newton's theory of color. They considered scientific procedures of analysis of natural phenomena unacceptable through means of experiments and preferred to meditate on unifying principles of all the forces of nature, hoping thus to be able to comprehend it in its totality. In 1802, the German philosopher Friedrich Schelling wrote:

"*Opticks* of Newton is the most obvious example of a structure entirely wrong that, in all its aspects, is based on observation and experimentation."

The German poet Goethe dedicated many years to a work with which he wanted to destroy Newton's theory of color, basing it on both experimental observations and passionate arguments. Goethe insisted on the purity of light in its natural state, rejecting Newton's hypothesis according to which white light is a mixture of color and suggested they were produced from the interaction between white light and its opposite, darkness. Although Goethe's observations on the perception of color would have some scientific validity, his theory on the physical nature of color couldn't survive examination based on detailed experiments and consequently the theory of color proposed by Newton became established definitively.

previous next

Color from **Project Physics Course**

Why is the sky blue?

Newton suggested that the apparent color of natural objects was that which they reflected or diffused mainly. In general it is not at all simple to predict from examination of the structure of a surface or from chemical composition which will be the color reflected or diffused from a liquid or solid. However, you can understand why the sky appears blue with very simple reasoning.

As we saw in paragraph 4, Thomas Young demonstrated that every color corresponds to a different wavelength of light, that can be expressed in Angstrom or, better, in nanometers. The part of the spectrum visible to humans is contained approximately between 700 nm of red light and 400 nm of violet light. The energy of a wave's incident can be diffused in all directions by obstacles of small dimension placed along the path of light. The percentage of energy diffused depends on the wavelength. This property can be verified through experiments on waves of water using an ondoscope. In general one can state that the greater the wavelength is in respect to the dimension of the obstacle, the less the light is diffused by the obstacle. For particles with dimensions less than a wavelength the quantity of diffused light is inversely proportional to the fourth power of the wavelength. This signifies that, since the wavelength of red light is around twice that of blue light, the diffusion of red light is around 1/16 of that of blue light. Now we can understand why the sky appears blue. The light of the Sun is diffused from the molecules of air and particles of dust suspended in the atmosphere. These particles in general are very small in respect to the wavelength of visible light, so light with a smaller wavelength, that of blue, will be diffused much more than those of a greater wavelength. When we look toward a clear sky, what enters your eyes is mostly diffused light. The shortest wavelength diffused by the sky together with the sensibility of the human eye to light determines the sensation of blue. If you look instead directly toward the Sun at sunset on a very hazy day, you receive light with the greatest wavelength, those not diffused, and then the Sun will appear reddish to you.

If the Earth didn't have atmosphere, the sky would appear black and the stars would be visible also in the day. In fact, rising to a height above 15,000 meters, where the atmosphere is rather rarefied, the sky appears black and one can see the stars during the day, as has been documented by astronauts.

When the air contains dust particles or drops of water, which dimensions are on the order of wavelengths of visible light (), all colors can also be strongly diffused. For example, the color of the sky changes according to the content of water vapour in the atmosphere, so on clear, dry days the sky is of a much more intense blue in respect to clear days with a high humidity percentage. The intensely blue skies of Greece and Italy, that for centuries have been a source of inspiration for poets and painters, are due to the exceptionally dry air.

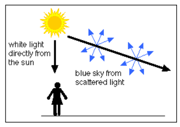
Why is the sky blue?
BY SCIENCE MADE SIMPLE, INC

LIGHT IN THE AIR

Light travels through space in a straight line as long as nothing disturbs it. As light moves through the atmosphere, it continues to go straight until it bumps into a bit of dust or a gas molecule. Then what happens to the light depends on its wave length and the size of the thing it hits.

Dust particles and water droplets are much larger than the wavelength of visible light. When light hits these large particles, it gets reflected, or bounced off, in different directions. The different colors of light are all reflected by the particle in the same way. The reflected light appears white because it still contains all of the same colors.

Gas molecules are smaller than the wavelength of visible light. If light bumps into them, it acts differently. When light hits a gas molecule, some of it may get absorbed. After awhile, the molecule radiates (releases, or gives off) the light in a different direction. The color that is radiated is the same color that was absorbed. The different colors of light are affected differently. All of the colors can be absorbed. But the higher frequencies (blues) are absorbed more often than the lower frequencies (reds). This process is called Rayleigh scattering. (It is named after Lord John Rayleigh, an English physicist, who first described it in the 1870's.)

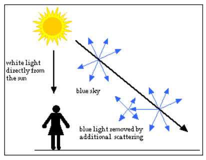


WHY IS THE SKY BLUE?

The blue color of the sky is due to Rayleigh scattering. As light moves through the atmosphere, most of the longer wavelengths pass straight through. Little of the red, orange and yellow light is affected by the air.

However, much of the shorter wavelength light is absorbed by the gas molecules. The absorbed blue light is then radiated in different directions. It gets scattered all around the sky. Whichever direction you look, some of this scattered blue light reaches you. Since you see the blue light from everywhere overhead, the sky looks blue.

As you look closer to the horizon, the sky appears much paler in color. To reach you, the scattered blue light must pass through more air. Some of it gets scattered away again in other directions. Less blue light reaches your eyes. The color of the sky near the horizon appears paler or white



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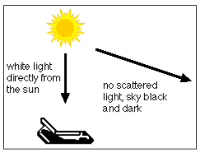
THE BLACK SKY AND WHITE SUN

On Earth, the sun appears yellow. If you were out in space, or on the moon, the sun would look white. In space, there is no atmosphere to scatter the sun's light. On Earth, some of the shorter wavelength light (the blues and violets) are removed from the direct rays of the sun by scattering. The remaining colors together appear yellow.

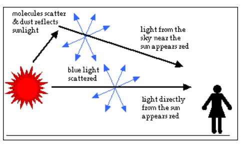
Also, out in space, the sky looks dark and black, instead of blue. This is because there is no atmosphere. There is no scattered light to reach your eyes.



WHY IS THE SUNSET RED?

As the sun begins to set, the light must travel farther through the atmosphere before it gets to you. More of the light is reflected and scattered. As less reaches you directly, the sun appears less bright. The color of the sun itself appears to change, first to orange and then to red. This is because even more of the short wavelength blues and greens are now scattered. Only the longer wavelengths are left in the direct beam that reaches your eyes.

The sky around the setting sun may take on many colors. The most spectacular shows occur when the air contains many small particles of dust or water. These particles reflect light in all directions. Then, as some of the light heads towards you, different amounts of the shorter wavelength colors are scattered out. You see the longer wavelengths, and the sky appears red, pink or orange.



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