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The light at the end of the rainbow

Everyone knows that rainbows present the brightest and best range of colours. But this has more to do with how we see natural colours than with rainbow optics

Raymond Lee and Alistair Fraser

JOHN CONSTABLE, a meticulous painter of the English sky, was a great champion of meteorological accuracy in painting. His enthusiasm was, if anything, more evident in print than on canvas. In 1830, he offered some observations that "can hardly fail to be useful to the Landscape Painter". With an air of patient reproach, he notes that the "morning and evening Bows are more frequent than those at noon, and are far more imposing and attractive from their loftiness and span; the colours are also more brilliant, 'Flashing brief splendour through the clouds awhile' ". For us, as for Constable, the rainbow evokes both curiosity and aesthetic delight: few other sights in the sky are as memorable as the rainbow's vivid colours. Our eyes tell us that the rainbow is a paragon of colour, so much so that "all the colours of the rainbow" has become a byword for variety and vividness. But analysis of the spectrum that we see in a rainbow does not bear this out.

To describe rainbow colours we must refer to some real, but seldom considered, idiosyncrasies of colour vision. For example, most of us are sure we know what "white" means. Our explanations may range from "white means that there is no colour", to "white must be an equal mixture of all colours". Surprisingly, neither statement is true. We can call many different kinds of light white, and our convictions will change with both time and place. Our descriptions of other colours can be equally fluid, but we can begin to make sense of the elusive colours of the rainbow, and improve on the state of affairs described by the physicist W. J. Humphreys in 1940: "The 'explanations' generally given of the rainbow may well be said

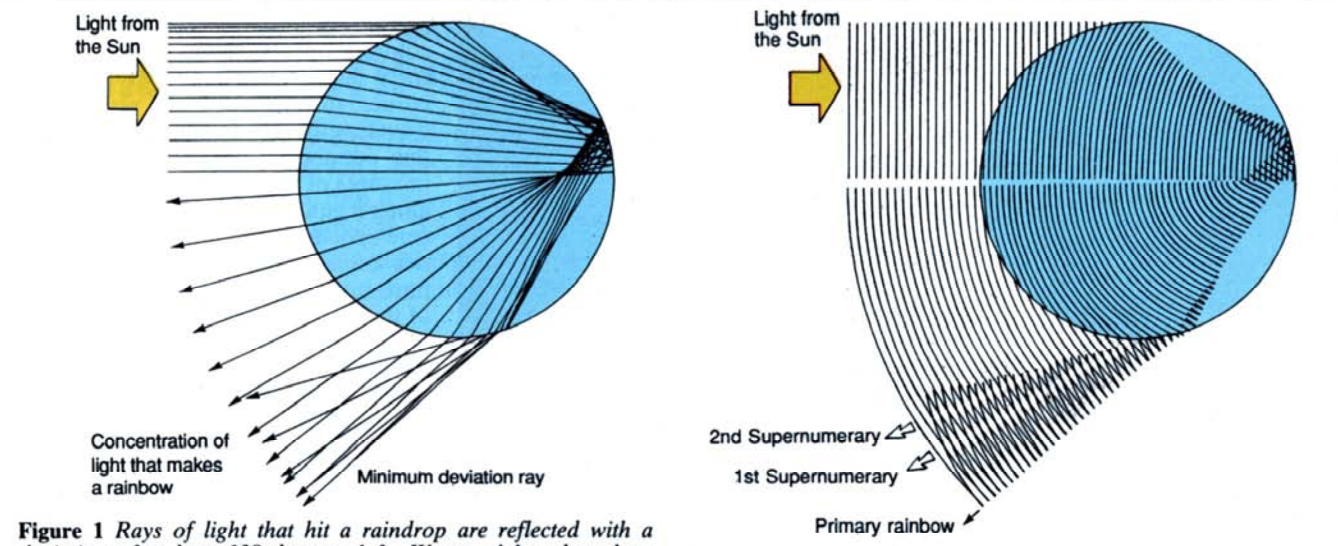

Figure 1 *Rays of light that hit a raindrop are reflected with a deviation of at least 138 degrees,* left. *Waves,* right, *show how interference makes several bows and the dark bands between them*

to explain beautifully that which does not occur, and to leave unexplained that which does."

