Color in nature

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When the sun shines onto the rain-darkened sky, nature's beautiful secret is revealed. In the arch that curves from the earth to the heavens we can read the origin of colors. Sunlight seems to 'take on' the color of anything it bounces off—a red rose or a green leaf—because all of these colors are already within the light, waiting to be sifted by an encounter with the tangible world. In the rainbow, raindrops do the sifting systematically, each band progressing through the visible spectrum from red to violet.

When Isaac Newton showed how this happened in the seventeenth century, he seemed to have solved at last the question that had puzzled and frustrated philosophers for centuries: what exactly is color? Yet Newton's answer was not the last word. Indeed, for some people it simply raised more questions. Painters struggled to understand what Newton's theory of light and color meant for the way they should apply their paints. The German Romantic philosopher Wolfgang von Goethe decided Newton's ideas were nonsense, and many were ready to agree with him. Even today it would be unwise to conclude that we fully understand color.

What did Newton say that created so much confusion and controversy? And why didn't his theory, brilliant though it was, tell the whole story? Why is color so hard to pin down?

Newton is often credited with 'explaining' (in John Keats' derogatory phrase, 'unweaving') the rainbow. But that is not quite what he did. Philosophers had known for centuries that light passing through glass, transparent minerals or water can generate a multitude of colors. The ancient Greeks speculated that rainbows are caused by sunbeams falling onto clouds, and in 1637 the French philosopher René Descartes showed that sunlight becomes focused into a circular arc when it bounces off raindrops.

It was Newton, however, who brought color to Descartes' rainbow. In1665 he split sunlight into the many-hued spectrum by passing it through a prism in a darkened room. He found that the individual colors could not be split further by a second prism. And if all the spectral colors were brought back together using a lens, they merged into a beam of white light. Newton deduced that the rays of different colors were being bent through different angles by the prism—and that the same thing happens in rainbows, where each raindrop acts like a tiny prism.

Newton decided that there were seven strands to this bow: red, orange, yellow, green, blue, indigo and violet. Schoolchildren are still taught the seven Newtonian colors, but in fact they are rather arbitrary: Newton's mystical thinking led him to imagine that the colors of the rainbow must mirror the seven notes of the musical scale. Most later color theorists chose to replace indigo and violet with just a single hue: purple or violet.

Color comes from plucking this rainbow. Objects absorb some of the colors, and reflect the rest. We see only the reflected rays, which determine the color we perceive. A red berry extracts green and blue from white sunlight; a yellow flower absorbs blue and red.

If color is just light, then what is light? Newton had a theory for this too, but it was not until another two centuries passed that the Scottish physicist James Clerk Maxwell gave us the modern answer. Light is a vibrating field of electrical and magnetic energy: an electromagnetic field, which can pass through empty space like a wave travelling across the sea. The frequency of the vibrations determines the color of the light: it gets progressively higher from the red to the violet end of the spectrum, while the wavelength gets steadily shorter.

Substances absorb light of a particular frequency because their clouds of electrons—the subatomic particles that bind one atom to another—have vibrations that resonate at the same frequency, like a guitar string humming in sympathy with a note sung loudly. These resonant frequencies depend on the chemical composition of the substance: which atoms it contains, and how they are joined together.

The pigments in flowers, animal skins and paintings derive their colors by absorbing light. But not all color is generated this way. The rainbow's variegated arc is not the result of light absorption by the raindrops, but of refraction: reflection of rays of different wavelengths at differing angles. This is an example of light ‘scattering’. The sky is blue because blue light is scattered by molecules and dust in the atmosphere more strongly than red light: the blue rays from the sun bounce towards our eyes from all directions. Distant hills are blue-tinted for the same reason: the light reflected from the hills is augmented by blue from the atmosphere before reaching our eyes.

Some animal and plant colors are caused by light scattering. The blues on butterfly wings, for example, are produced by the microscopically ribbed surface of the tiny wing scales, the ridges spaced at just the right separation to reflect blue light but not red. The color of this scattered light can vary depending on which angle you view it from, giving rise to the iridescence of insect cuticle and the shimmering colors of a peacock's tail.

Artists and technologists interested in making colors have long recognized that there are two basic types of colored materials: those that come from the geological earth and those that come from the living world. The colored materials are respectively classed as inorganic (‘non-living’) and organic. When chemists today speak of ‘organic’ substances, however, they don’t necessarily mean ones that originated in living organisms. Rather, they mean materials whose building blocks are carbon-based molecules. Many organic materials today are synthetic, made using industrial chemical techniques from the carbon compounds in crude oil, alcohol and other raw sources.

