BRIGHT EARTH

THE INVENTION OF COLOUR

PHILIP BALL

'BRILLIANT...IN EVERY SENSE'
GUARDIAN

VINTAGE

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Bright Earth

The Invention of Colour

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Preface

For the past two years I have been learning to speak a new language. Or rather, not so much to speak it as to think it, for painterly colour is a language that words struggle to convey. Here, for example, is German art critic Lorenz Dittmann on Jean-François Millet's *The Gleaners* (1857):

> The unusually restrained colours . . . follow a closely-stepped sequence: reddish tones in the central figure, based around copper-reddish, brownish and bright carmine; delicate nuances of colourful greys in the standing figure to the right: silvery bright blue-grey, dove-grey, blue and turquoise greys . . . the barely definable, shimmering brownish tone of the field in the middle distance takes on a slender pink-violet tone against the grey-scale of the figure at the back, which is echoed again in the slightly darkened foreground.

Do you see the image? Of course not, although the words begin to paint a picture of their own. Colour, like music, takes a short cut to our senses and our emotions. The Church understood this in the Middle Ages; so have the greatest painters, as well as propagandists, advertisers and designers. No wonder philosophers and linguists so love to debate colour – it tempts, teases and eludes them, at the same time as it promises wonders and deep secrets.

Well then, where does one start to learn this language? I am quite sure that there is no best answer. I have approached it through the *substance* of colour; and if that is partly because I have trained as a chemist, it is also because I relish paint and pigments as materials, with appearances, smells, textures and names that entice and intoxicate. Here is one language of colour that I can interpret already: phthalocyanine speaks to me of chlorophyll and blood, vermilion conjures up the sulphur and mercury of the alchemists. Yet the

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painter's use of colour has not only its unique chemistry but also its historical traditions, its psychology, its prejudices, its religiosity and mysticism.

I imagine that, were I ever to acquire fluency in a foreign language, I would, on entering the country in which it is spoken, experience something of what I felt after revisiting the National Gallery several months into this project. Through the agency of colour I could begin to understand, or at least to catch fragments of, what was being said on the walls all around. Where before there were two-dimensional images in gilded frames, there was now a living world. Each picture seemed as though it had just left the artist's workshop or studio, the paint's transition from palette to panel or canvas visible in the brush-marks. Of course, time too has left its mark: paintings often need more decoding than the artist intended, as greens darken to black and reds fade to pink. In the end, the language of colour is really about learning to see.

I have been deeply fortunate to benefit, in this learning process, from the advice of people who have far greater fluency in the language of colour than I shall ever attain. My thanks go to Tom Learner at the Tate Gallery, Jo Kirby at the National Gallery, John Gage at the University of Cambridge, Martin Kemp at the University of Oxford, Helen Skelton and David Lewis at the University of Leeds, and most of all to Joyce Townsend at the Tate, who not only helped with materials and information but read the entire draft manuscript diligently. I am indebted to the Royal College of Art for the use of its splendid Colour Reference Library, and to my editors Andrew Kidd and John Glusman for helping the book find its shape. The sustaining interest and enthusiasm of many friends and colleagues are, of course, the nutrition that every writer needs, and can never adequately acknowledge.

Philip Ball
London, 2001

Note: I have often used the masculine third person to denote a generic painter until the twentieth century. This is simply an attempt to be consistent with the historical record: female painters were

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usually such rare exceptions that 'his or her' would jar with the context. We can deplore the inequities of earlier ages without trying to deny them. But, as Plate 4.2 shows, some women were able to become painters even in the most chauvinistic of times.

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1. The Eye of the Beholder

THE SCIENTIST IN THE STUDIO

The starting point is the study of colour and its effects on men.

Wassily Kandinsky, *Concerning the Spiritual in Art* (1912)

Then the man in the blue suit reaches into his pocket and takes out a large sheet of paper, which he carefully unfolds and hands to me. It is covered with Picasso's handwriting – less spasmodic, more studied than usual. At first sight, it resembles a poem. Twenty or so verses are assembled in a column, surrounded by broad white margins. Each verse is prolonged with a dash, occasionally a very long one. But it is not a poem; it is Picasso's most recent order for colours . . .

For once, all the anonymous heroes of Picasso's palette trooped forth from the shadows, with Permanent White at their head. Each had distinguished himself in some great battle – the Blue Period, the Rose Period, Cubism, 'Guernica' . . . Each could say: 'I too, I was there . . .' And Picasso, reviewing his old comrades-in-arms, gives to each of them a sweep of his pen, a long dash that seems a fraternal salute: 'Welcome Persian red! Welcome emerald green! Cerulean blue, ivory black, cobalt violet, clear and deep, welcome! Welcome!'

Brassaï, *Conversations avec Picasso* (1964)

'I believe that in future, people will start painting pictures in one single colour, and nothing else but colour.' The French artist Yves Klein said this in 1954, before embarking on a 'monochrome' period in which each work was composed from just a single glorious hue. This adventure culminated in Klein's collaboration with Paris paint retailer Edouard Adam in 1955 to make a new blue paint of

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unnerving vibrancy. In 1957 he launched his manifesto with an exhibition, 'Proclamation of the Blue Epoch', that contained eleven paintings in Klein's new blue.

By saying that Yves Klein's monochrome art was the offspring of chemical technology, I mean something more than that his paint was a modern chemical product. The very *concept* of this art was technologically inspired. Klein did not just want to show us pure colour; he wanted to display the glory of *new* colour, to revel in its materiality. His striking oranges and yellows are synthetic colours, inventions of the twentieth century. Klein's blue was ultramarine, but not the natural, mineral-based ultramarine of the Middle Ages: it was a product of the chemical industry, and Klein and Adam experimented for a year to turn it into a paint with the mesmerizing quality the artist was seeking. By patenting this new colour, Klein was not simply protecting his commercial interests but hallmarking the authenticity of a creative idea. One could say that the patent was a part of his art.