Basically, a rainbow is an image of the Sun distorted by falling raindrops. To explain how a rainbow is formed, we need to look in some detail at the way light passes through a raindrop. Imagine a ray of sunlight hitting the centre of a raindrop, at right angles to its surface. Some of this light goes straight through the middle of the drop and some of it is reflected back on itself—in other words, it is deviated by an angle of 180° from its original path. Other rays of sunlight parallel to this one enter the drop nearer to its edge, and therefore at more glancing angles to its surface. The rays are refracted (bent) as they enter the raindrop, then are reflected from its rear surface and refracted again as they emerge into air. But these rays are not scattered evenly at all angles between 0° and 180°: they all fall within 42° of the ray that passes through the middle of the drop—that is, they deviate from their original path by at least 138° (see Figure 1).

The ray that emerges at an angle of 138° from its original path, the minimum deviation ray, is the key to understanding how a rainbow is formed. Because of the optical properties of water, rays that are reflected once inside a spherical raindrop cannot deviate by less than this angle. As a result, the minimum deviation ray has many neighbours leaving the drop at nearly the same angle. It is this concentration of rays, all deflected by 138°, that forms the rainbow.

But why should the bow be a circular arc? Imagine that you are standing with the Sun behind you, looking up at a rainbow.

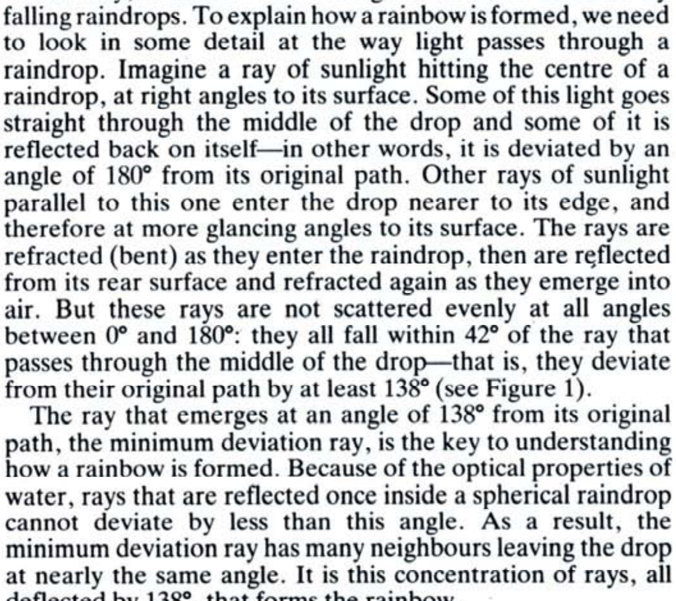

Figure 2 *Rainbow light is reflected from raindrops at an angle of about 138 degrees to the Sun's rays, making a cone of light converging on the observer at around 42 degrees*

You are looking along the surface of an imaginary 42° cone: as raindrops fall, they lie for an instant on the cone, and the rainbow that you see is a mosaic of minimum deviation rays from all these drops (see Figure 2). Only drops on the cone can send you the rainbow light. For the bow to last more than an instant the drops must fall continuously.

And because the edge of a shower of rain can pass quickly across the position where the rainbow might form, the bow can appear or disappear rapidly. As long as you see sunlit drops at the correct angle, the rainbow will be with you. However, if any part of the circle where the rainbow can form lacks either drops or direct sunlight, then that part of the bow will not exist. This accounts for the fragments of rainbows we often see.