Traditionally, inorganic materials furnished pigments whereas organic materials provided dyes. The colors of dyes would usually fade when exposed to sunlight, because light breaks down the delicate light-absorbing carbon molecules.

Brightly colored inorganic substances usually contain metal elements. Some metals are apt to lend particular colors to their compounds: copper minerals are often green or blue, iron minerals red or yellow, cobalt minerals deep blue. Chromium is something of a chameleon, offering colors ranging from bright yellow to deep green and rich red. Its very name comes from the Greek word for color.

While rose quartz acquires its color from impurities of titanium or manganese, no such metals tint the rose itself: flowers and other living organisms are colored by organic compounds. Tyrian purple, the famous imperial dye of ancient Rome, was squeezed from shellfish; blue indigo was the frothy extract of a weed.

Nature owes its verdancy to chlorophyll, an organic molecule studded with a magnesium atom which imbibes the red and blue of the sun's rays. Chlorophyll channels this energy into the metabolic processes of plant cells. The light-absorbing heart of the hemoglobin in our blood is similar to that of chlorophyll, except that iron in all its ruddiness substitutes for magnesium. No longer do John Donne's words reflect our state of ignorance: ‘Why grass is green, or why our blood is red/Are mysteries which none have reach'd into.’

Why roses are red and daffodils yellow is a question of the same order. The yellows, oranges and reds of many flowers, as well as of carrots, tomatoes and sweetcorn, are produced by substances called carotenoids. These so-called auxiliary pigments broaden the light-absorbing abilities of leaves, though their presence is usually masked by the strong absorption from chlorophyll. When in autumn the chlorophyll decays as the leaf dies, the golden colors of the auxiliary pigments shine through.

In his book *Opticks*, where Isaac Newton set out his theory of color in 1704, he did a curious thing. He bent the spectrum into a circle, marrying up red against violet so that the progression between all the colors became continuous. Newton invented the ‘color wheel’.

This prismatic mandala organizes color into a pleasingly symmetrical pattern. Subsequent color theorists made the wheel even more symmetrical by cutting it up into six equal slices: red, orange, yellow, green, blue and violet.

The color wheel has come along way since then. Its modern incarnation is less pleasing to the eye but a lot more infomative: a figure drawn up by the Commission Internationale de l'Eclairage (CIE), called the CIE chromaticity diagram. The ‘pure’ colors of Newton's spectrum lie around the tongue-shaped edge, while the colors inside it are made by mixing these spectral rays. The artificiality of uniting red and violet in the color wheel is emphasized by the flat base of the tongue. Along here the purples and magentas are not found in even the finest unweaving of the rainbow's strands.

Yet even the CIE diagram doesn't encompass all colors. There is no brown, for instance, nor gray or pink. There is a lot more ‘color space’ than any single color wheel can accommodate. Brown and gray don't feature on the CIE diagram because it doesn't show the colors produced by variations in brightness: gray is a ‘dim’ white, while brown is a ‘dim’ yellow or orange. To map out all of color space we really need a whole stack of CIE diagrams in which the white centre gets progressively greyer.

One of the first cartographers of this three-dimensional color space was the American artist and teacher Albert Munsell. His color maps, developed over about 30 years from the early 1900s, plot colors in discrete steps as a series of ‘tiles’. Schemes like Munsell’s provide us with the color charts familiar from the catalogues of paint companies.

In truth, of course, colors merge smoothly in color space, like the evening sky shifting from fire orange to cobalt blue. All the same, we tend to pick out kingdoms and label them ‘red’, ‘blue’ and so forth. How many kingdoms are there? Newton claimed that there were seven colors in the rainbow, from which all others were made. But by the seventeenth century, painters had decided that they could manage with just three: red, yellow and blue, as well as black and white to lighten and darken them. These three were considered the ‘primary’ colors. Mixtures of each pair give us the three ‘secondaries’ that fill in the rest of the spectrum: orange, green and violet.

Painters’ experience with mixing colors seemed at odds with what Newton claimed. Red, yellow and blue paints mix to a murky brown, whereas Newton claimed that the entire rainbow of hues mixes to give white. This apparent inconsistency offered plentiful ammunition to Newton's detractors, like Goethe. Any fool could see that no mixture of pigments gave one pure white, or anything like it.