Yves Klein's use of colour became possible only when chemical technology had reached a certain level of maturity. But this was nothing new. For as long as painters have fashioned their visions and dreams into images, they have relied on technical knowledge and skill to supply their materials. With the blossoming of the chemical sciences in the early nineteenth century it became impossible to overlook this fact: chemistry was laid out there on the artist's palette. And the artist rejoiced in it: 'Praise be to the palette for the delights it offers . . . it is itself a "work", more beautiful, indeed, than many a work,' said Wassily Kandinsky in 1913. The Impressionist Camille Pissarro made the point forcefully in his *Palette with a Landscape* (1878), a pastoral scene constructed directly on his palette by pulling down the bright colours dotted around its edges.

The Impressionists and their descendants – van Gogh, Matisse, Gauguin, Kandinsky – explored the new chromatic dimensions opened up by chemistry with a vitality that has arguably not been equalled since. Their audiences were shocked not only by the breaking of the rules – the deviation from 'naturalistic' colouration – but by the sight of colours never before seen on canvas: glowing orange, velvety purples, vibrant new greens. Van Gogh dispatched

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his brother to acquire some of the brightest and most striking of the new pigments available, and wrought them into disturbing compositions whose strident tones are almost painful to behold. Many were dumbfounded or outraged by this new visual language: the conservative French painter Jean-Georges Vibert rebuked the Impressionists for painting 'only with intense colours'.

It was a complaint that echoes back through the ages, to be heard whenever chemistry (or foreign trade, which also broadens a culture's repertoire of materials) has made new or superior colours available to painters. When Titian, Henry James's 'prince of colourists', took advantage of having the first pick of the pigments brought to the thriving ports of Venice to cover his canvases with sumptuous reds, blues, pinks and violets, Michelangelo remarked sniffily that it was a pity the Venetians were not taught to draw better. Pliny bemoaned the influx of bright new pigments from the East that corrupted the austere colouring scheme Rome had inherited from Classical Greece: 'Now India contributes the ooze of her rivers and the blood of dragons and of elephants.'

That the invention and availability of new chemical pigments influenced the use of colour in art is indisputable. As art historian Ernst Gombrich says, the artist 'cannot transcribe what he sees; he can only translate it into the terms of his medium. He, too, is strictly tied to the range of tones which his medium will yield.'[1] So it is surprising that little attention has been given to the matter of how artists obtained their colours, as opposed to how they used them. This neglect of the material aspect of the artist's craft is perhaps a consequence of a cultural tendency in the West to separate inspiration from substance. Art historian John Gage confesses that 'One of the least studied aspects of the history of art is art's tools.' Anthea Callen, a specialist in the techniques of the Impressionists, makes a stronger criticism:

> Ironically, people who write on art frequently overlook the practical side of their craft, often concentrating solely on stylistic, literary or formal qualities in their discussion of painting. As a result, unnecessary errors and misunderstandings have grown up in art history, only to be reiterated by succeeding generations of writers. Any work of art is determined first and

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foremost by the materials available to the artist, and by the artist's ability to manipulate those materials. Thus only when the limitations imposed by artists' materials and social conditions are taken fully into account can aesthetic preoccupations, and the place of art in history, be adequately understood.[2]

One might expect the 'craft' aspects of art to suffer less neglect when the use of colour is under discussion – for surely the nature of materials should then come naturally to the fore? But it is not always so. Faber Birren admits in his classic *History of Color in Painting* that 'the choice of colours for a palette or palettes is not in any way concerned with chemistry, or with permanence, transparency, opacity or any of the *material* aspects of art'. This extraordinary omission of the substantial dimension of colour is surely the precondition for such absurdities as Birren's assigning cobalt blue to the palette of Rubens and his contemporaries, almost two centuries before its invention.[3] In view of the attention that Birren gives to the hues required for a 'balanced palette', it is indeed odd how little concerned he is with whether artists of different eras had access to them.

Paint and the painter

Every painter must confront the question: what is colour *for*? Bridget Riley, one of the modern artists most concerned with colour relationships, has expressed the dilemma very clearly:

> For painters, colour is not only all those things which we all see but also, most extraordinarily, the pigments spread out on the palette, and there, quite uniquely, they are simply and solely colour. This is the first important fact of the painter's art to be grasped. These bright and shining pigments will not, however, continue to lie there on the palette as pristine colours in themselves but will be put to use – for the painter paints a picture, so the use of colour has to be conditioned by this function of picture making . . . The painter has two quite distinct systems of colour to deal with – one provided by nature, the other required by art – perceptual colour and pictorial colour. Both will be present and the painter's work depends upon the emphasis they place first upon the one and then upon the other.[4]

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This is not a contemporary conundrum, but one that has confronted artists of all eras. And yet there is something missing from Riley's formulation of the artist's situation. Pigments are not 'simply and solely colour', but substances with specific properties and attributes, not least amongst them cost. How is your desire for blue affected if you have just paid more for it than for the equivalent weight in gold? That yellow looks glorious, but what if its traces on your fingertips could poison you at your supper table? This orange tempts like distilled sunlight, but how do you know that it will not have faded to dirty brown by next year? What, in short, is your relationship with the materials?