Because of the fixed relationship between the rainbow and the Sun, we cannot see a rainbow in a distant shower if the Sun is higher than 42° above the horizon (assuming that we are on level ground). Conversely, as Constable noted, we can see more of the arc of a rainbow when the Sun is lower in the sky. Because the larger segments of a rainbow arc are more visually impressive, people are more likely to notice rainbows that occur late or early in the day.

The rainbow's colours arise because the minimum deviation ray is at a slightly different angle for each colour. At the minimum deviation, a ray of blue light is bent through about 139°, and red through 138°, so red will be on the outside of the rainbow, closest to the Sun, and blue will be towards the inside. In between the two, there will be a continuous spread of colours, depending on the minimum deviation of different wavelengths of light. The familiar sequence, red, orange, yellow, green, blue, indigo, violet, suggests the hierarchy. But not all of these may be clear in a particular rainbow, and colours may vary along the bow itself.

We can explain this variability in a quite straightforward way by treating light as a wave. Light waves interfere in a fashion similar to waves in water. If you drop two stones into a pool, the expanding rings of waves will intersect. Where the wave crests coincide, they reinforce each other to produce a larger wave than either of the originals. Alternatively, if a wave crest of one ring is combined with a trough from the other, they cancel out and the water stays level. Although light waves are electromagnetic, not mechanical, and oscillate much faster than water waves, the interference analogy holds on the scale of small raindrops. Cancellation of light produces darkness and reinforcement yields more intense light than in the original

Lee & Fraser

Figure 3a *A partial primary rainbow in the skies of Pennsylvania;* **3b** *Brighter and more vivid rainbow colours from Seattle*

source. An interference pattern of dark and light bands results, and the separated colours in the first bright band form the main, or primary, rainbow. But the interference pattern also forms extra, or supernumerary, rainbows with pastel colours that appear within the primary bow. Interference also produces the dark bands that separate the primary and supernumerary bows. The spacing and width of interference bows depends on the size of the raindrops; smaller drops yield broader bows. As a result, the range of sizes of drops in a shower partly determines the intensity and vividness of rainbow colours.

This picture of raindrops concentrating light to form a rainbow shows that a primary rainbow should be brighter than its background, but sometimes, as in Figure 3a, this distinction is not clear. Several factors can cause this: a background whose brightness is not uniform, clouds or haze that partially obscure the Sun, or a thin band of rain. In each case, the dullness of the primary bow compared with its background means that an observer notices the rainbow's pattern of colours, rather than its brightness. For the supernumerary bows, even the coloured patterns will be invisible if the contrast between them and their background is quite low. One consequence is that if any of the bows are dim, then their colours will be pastel. But how much brighter and purer are the rainbow colours in a bright bow, such as the one in Figure 3b, compared with a pastel one? How can we quantify "all the colours of the rainbow"?

Thus far, we have used terms like "brightness," "colour," and "vividness" only qualitatively. Because researchers cannot yet describe colour in a purely neurological, quantitative way, visual perception remains intrinsically subjective. Instead, we assume that if we quantify the responses of individuals to light of known physical properties, then we have objectively measured their subjective colour experience. Not surprisingly, we can choose among many different methods of measuring colour, collectively known as colorimetry, to describe the rainbow. Although no single system is universally accepted, one used widely in science and industry, developed by the Commission Internationale de l'Eclairage (CIE), is especially useful since it relates light spectra and colour perception mathematically.