The physicist James Clerk Maxwell dispelled the confusion in 1855, when he showed that three kinds of light (as opposed to pigments) suffice to generate almost any color: orange-red,blue-violet and green (a triad that is usually denoted simply as red, blue and green.) Mixing light, Maxwell explained, is not the same as mixing pigments. By blending light rays of different wavelengths, one is synthesizing color by adding various components. This is called additive mixing, and it is how television screens make color. A blend of pigments, on the other hand, subtracts wavelengths from white light. A red pigment plucks out the blue and green rays, and much of the yellows; only red light is reflected. A yellow pigment might take out the reds, blues, and much of the greens. So a mixture of red and yellow reflects only those rays in the narrow range where the absorption of both materials is not too strong—in the orange part of the spectrum. Each time a pigment is added to a mixture, another chunk of the spectrum is subtracted from the reflected light. As a result, the color gets muddier. Making colors by mixing pigments is called subtractive mixing.

Goethe may have been unfair to Newton, but he was right to stress that color is not about light alone. There is also the matter of how we perceive it—and this is the trickiest business of all. Maxwell agreed: "The science of colour must be regarded as essentially a mental science", he averred.

In 1801 the English scientist Thomas Young proposed a theory of color vision based on the primary colors. He assumed that the retina—the part of the eye that light stimulates—contains light-sensitive ‘particles’ that respond to the rays by vibrating in resonance. These vibrations, said Young, create a signal that is dispatched along the optic nerve to the brain. Young suggested that just three types of ‘particle’, each sensitive to one of the three primary colors, were enough to enable us to perceive a full range of colors. People who are color-blind, said Young, lack one type of light receptors.

Young’s ‘particles’ can now be identified with light-sensitive cells in the retina of our eye. We now know that these cells are distinguished by another feature too: their shape, which is either rodlike or conelike. There are 120 million rods and five million cones in each human retina.

Rods and cones stimulate nerve signals when they are struck by light. Experiments in the 1960s confirmed Young’s hypothesis by showing that cone cells come in three varieties with different color sensitivity. Some respond most strongly to yellow light, some to green and some to violet. The three types of cone are often, and somewhat misleadingly, equated with Maxwell’s additive primaries of red, green and blue. It is better to denote them as responsive to, respectively, long (L), medium (M) and short (S) wavelengths of visible light.

Together these three types of cone cell allow us to perceive all colors. A mixture of red and green rays, for example, can stimulate the L and M cone cells in the same ratio (about 70:30) as does pure yellow light—and so the color sensation is identical in both cases. This is why additive mixing of red and green makes yellow.

The overall sensitivity of the eye to any particular color is the sum of the responses for all three types of cone. The neural signal increases steadily from red to yellow and then declines from yellow to violet. So yellow is perceived as the brightest color. Curiously, yellow is regarded in many cultures as the least attractive color, and its metaphorical and symbolic associations are often derogatory. The S cones are the least sensitive of the three, which is why fully saturated blue looks relatively dark.

Rod cells, in contrast, send out an identical neural response regardless of the wavelength of light they absorb. So all rods are good for is distinguishing light from dark. They are extremely sensitive, and are the main light receptors we use in very dim illumination, such as starlight. Because they don't encode any information about wavelength, we find it hard to identify colors in such conditions. But as rods absorb blue-green light more strongly than other colors, objects that reflect these colors (such as leaves) appear brighter than red objects at night.

Many animals have better color vision than we do. Several types of birds and fish have four types of color-sensitive cone cells, giving them greater sophistication in distinguishing colors. Bees, like us, have three color sensors in their eyes, but their sensitivities are shifted to shorter wavelengths relative to ours - so bees can see in the ultraviolet. They use their color vision to search for nectar and can distinguish flower colors invisible to us. Many birds see in the ultraviolet too. Some may use this ability to find a mate or fruits that reflect UV light. Kestrels may track voles by homing in on their urine trails, which absorb UV light strongly and so are visible to the birds as dark streaks. At the other end of the spectrum, the night vision of owls may extend into the infrared.

Color vision helps animals to find their way in the world. Two objects of different color but similar overall brightness can't be easily distinguished without color clues: it could be hard to make sense of a sports game watched on an old black and white television if one team wore red and the other green. To tell colors apart, we need at least two different types of cone cell. And indeed most mammals possess only this minimal kind of color discrimination, which relies on cones sensitive to violet and yellow-green light.