Raw colour supplies more than a physical medium from which artists can construct their images. 'Materials influence form,' said American artist Morris Louis in the 1950s; but 'influence' is too weak a word when we are faced with the explosive vibrancy of Titian's *Bacchus and Ariadne* (1523), Ingres's *Odalisque with a Slave* (1839–40) or Matisse's *Red Studio* (1911). This is art that follows directly from the impact of colour – from possibilities delimited by the prevailing chemical technology.

But although technology made Yves Klein's monochromes possible for the first time, it would be meaningless to suggest that Rubens did not paint them because those colours were not available to him. It is equally absurd to suppose that, but for a technical knowledge of anatomy and perspective and the chemical prowess to extend the range of pigments, the ancient Egyptians would have painted in the style of Titian. Use of colour in art is determined at least as much by the artist's personal inclinations and cultural context as by the materials to hand.

So it would be a mistake to assume that the history of colour in art is an accumulation of possibilities proportional to the accumulation of pigments. Every choice an artist makes is an act of exclusion as well as inclusion. Before we can gain a clear understanding of where technological considerations enter the decision, we must appreciate the social and cultural factors at work on the artist's attitudes. In the end, each artist makes his or her own contract with the colours of the time.

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Leonardo's quest

Ernst Gombrich asserts that 'art is altogether different from science', but the reason he gives will bring a rueful smile to the lips of many a scientist: 'art itself can hardly be said to progress in the way in which science progresses. Each discovery in one direction creates a new difficulty somewhere else.' One can see that Gombrich never dabbled in science.

Exploring the link between art and science is back in fashion; but the debate is dominated by the supposition of cognate ideas and sources of inspiration. Artists of all persuasions today may be found mining the rich seam of association that crystallizes from our genetic inheritance, just as one can draw analogies between relativity and Cubism, between quantum mechanics and the works of Virginia Woolf.

This is all well and good in so far as it speaks of the much-needed cultural assimilation of scientific ideas (albeit commonly in a distorted or half-digested form). But it appears that we are happier in the realm of the intellectual than that of the tangible.

Yet this Cartesian-like division of material and mind has not always reflected the attitude of the practising artist. It is only in the past half-century or so that every conceivable subdivision and admixture of the rainbow has been available in off-the-shelf tubes. Until the eighteenth century, most artists ground and mixed their own pigments, or at least had this process conducted in their studios. The almost sensual pleasure in the material component of colour evinced by medieval craftsmen like the Italian Cennino Cennini demonstrates that artists of his time were on intimate terms with their paints, and possessed some considerable skill as practical chemists.

Moreover, before the Age of Reason the distinction between 'art' and 'science' was not synonymous with that between intuition and rationality. In medieval times, men of science were chroniclers of antique knowledge and theory – a practice that did not necessarily require an inquiring mind. 'Art', on the other hand, implied technical or manual skill, and a chemist was as much an artist as was a painter. The artist was valued not for his imagination, passion or inventiveness, but for his ability to do a workmanlike job.

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This was the world in which Leonardo da Vinci lived and worked. Vladimir Nabokov once said that he would be more interested in C. P. Snow's famous 'Two Cultures' debate if their disjunction did not seem to him more of a ditch than an abyss. Leonardo barely seemed to notice so much as a ditch. The ease with which he passed between his roles as artist, technologist and natural philosopher remains remarkable even when we remember that these distinctions were by no means as rigid during the Renaissance as they are today.

Scholarly circles in Leonardo's fifteenth-century Florence were alive with discussion about the role of reason, geometry and mathematics in art. Leonardo himself was a firm advocate of the need for the artist to imitate nature as exactly as possible, which entailed learning the mathematical rules that governed nature: 'Those who devote themselves to [artistic] practice without science are like sailors who put to sea without a rudder or compass and who can never be certain where they are going.'[5] Yet how readily we see Leonardo's boundary-straddling through modern eyes. In stressing the importance of science in art, Leonardo had an agenda that was very much a product of its time. By emphasizing the role of mathematics, he attempted to elevate the status of painting to a Liberal Art, alongside geometry, music, rhetoric and astronomy. These Arts were those deemed worthy of serious intellectual study at the universities, whereas painting had been regarded since the Middle Ages as a craft, a lowly manual skill. Such activities in the classical past had often been performed by slaves, and painters of Leonardo's time were desperate to throw off this stigma. By arguing for the acceptance of painting as a Liberal Art, they sought to advance their own social standing.

Artists would plead their cause by pointing out that many great men of antiquity had shared their trade, and that kings and (more recently) popes had conferred favour upon them. In his book *Della Pittura* (*On Painting*) (1435), the Florentine architect and artist Leon Battista Alberti (1404–72) reminded his readers that

> The number of painters and sculptors was enormous in those days, when princes and people, and learned and unlearned alike delighted in painting . . . Eventually Paulus Aemilius and many other Roman citizens taught

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their sons painting among the Liberal Arts in the pursuit of the good and happy life. The excellent custom was especially observed among the Greeks that free-born and liberally educated young people were also taught the art of painting together with letters, geometry and music.[6]

Leonardo, Alberti and their fellow painters questioned how poetry could be accepted as a Liberal Art while the creation of beautiful images in paint rather than in words was not. 'Write up in one place the name of God,' said Leonardo, 'and put a figure representing him opposite, and see which will be the more reverenced.'[7]

The artist's cause demanded that artists dissociated themselves from craftsmen, and allied their skills with mathematics and abstract thought. 'Painting', said Alberti, 'was honoured by our ancestors with this special distinction that, whereas all other artists were called craftsmen, the painter alone was not counted among their number.'[8] This could not but have encouraged artists to downplay the material aspects of painting, such as the creation and grinding of pigments. In turn, this surely contributed to the desire of the Florentine painters to emphasize drawing and line (*disegno*) above the use of colour (*colore*), initiating a dispute that lasted for centuries. Dismissive comments such as those of Equicola in the sixteenth century could only have egged them on: 'Painting has no other concern except with copying nature with various appropriately chosen colours.'