Figure 4 illustrates a recent CIE colorimetric standard, the 1976 uniform chromaticity scale diagram (UCS). Think of this as a colour wheel that has been reshaped to accommodate the way people see colours. Pure colours lie on the border of the diagram, and less pure, less vivid, colours are inside it. The curved border represents the monochromatic colours, each made by one wavelength of light. These are known as spectrum colours in colorimetry, and range from the blues with short wavelengths at the bottom corner, through greens to reds with long wavelengths at the upper right. A straight line connects these two extremes, and mixtures of monochromatic red and blue along it generate purples. Purples are not true spectrum colours, because they are not monochromatic, but they are the purest possible colours that link the ends of the visible spectrum. One point in the interior of this diagram is a white, and is known as an achromatic stimulus. We can form any other colour in the interior of the diagram by mixing a specific amount of this achromatic stimulus with a spectrum colour (or a purple). Pick the spectrum colour by drawing a straight line that connects the achromatic stimulus, the colour of interest, and the curved edge of the diagram. The resulting spectrum colour defines the dominant wavelength of the arbitrary colour. Also, the position of the arbitrary colour, between white and its spectrum colour, expressed as a fraction, gives a mathematical definition of its purity. A spectrum colour has a purity of 100 per cent, while white's purity is 0 per cent. So this quantifies the descriptive terms "hue" or ("colour") and "vividness" as dominant wavelength and purity, respectively.

The colour diagram sits within a rectangular coordinate system. The coordinates u' and v' come from experiments in which people matched the colours of test lights by mixing red, green and blue reference lights in varying intensities. Roughly speaking, the u' coordinate represents the balance between green and red in a colour, and v' indicates the relative amount of blue. In order to convey a sense of what these numbers mean, we have calculated and displayed the colours that fill the interior of the UCS diagram (Figure 4). We produced the diagram without markedly varying brightness, the remaining attribute of colour sensation, but the plot turned out to show three bright spokes radiating from the white point, the achromatic stimulus. The CIE quantifies brightness by psychophysical experiments similar to those for colour matching (the CIE further distinguishes between the brightness of objects that emit light and the relative lightness of objects that reflect light). Ironically, the three bright spokes in Figure 4 nicely illustrate a visual idiosyncrasy that the UCS diagram was not meant to display. In fact, the spokes are artefacts of the way that our visual systems enhance contrast. You can demonstrate that the bright lines are not real by covering one side of a spoke with a piece of paper; the apparent contrast between the ▶

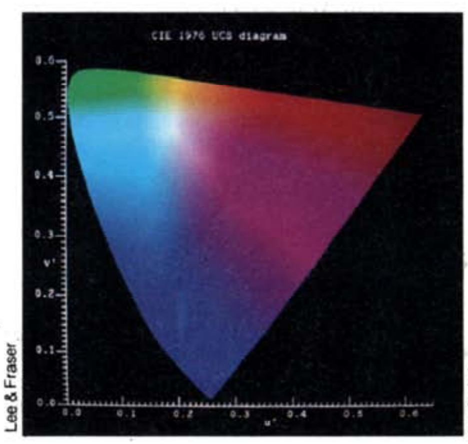

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Figure 4 *All the colours in the CIE 1976 UCS diagram*

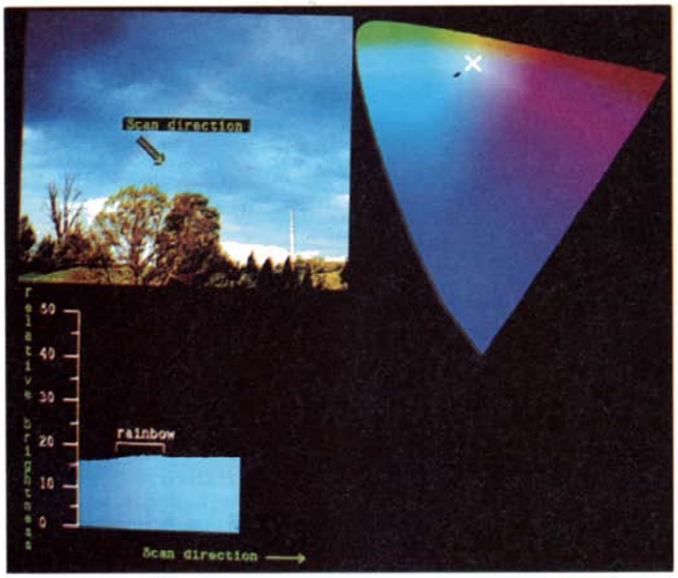

Figure 5 *Little variation in colour or brightness came from the rainbow of Figure 3a, in a scan across a radius*