Between 30 and 35 million years ago, however, our primate ancestors began to develop the three-color (trichromatic) color sensitivity that humans, apes, and Old World monkeys possess today. Our M and L cones differ only slightly in their wavelength sensitivity, leading scientists to conclude that both arose from the mutation into two forms of a single gene that encodes the light-sensitive protein (photopigment) of the primitive yellow-green cone cell. Curiously, the first monkeys to reach South America (presumably on rafting islands of vegetation) did not acquire these two different forms of the gene. As a result, the history of color vision in New World primates is dramatically different. Most New World monkeys have two-color (dichromatic) vision, although the existence of two forms of the gene for the medium-wavelength photopigment, which sits on the X chromosome, renders a high proportion of females trichromatic. (With two X chromosomes, they are likely to acquire both forms of the photopigment, with differing sensitivities.) The owl monkey, meanwhile, gets by with just a single kind of photopigment – it lacks S cones. This is not a disadvantage, however, because owl monkeys are nocturnal, and the ability to distinguish colors is of little help at night. Thus the monkeys have ditched the S cones in adapting to night life.

The difference between two- and three-color vision is significant. In a forest of dappled light, primates with dichromatic vision can't see much visual difference between mature green leaves (which are rarely eaten) and the ripe, pulpy orange and yellow fruits of rain forests, such as bananas. In contrast, the peak sensitivities of the three cones in the trichromatic system are perfectly placed to provide good visual discrimination between these colors, helping monkeys find their food. This would explain why the peaks are not spread out more evenly across the spectrum: that might give us smoother color vision overall but would make it harder to distinguish colors in the orange-yellow-green range - distinctions crucial to our hungry tree-dwelling ancestors.

Some researchers think that linking primate color vision to fruit-eating doesn't explain everything, however. Primates also eat leaves, nuts, insects and other prey. Since young, succulent leaves in rain forests are often red, folivory may have provided another impetus for color vision to evolve as it did, providing us with a clear red-green distinction. The New World howler monkey, which has a notably folivorous diet, has evolved trichromaticity independently of Old World primates. Dichromatic humans, who lack L or M cones, are unable to experience the lush diversity of hues in fall leaves.

Yet at least to some degree you could say that when we visit art galleries with a visual apparatus fine-tuned to locating bananas. Perhaps Andy Warhol was on to something.

Boxes

Blue

Julius Caesar's legions were awed by the fierce blue warriors who resisted the Roman conquest of Britain. 'All Britons dye themselves with woad which makes them blue', Caesar recorded, 'so that in battle their appearance is more terrible.'

Woad was extracted from the plant *Isatis tinctoria*, which grew throughout Europe and Asia. The blue colorant is chemically identical to indigo, a dye made from plants of the *Indigofera* family. Indigo plants were cultivated in Asia, and the Romans themselves imported the dye from the East for painting the parade shields of their armies.

Indigo was traded as hard, brick-like lumps of the dried dye, and the Roman writer Pliny in the first century AD did not even realise that it came from a plant: he called it a 'silt that forms in frothy water and attaches itself to reeds.'

Manufacturing indigo and woad was indeed a frothy business. The blue dye was extracted by letting the plants ferment and scraping off the colored foam that rises to the surface of the vat. It is not a nice process: an ancient recipe tells how the plants must be soaked in urine under the heat of the sun and trampled daily. The fermenting urine gives off ammonia gas, one of the first noxious industrial emissions. Practices like this meant that ancient dyemakers were often shunned and banished to the outer reaches of town.

The plants themselves were scarcely more benign. The woad plant robs the soil of nutrients, forcing medieval woad growers to keep moving to find fresh land. They left infertile wasteland in their wake, and the devastation became so bad that laws were passed in medieval Europe to curb it.

Red

The Philosopher's Stone is red. That, at least, was what alchemists believed: 'Red is last in the work of Alkimy', said the alchemist Norton of Bristol in the fifteenth century. To make the Stone, which could transform base metals like lead into gold, you had to guide the raw ingredients through a series of color changes that ended in red.

But what was this mythical substance, sometimes called the Red King? Medieval alchemists experimented with a range of red-colored substances, among them the precious pigment known as vermilion. This is a compound of sulphur and mercury, and was probably first made by ancient Chinese alchemists.