By the late fifteenth century Leonardo and his fellow painters had largely won their battle – but at the cost of simply reinforcing the bigotry that they inherited from Classical times. Nowhere does Leonardo challenge the underlying hierarchy that values the intellectual over the manual. Instead, he seeks to relocate the craft of the medieval painter on an abstract plane. Thus did art begin to fragment into the 'pure' and the 'applied', a distinction not seriously challenged until the nineteenth century. In *The Two Paths* (1859), John Ruskin deplored art's own 'two cultures' and argued that decorative art and craft should not be regarded as 'a degraded or separate kind of art'. With William Morris and others, Ruskin tried to reunite the craftsperson with the fine artist in the Arts and Crafts movement. It is not clear that they enjoyed much success: Art Nouveau came and went, but artistic elitism remains.

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Chemistry and art

The relation of painting to the Liberal Arts in Leonardo's time was wholly analogous to the standing of chemistry in relation to natural philosophy, or what we would now call science. Those who pursued the chemical arts, who dwelt in smoky laboratories and wrought useful things, were excluded from the lofty halls of academic science. Science historian Lawrence Principe says of this pre-scientific chemistry or 'chymistry':

It has long been recognized that one of the 'problems' of chymistry before the eighteenth century was its status as a practical or technical art rather than as a branch of natural philosophy. The low status of chymistry as determined by its use amongst low technical appliers militated against its acceptance by many natural philosophers.[9]

Thus the Anglo-Irish chemist Robert Boyle, in his polemical *Sceptical Chymist* (1665), denounces the ignorance of the 'vulgar chymists', including not only the out-and-out cheats who sought to profit from faked alchemical transformations but also the 'laborants' such as the dyers, distillers and apothecaries who lacked theoretical knowledge. Leonardo had nothing at all to gain by aligning his cause with such a crowd, and so there is good reason for him to gloss over the chemical aspects of art.

That cannot, however, excuse the persistent perception of unseemliness in the idea that science provides art not only with concepts but with materials. The snobbery and ignorance apparent in the words of the Bauhaus architect Le Corbusier (Charles-Edouard Jeanneret) and his collaborator Amédée Ozenfant in 1920 are breathtaking:

. . . it is form which comes first, and everything else should be subordinated to it . . . Cézanne's imitators were quite right to see the error of their master, who accepted without examination the attractive offer of the colour-vendor, in a period marked by a fad for colour-chemistry, a science with no possible effect on great painting. Let us leave to the clothes-dyers the sensory jubilations of the paint tube.[10]

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Let's not be too distracted by the absurdity of the suggestion that Cézanne – not the Impressionists or the Fauves, but Cézanne! – was an undiscerning dauber of raw colour. What is more telling is the way that Le Corbusier denigrates manual skills and delight in substance, in favour of 'form' and abstract space. This passage could almost have been written by the most bigoted of late-sixteenth-century Italian scholars praising *disegno* over *colore*. To deny that colour chemistry can have any possible effect on 'great painting' is, in the end, to claim that great art is all in the head, and cheapened by the sad necessity to reconstruct it from mere matter.

The connection to chemistry was perhaps deemed less distasteful in the nineteenth century, when chemists enjoyed unrivalled respectability (even Goethe used their metaphors). An anonymous writer on artistic technique in 1810 says cautiously: 'Chemistry is to painting what anatomy is to drawing. The artist should be acquainted with them, but not bestow too much time on either.' Yet even this much may be seen as a swan-song to the era when the painter was of necessity something of a chemist, when a training in art required at least as great an attention to the mechanical and practical aspects as to the aesthetic and intellectual. By the end of the nineteenth century, the artist was wholly reliant on scientifically adept professionals – 'colourmen' – to attend to the chemical aspects of their profession. One consequence of this rift is that the colours of some works of that period have weathered less well than the jewel-like fifteenth-century paintings of Jan van Eyck.

Chemistry is a topic that strikes fear into many a heart, and there seems little point in seeking to evade that fact. Unusually among artists, students of ceramics are one group who still have to learn some real chemistry – the whole package: balanced equations, the Periodic Table, atomic weights and so forth. In my experience, this does not make them feel any better about it. There appears to be something intimidating about the dizzying varieties in which matter is composed from elemental blends; and if we are honest about it, something vaguely ominous and unsettling about the grey metallic minarets and pipelines within which these blends are industrially concocted today. It is a challenge to the imagination to connect

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these ugly factories and alien or unsettling names – cadmium, arsenic, antimony – with the stuff that, smeared over canvas, leaves us breathless in art galleries. Can such a villain (and the chemical industry's transgressions are not at all imaginary) be responsible for this beauty?

The truth – a dirty truth, if you will – is that new colours for artists have long been a by-product of industrial chemical processes that reach out to a much wider market. Without the engine of commerce to drive it, the manufacture of these new pigments would simply have not been viable. Artificial copper blues or 'verditers', the principal cheap alternatives to expensive blue pigments from the fifteenth to the eighteenth century, were a side-product of silver mining. They were largely replaced by Prussian blue, produced primarily for the massive textile dyeing industry rather than for the tiny market in artists' colours. The Mars colours (artificial iron oxides) could not have been made without the availability of cheap sulphuric acid, which was manufactured primarily as a textile bleach. The pigment known as patent yellow was an offshoot of the soda industry, while the manufacture of chrome yellow was stimulated by its use in cotton printing. Textile dyeing also led to a better understanding of the use of metals for the fixing (mordanting) of dyes, which then drove improvements in the preparation of 'lake' pigments in the early nineteenth century. The almost ubiquitous white pigment of the twentieth century, titanium dioxide, is produced almost entirely for commercial paints – the amount diverted to artists' materials is trivial.