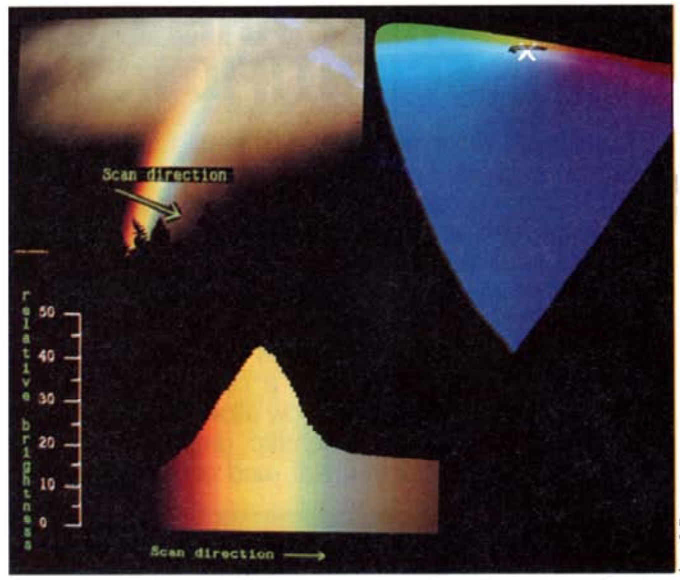

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Figure 6 *This rainbow, from figure 3b, is distinctly brighter than its background, but analysis reveals a modest range of colours*

► spoke and its surroundings disappears. Far from being mere curiosities, these illusory spokes hint that visually complicated images like the rainbow may offer some surprises.

An important step in describing the colours of the rainbow is defining the term "white". We call sunlight white, even through it is not spectrally uniform, that is, it does not contain equal amounts of all colours. As the Sun's elevation changes during the day, the spectrum of direct sunlight also changes. If the Sun is more than, say, 30° above the horizon, most of us would readily call the illumination white. As the Sun sets, its spectrum is increasingly dominated by longer wavelengths and sunlight appears redder. Yet most people would maintain that sunlight is white until the Sun is only a few degrees above the horizon. This is called colour constancy. We need to consider the colour constancy of sunlight as we analyse rainbows.

We analysed the rainbow colours of Figure 3 by digitising the original slides and slides of a card containing many different samples of colours. If the same spectrum of sunlight generates the rainbow and illuminates the colour card, we can use the composition of colours on the card to quantify the unknown colours of the rainbow. Figures 5 and 6 show some typical results. In these Figures, we sample colours along a radius to the bow, and draw a black line through the resulting chromaticities on a 1976 UCS diagram. At the bottom of the Figures, we use a coloured bar graph to show how rainbow brightness changes with radius.

The time and location of Figures 3a and 3b specify the elevation of the Sun, which in turn lets us estimate its spectrum. We simulate colour constancy in Figures 5 and 6 by making the achromatic stimulus, the perceived white on the diagram, coincide with the spot that matches the colour of the sunlight; we mark this site with an "x". Because the Sun was lower in Figure 3b than in Figure 3a, this point moves toward red in Figure 6. Although the changing colour of the sunlight shifts the rainbow's objectively measured colours, people tend to see them as the same, at least until the Sun is quite close to the horizon. However, colour constancy does not change the fact that there are fewer distinct yellows, oranges, and reds near sunset and sunrise.