Islamic alchemists of the eighth and ninth century had the notion that all metals were mixtures of especially pure forms of sulphur and mercury. So making gold from lead was simply a matter of adjusting the balance. This made vermilion of great interest. A natural, mineral form of mercury sulphide, called cinnabar, is listed in some Chinese recipes for making the Stone.

The Anglo-Irish chemist Robert Boyle was an avid alchemist, and he believed shortly before his death that he had found how to make a rudimentary form of the Stone, a 'red earth' that probably contained mercury. Isaac Newton obtained some of Boyle's mysterious red powder and experimented on it. Shortly afterwards, Newton had some kind of mental breakdown, and his sickness may have been caused by mercury poisoning: high levels of this toxic metal have been found in preserved samples of Newton's hair.

Brown

Brown may be the least glamorous of all colors. It is the hue of mud and grime, and the murky result we get from mixing all the colors on the palette. It is the color of decay, for what is soil after all but rotted vegetable matter? Fall leaves are still beautiful when red and golden, but we lose interest when they become brown.

Some languages don't even deign to give brown an unambiguous name. Translated into French, it is usually rendered as *brun*. But *brun* can also imply simply 'dark' (when referring to a hair color, for instance), while the French would always designate some brown objects as *marron* or *beige*, never *brun*.

You can scan the visible spectrum in vain for brown: it is not there. The Impressionist painters decided that brown was antithetical to their prismatic technique, and several of them banished brown from their palette. When Monet wanted a brown, he typically mixed it from primary colours rather than using the traditional 'earth' pigments like sienna and umber.

Although brown can be made by mixing primary colors, it can also be made from yellow alone. When yellow light becomes very dim—for example, if a surface absorbs most light but reflects a little yellow—we perceive it as brown. Green shares this peculiarity: when dim, it seems to change color, becoming olive. Blues, purples and reds, on the other hand, retain their principal hue much more clearly: most people will still call dark blue 'blue'.

Yellow

Can yellow be trusted? Traditionally it is the least popular of colors: fashion designers tend to avoid it, since few people think they look good in yellow. Yellow eyes are a sign of illness, or of devilry, or both: Frankenstein's monster had yellow, watery eyes.

The yellow naval flag once signified sickness on board ship. This highlights too the value of yellow as a danger signal: it is highly visible. The human eye responds most strongly to the yellow part of the spectrum, so that it appears brighter than other colours. Poisonous insects use yellow to warn larger predators not to try eating them; yellow signs warn us of toxic or radioactive hazards.

In the Middle Ages, painters had good reason to be wary of glorious yellow orpiment, for it contained deadly arsenic. 'Beware of soiling your mouth with it', advised the Florentine craftsman Cennino Cennini around 1390. Van Gogh used safer yellows, but he wrought them into sickly, incandescent suns that seem to promise no warmth.

Yellow meant cowardice and treachery, which is why Judas wears a yellow cloak in Giotto's *Betrayal of Christ*. But this was a Western prejudice. In China yellow is a noble colour, and from the seventeenth to the twentieth century only the Ch'ing emperors could wear it.

White

Is white a color at all, or just its absence? We associate white with bleaching, fading, the removal of color. But Isaac Newton showed that white comes from the union of all the spectrum's colors. White light holds all the others within it.

White is a color for people who don't like color. For the French modernist architect Le Corbusier, white restored purity to the decadence of bright color. By applying a coat of whitewash, he said, 'we would perform a moral act: to love purity! We would improve our condition.' The sculpture and architecture of the ancient Greeks was once deemed noble and pure because of its whiteness. (We now know it is like this simply because the paint has fallen off.)

Le Corbusier crusaded for whiteness to suppress 'the distracting din of colors'. He is not alone; many a minimalist modern interior rejoices in the order and control that white is deemed to produce. The Dutch painter Theo van Doesburg, a colleague of Piet Mondrian, celebrated white as 'the color of modern times, the color which dissipates a whole era.' Mondrian himself filled his black grids with squares of mostly white, and the Russian painter Kasimir Malevich went further, painting white squares on white backgrounds in his 'Suprematist' works. White, he said, is the ultimate colour, the 'true, real conception of infinity.'

It seems we agree, for the pigment produced commercially in by far the greatest quantities is titanium white. It blanches everything we make, from window frames to office interiors and motor cars.