Might it be exciting to see not only an art history but also an art that reflects these connections? The commercial aspects of colour manufacture have indeed influenced some twentieth-century artists. But aren't naked pigments already works of art – the products of skill and creativity, and substances of glorious elegance and splendour? The Anglo-Indian artist Anish Kapoor thinks so (Plate 1.1), and Yves Klein did too.

It is commonly asserted that the interaction between art and science is a one-way street; but the relationship between chemistry and art has been to their mutual benefit. The modern chemicals industry was spawned and nurtured largely by the demand for

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colour. Important advances in synthetic chemistry in the nineteenth century were stimulated by the quest for artificial colours. Many of the world's major chemicals companies – BASF, Bayer, Hoechst, Ciba-Geigy – began as manufacturers of synthetic dyes. And the reproduction of art and colour in photography and printing has given rise to major technological companies such as Xerox and Kodak.

There is, meanwhile, ample precedent for the collaboration between art and chemistry personified in Klein and Adam. Michael Faraday advised J. M. W. Turner on his pigments. The German chemistry Nobel Laureate Wilhelm Ostwald worked with the German paint industry in the 1920s, and his theory of colour was hotly debated at the Bauhaus where Klee and Kandinsky taught. In more distant times, painters consorted with alchemists to procure their colours. In this story about science, technology, culture and society, there are no chickens and no eggs. Chemical science and technology and the use of colour in art have always existed in a symbiotic relationship that has shaped both their courses throughout history. By tracing their co-evolution, we shall see both how art is more of a science, and science more of an art, than is commonly appreciated on either side of the fence.[11]

Fear and loathing of colour

Yves Klein invites us to engage with the beauty of raw colour. This goes against our training. What is brightly coloured? Children's toys, the Land of Oz. And so colour threatens us with regression, with infantilism. Cultural theorist Julia Kristeva claims that 'the chromatic experience constitutes a menace to the "self" . . . Colour is the shattering of unity.'[12] What else is coloured? Vulgar things, vulgar people. Colour speaks of heightened emotions, even linguistically, and of eroticism. Pliny is not alone in xenophobically attributing strong colour to a kind of decadent Orientalism. Le Corbusier asserted that colour was 'suited to simple races, peasants, and savages'. Needless to say, he found it in abundance in his 'journey to the East', and was repelled: 'What shimmering silks, what fancy, glittering marbles, what opulent bronzes and golds . . . Let's have done with

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it . . . It is time to crusade for whitewash and Diogenes'[13] – which is to say, for cool reason over all this unseemly passion.

The nineteenth-century art theorist Charles Blanc (what's in a name?) insisted that 'design must maintain its preponderance over colour. Otherwise painting speeds to its ruin: it will fall through colour just as mankind fell through Eve.'[14] Here, then, is another reason to distrust colour: it is feminine. Contemporary artist David Batchelor argues that a fear of colour – chromophobia – pervades Western culture.[15] 'Man', said Yves Klein, 'is exiled far from his coloured soul.'[16]

But perhaps chemists, who are on intimate terms with the materiality of colour, who have seen the majestic rainbow progression of manganese through its different states of oxidation, who have watched the royal, clear blue of ammoniacal copper sulphate emerge from the pale, opaque blue of its alkaline precipitate – perhaps they are especially attuned to and appreciative of unadulterated colour. Oliver Sacks recalls the allure of chemistry's liquid colours in his childhood:

> My father had his surgery in the house, with all sorts of medicines, lotions, and elixirs in the dispensary – it looked like an old-fashioned chemist's shop in miniature – and a small lab with a spirit lamp, test tubes, and reagents for testing patients' urine, like the bright-blue Fehling's solution, which turned yellow when there was sugar in the urine. There were potions and cordials in cherry red and golden yellow and colourful liniments like gentian violet and malachite green.[17]

To the chemist, colour is a bountiful clue to composition and, if measured carefully enough, can reveal delicate truths about molecular structure. It takes a particular turn of mind to see chromatic beauty lurking in the molecular structures of alizarin and indigo, to sense the rich hues within the stark, schematic depictions of these dye molecules. The Italian chemist and writer Primo Levi intimates how this relation between colour and constitution broadens the chemist's sensitivity to colour:

> I find myself richer than other writers because for me words like 'bright',

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'dark', 'heavy', 'light', and 'blue' have a more extensive and more concrete gamut of meanings. For me 'blue' is not only the blue of the sky. I have five or six blues at my disposal.[18]

Naming colours

Before we can adequately explore what colour means to the artist, we must ask what we mean by colour itself. This might seem uncontentious enough. In spite of the old solipsism that I can never know if my experience of 'red' is the same as yours, we both agree when the term is appropriate and when it is not. Yet there are hordes of 'lower-level' colour terms in most modern languages over which the scope for dispute is limitless: when does puce become russet, burgundy, rust-red? This is partly a matter for perceptual psychology; but the language of colour reveals much about the way we conceptualize the world. Linguistic considerations are often central to an interpretation of the historical use of colour in art.

Pliny claims that the painter in Classical Greece used only four colours: black, white, red and yellow. This noble and restrained palette, he said, is the proper choice for all sober-minded painters. After all, didn't Apelles, the most famous painter of that golden age, choose to limit himself within this austere range?