This method of colour analysis springs some surprises. The rainbow chromaticities in Figure 5 span so little of the UCS diagram that the bow scarcely exists, yet we photographed this rainbow because it was easy to see, not because it seemed especially pastel. On the brightness scale, the bow hardly differs from its background, probably a result of hazy sunlight or a thin shower of rain. Because the brightness of the rainbow is so low, mixing its colours with the bluish background of clouds makes the bow a sequence of blues modulated only slightly by red and yellow. The rainbow has purities lying between 14 per cent and 18 per cent, a range of only 4 per cent. Most of this colour purity is due to the clouds; the bow's colour contrast with its background is quite small. Since bows like this are not uncommon, the rainbow begins to seem a rather sorry colour standard.

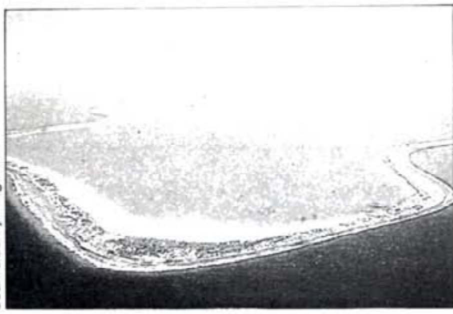
The rainbow in Figure 3b looks like a better example of "all the colours of the rainbow". Its colours seem both bright and pure. Our analysis in Figure 6 supports this hunch, but not as well as we might imagine. Certainly this splendid rainbow is markedly brighter than its background, and its spread of colours is appreciably larger than that in Figure 3a. Colour purities vary between 7 per cent and 51 per cent, a range of 44 per cent, giving a much larger spread than the other bow. Nonetheless, even this quite vivid rainbow spans only a small fraction of the range of colours that we perceive, and only the yellows of the bow are especially pure.

These results do not mean that we must discard the old saw about the rainbow. Although the maximum purities in even the most spectacular rainbows are well under 100 per cent, we need to remember how we defined this maximum purity. Monochromatic light sources are all but absent from the environment in which we have evolved. While we can see light of 100 per cent purity, we almost never find it in nature. Of all the atmospheric colours, only the Sun's reddened disc exceeds the rainbow's purity: the purity of the best blue sky is only about 40 per cent. Among celestial displays, spectacular rainbows provide the best range of reasonably pure hues. Although "all the colours of the rainbow" only hint at the range of our colour vision, they do sometimes offer a splendid natural colour catalogue. □

Raymond Lee is a postdoctoral researcher in the meteorology department at Pennsylvania State University, looking at the colours of daylight, the rainbow, and icebergs. **Alistair Fraser** is professor of meteorology at Pennsylvania State University. He and Raymond Lee are writing a book about the science, mythology and art of the rainbow for Penn State Press.

Further reading *Rainbows, Halos and Glories* by R. Greenler, Cambridge University Press, 1980; *Clouds in a Glass of Beer: Simple Experiments in Atmospheric Physics* by C. F. Bohren, John Wiley and Sons, 1987; *The Nature of Light and Colour in the Open Air* by M. Minnaert, Dover Publications, 1954.

CONTENTS

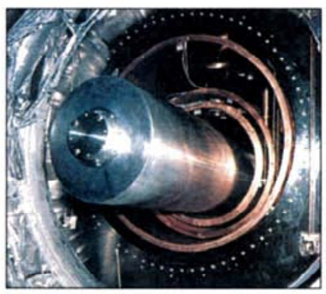


Jean Gaumy/Magnum

Atomic atoll: leaks may be spreading into the sea off Mururoa, p 12

Janet Bell/SPL

Crystal gazing: nanotechnology transforms the possibilities for engineers, p 53



CERN

Gravity's telescope: new signals from space, in the shape of gravitational waves, could increase astronomers' understanding of the Universe, p 30

Victoria & Albert Museum

Over the rainbow: how do we see colours? p 40

This week's cover *by Tim Malyon*

NEXT WEEK

The best of British rubbish

Britain aims to recycle half of what can be recovered from our domestic waste by the end of the century. To do this we shall need some clever technology.

So you want to work in Japan?

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Zimbabwe's wildlife farms

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