We cannot check the accuracy of this claim, for all of Apelles' works are lost, along with almost every other painting his culture produced. Yet we do know that the Greeks possessed a considerably wider range of pigments than these four. As for the Romans, no fewer than twenty-nine pigments have been identified in the ruins of Pompeii. Might Pliny have exaggerated the paucity of Apelles' palette? And if so, why? In part, the reason might be metaphysical: four 'primary' colours equate neatly with the Aristotelian quartet of elements: earth, air, fire, water. But the breadth of colour use in classical painting may also be obscured by linguistics. In interpreting archaic writings on the use of colour in art, there is for example ample scope for confusion of red and green. The medieval term *sinople* – derived from Pliny's *sinopis*, which in turn stemmed from the geographical source of a red earth pigment at Sinope on the

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Black Sea – could refer to either red or green until at least the fifteenth century. The Latin *caeruleum* carries a similar ambiguity between yellow and blue (its root is the Greek *kuanos*, which can in some contexts denote the dark-green colour of the sea). There is no Latin word for brown or grey, but this does not imply that the Roman artists did not recognize or use brown earth pigments.

How could red and green ever be conflated? From a modern-day perspective this appears absurd, because we have in our minds Isaac Newton's rainbow spectrum and its corresponding colour terminology, with its seven bands firmly delineated. The Greeks saw a different spectrum, with white at one end and black at the other – or more properly, light and dark. All the colours lay along the scale between these two extremes, being admixtures of light and dark in different degrees. Yellow was towards the light end (it appears the brightest of colours for physiological reasons). Red and green were both considered median colours, midway between light and dark – and so in some sense equivalent. The reliance of medieval scholars on Classical Greek texts ensured that this colour scale was perpetuated for centuries after the temples of Athens stood in ruins. In the tenth century AD, the monk Heraclius still classified all colours as black, white and 'intermediate'.

The confusion of blue and yellow may have been purely linguistic, or it may have its origin in the naming of colours after the materials that supplied them (see page 264). For reasons that are far from clear, blue and yellow are categorized together in many languages and cultures, including some Slavic tongues, the Ainu language of northern Japan, the Daza language of East Nigeria and that of the Mechopdo Native Americans in northern California. The Latin *flavus*, meaning yellow, is the etymological root of *blue*, *bleu* and *blau*. The location of blue at the dark end of the scale gives us another reason to be wary of its apparent exclusion from Pliny's list: it was seen as a variant of black, and Greek terms for the two overlap.

Thus whether or not an artist considers two hues to be different colours or variants of the same colour is largely a linguistic issue. The Celtic word *glas* refers to the colour of mountain lakes and straddles the range from a brownish-green to blue. The Japanese *awo* can mean 'green', 'blue' or 'dark', depending on the context;

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Vietnamese and Korean also decline to distinguish green from blue. Some languages have only three or four colour terms.

As there are no culture-independent concepts of basic colours, it seems impossible to establish a universal basis for a discussion of colour use. In 1969, however, anthropologists Brent Berlin and Paul Kay attempted to bring some order to the mass of conflicting categories by proposing a kind of colour hierarchy, according to which hues emerge in a universal order as the complexity of a culture's colour terminology increases. First, they said, comes a distinction between light and dark, or white and black. Australian Aboriginals and speakers of the Dugerm Dani tongue of New Guinea have only two colour terms with essentially these meanings. Red is the next colour to be identified as a distinct hue. Then either green or yellow is added to the list, followed by the other of the two. After this comes blue, and gradually the more complex secondaries and tertiaries are included – brown first, then (in any order) purple, orange, pink and grey. So according to Berlin and Kay, there can be no language that has terms for just black, white and green, or just yellow and blue. Colour vocabulary, they said, unfolds in a strict sequence.

The validity of Berlin and Kay's idea, which was based largely on anthropological and linguistic studies of contemporary non-technological cultures, has been much questioned. For example, Hanunoo, which is spoken by a Malayo-Polynesian people in the Philippines, has four colour terms: 'dark' and 'light', which we can equate readily enough with black and white; but also 'fresh' and 'dry' (in so far as they can be matched with English words at all). Some prefer to ally these two with green and red, but they seem to allude to texture as much as to hue. There is no Hanunoo word meaning 'colour'.

Berlin and Kay's synoptic scheme nevertheless affords some foundation for a discussion of what has been meant by 'colour' through the ages, and there seems good reason to regard it as expressing at least a partial truth. A part of the difficulty in applying the theory is that it presupposes the existence of 'basic' colour terms – words for hues that have no dependence on context. This is not always true even in complex modern languages. French *brun*, for instance,

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is not the strict equivalent of English *brown* but can be supplanted by *marron* or *beige* in certain situations, while implying 'dark', rather than a specific hue, in others.

It is all but impossible to identify basic colour terms, in the sense of Berlin and Kay, in ancient Greek. This has led some commentators to assume that the Greeks had poor colour awareness. In 1921, Maurice Platnauer claimed that 'colours made a much less vivid impression upon their senses . . . or . . . they felt little interest in the qualitative differences of decomposed and partially absorbed light'.[19] Colour technologist Harold Osborne reiterated the point in 1968, saying that the Greeks were 'not given to careful discrimination of colour hue'.

But there is no reason to suppose that our ability to distinguish colours is limited by the structure of our colour vocabulary. We can tell apart hues to which we cannot ascribe names – indeed, the vast majority of distinguishable hues are not named specifically in any language. So we should rather conclude that for the Greeks, 'colour' had a somewhat different meaning (although they had a word – *chroma* or *chroia* – that is usually translated in this way). Since their colours lay on a scale between light and dark, brilliance or lustre, as well as hue, could be valid discriminants. Platnauer suggested that 'it is lustre or superficial effect that struck the Greeks and not what we call colour or tint' – an over-simplification, perhaps, but probably true in essence. He points out that the same word is used in Greek literature to describe darkened blood and a cloud, or the glint of metal and a tree. This is presumably the explanation for Homer's famously puzzling 'wine-dark' sea (*oinopos*) in the *Odyssey*. Wittgenstein voiced the same idea in his *Remarks on Colour*: 'Mightn't shiny black and matt black have different colour names?' (In his black monochromes of the 1960s the American minimalist artist Ad Reinhardt used these two as if they were indeed distinct colours.)

The Greeks certainly possessed colour terms – but none that are obviously 'basic'. 'Red' is generally equated with *eruthos* (to which it is etymologically related); but there is no good case for giving this term primacy over *phoinikous* or *porphurous*, as there is for red over scarlet or crimson. Similarly, green could be rendered as *chloros*, *prasinos* or *poödes*, depending on the context.

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Linguist John Lyons suggests it is safest to conclude only that colours 'are the product of language under the influence of culture'. The fluidity of colour terminology led to a frequent reliance on materials, rather than abstract concepts of hue, as the basis of a discussion about artists' use of colour. Pliny's four classical colours were not simply 'black', 'white' and so forth, but 'white from Milos' and 'red from Sinope on the Black Sea' – they were embodied in specific pigments. Without a secure theoretical basis for classification, talk of colour needs to be rooted in the physical substances that provide it. Yet this simply creates fresh scope for ambiguity, for the substance can mutate into a colour term in its own right. Scarlet, for example, was once a kind of medieval dyed cloth, which need not have been red at all.

True colours

It is tempting to regard modern and abstract painters as the first consciously to decide that they would not simply try to paint 'what they saw'. Yet the most casual of glances at any image from the Renaissance or the Baroque period shows how much the work is guided by certain conventions, and at the same time by imagination and interpretation, rather than being an attempt to depict nature as faithfully as possible. Many artists through the ages have talked of painting 'true to nature' – but this means many things, of which the advent of photography has encouraged us to select just one.

For example, until the late nineteenth century, using colour to mimic nature was necessarily an artifice in at least this respect: nearly all paintings were produced in studios with reliance on the painter's judgement about 'proper' composition and contrast. It was only when painting of finished works (as opposed to reference studies) out of doors was pioneered by the French Realists, and later adopted by the Impressionists, that artists began to liberate themselves from academic notions about light and shade, to see the purples and blues in shadows, the yellows and oranges in 'white' sunlight.

Let us nevertheless accept the idea that Western art from antiquity to the advent of abstraction has purported to depict the forms of

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modernist like Mondrian rather than the blending and contrasting hues of the Venetian Old Masters. Moreover, Alberti betrays an abiding concern with the integrity of the pure pigment – with preserving the raw colour and avoiding practices that would muddy it or degrade its brilliance. Highlight and shadow, he advises, should be rendered simply by adding white and black – and with great restraint, lest the virtue of the colour be degraded:

> Those painters who use white immoderately and black carelessly, should be strongly condemned. It would be a good thing if white and black were made from those pearls Cleopatra dissolved in vinegar, so that painters would become as mean as possible with them, for their works would then be both more agreeable and nearer the truth.[21]

Here 'truth' means true to the glory of the materials rather than capturing what nature reveals to the eye. All the same, Alberti's remarks on colour reflect the Humanism of the Renaissance more than the symbolic materialism of the Middle Ages. His book concerns itself only with secular painting, whereas Cennino makes several references to religious works, like a workman describing how to lay the bricks for a church. For Alberti, the use of the finest colours is not to please God but to satisfy the patron who has commissioned the work and who, in all likelihood, contractually specified the pigments to be used.

Leap into the void

At the centre of Alberti's discussion of colour is the question that all painters had to address once the prescriptive approach of the Middle Ages was discarded: how to *organize* colour. The artist of the twentieth century faced the same question, although the rules had changed dramatically. Whereas Renaissance painters disagreed over *how* to paint, they had little dispute over *what* to paint. But in the early twentieth century, painters began first to abandon 'naturalistic' colouring and then to discard naturalistic form.

The consequent problem was analogous to that confronting the contemporaneous atonal composers: if trees can be blue, skies pink,

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faces yellow, how does one choose the colour at all? Without a 'natural' reference – the mathematical rules of musical harmony, or the hues of nature – how does one escape the incoherence threatened by such multiplicity of choice? What is the appropriate organizational system that apportions colours 'truthfully'?

Arnold Schoenberg found a musical answer in serialism – the twelve-note compositional method. But nothing so general was to emerge for the modern colourist. Wassily Kandinsky (1866–1944) recognized almost with horror the obligation of the abstract artist to discover guiding principles: 'A terrifying abyss of all kinds of questions, a wealth of responsibilities stretched before me. And most important of all: what is to replace the missing object?'[22] His answer was a very personal and subjective one. He sensed that colours have symbolic and spiritual connotations. This belief seems to have been profoundly influenced by the fact that Kandinsky experienced synaesthesia, a perceptual condition in which two sensory sensations are simultaneously triggered by the same stimulus. This is most commonly manifested as 'colour-hearing': the association of specific colours with timbral or pitch sensations. The composer Alexander Scriabin was affected by the same condition: he heard the key of C major as red and D major as yellow, and he composed in colours for a 'keyboard of light' (*clavier à lumière*).

Kandinsky was deeply influenced by Theosophy, a spiritual philosophy derived from Wolfgang von Goethe's simplistic division of the world into polar contrasts. Theosophy appealed also to the Dutch painter Piet Mondrian (1872–1944), whose efforts to arrange rectangles of primary colours on a heavy black grid evoke a kind of mathematical angst. He was an advocate of the Theosophist M. H. J. Schoenmaekers, who argued that all colours except the three primaries were superfluous – providing Mondrian with his own distinctive answer to the problem of colour.

Theosophy's dogmatic categorization is reflected in Kandinsky's conviction that colour acts as a universal language of the soul. Of course, colour *does* speak to our emotions – but not, it seems, in a way that everyone agrees on, independent of cultural conditioning. Yet Kandinsky believed there are concrete, objective colour associations, so that an abstract composition can, through the calculated

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use of colour, invoke a very particular emotional response. It was simply a matter of cracking the code – or, in a more Kandinskian metaphor, of using colour mechanistically to pluck the strings of the emotions:

> Generally speaking, colour directly influences the soul. Colour is the keyboard, the eyes are the hammers, the soul is the piano with many strings. The artist is the hand that plays, touching one key after another purposively, to cause vibrations in the soul.[23]

Kandinsky explained his chromatic language in his book *Concerning the Spiritual in Art* (1912), where we find such claims as this:

> Yellow is the typical earthly colour. It can never have profound meaning. An intermixture of blue makes it a sickly colour . . . Vermilion is a red with a feeling of sharpness, like glowing steel which can be cooled by water . . . Orange is like a man, convinced of his own powers . . . Violet is . . . rather sad and ailing.[24]

He attempted to establish these 'meanings' of colours through 'scientific' experiments at the Bauhaus art and design school in Germany. He distributed a thousand test cards to a 'cross-section of the community' on which recipients were asked to match the three primary colours to three geometric shapes – a square, circle and triangle. There was some consensus that the triangle was yellow, but disagreement about whether blue belonged in the square or the circle.

A link between colour and music is not unique to synaesthetics, but has been perceived since the time of ancient Greece. Kandinsky, himself a violinist and cellist, collaborated with Schoenberg and hoped to find a way of incorporating 'dissonance' into existing, 'harmonious' schemes for organizing colour. He felt that a work of art should have a symphonic structure, and his 'colour-music' compositions are generally regarded as some of the first truly abstract paintings, devoid of all reference to recognizable objects (Plate 1.2).

Kandinsky's fruitless search for the emotional language of colour, like the tangles of colour linguistics, reminds us that it is futile to be

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dogmatic about colour. There can be no consensus about what colours 'mean', nor how to use them 'truthfully'. Colour theories – and we will encounter several later – can assist the construction of good art, but they do not define it. In the end, the modern artist's struggle to find form for colour is an individual quest. To Bridget Riley, it is precisely this that makes colour so powerful a medium of artistic expression:

> . . . just because there is *no* guiding principle, *no* firm conceptual basis on which a tradition of colour painting can be reliably founded, this means that each individual artistic sensibility has a chance to discover a unique means of expression.[25]

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2. Plucking the Rainbow

THE PHYSICS AND CHEMISTRY OF COLOUR

There is no such thing as colour, only coloured materials.

Jean Dubuffet (1973)

Inorganic nature has only the language of colour. It is by colour alone that a certain stone tells us it is a sapphire or an emerald.

Charles Blanc, *Grammar of Painting and Engraving* (1867)

What is paint after all? Colored dirt.

Philip Guston

Much currency has been made, in the tug-of-war between art and science, of Isaac Newton's 'unweaving the rainbow'. John Keats expresses it thus in *Lamia* (1819), a poetic lament about the detrimental effect (as he perceived it) of scientific knowledge on mystery and wonder in the world. Yet the bright arc's threads remained tangled in art long after Newton had elucidated their prismatic sequence. We can hardly be surprised that an anti-Newtonian like Goethe would rearrange the colours to oppose nature; but even a keen observer of nature like John Constable was known to get the order wrong in the secondary bow (where the sequence is inverted). The Pre-Raphaelite artist John Everett Millais had to correct the same mistake hastily after it was pointed out to him in his *Blind Girl* (1856).

Newton's achievement was not, in any event, to demonstrate that daylight was woven of many hues which the rainbow separates. That much had long been evident in the spectrum prised from sunlight when it passes through glass. Nor was it Newton who

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modern idea. I feel sure that Leonardo would have damned any book that claimed to speak of colour without explaining it.

The many causes of colour

'Colour always answers to the sort or sorts of the Rays whereof the Light consists, as I have constantly found in whatever Phaenomena of Colours I have hitherto been able to examine.'[2] By making light not the activating principle of colour as Aristotle believed, nor the vehicle of colour as perceived in medieval thought, but the medium of colour itself, Newton was inviting the inquiry: what, then, is light?

It was not until another two centuries had passed that the Scottish physicist James Clerk Maxwell gave the answer. Light, said Maxwell in the 1870s, is a vibrating electromagnetic field: a combination of self-supporting electric and magnetic fields oscillating in step but oriented perpendicular to one another, like two ropes tied to a pole and shaken vertically and horizontally. The frequency of the vibrations determines the colour of the light, and increases progressively from the red to the blue end of the visible spectrum. Electromagnetic radiation with lower frequencies than red light is infra-red, or, at still lower frequencies, microwaves and radio waves. High frequencies beyond the blue and violet correspond to ultraviolet, and then to X-rays and gamma rays.

The wavelength of the vibration is inversely related to the frequency: it declines as frequency increases. Frequency and wavelength are the modern correlates of Newton's 'vibrations of several bignesses'.

This picture was refined at the beginning of the twentieth century with the realization that, with that perversity for which quantum theory is notorious, light is not just wave but particle too. Light comes in packets or 'quanta', each containing an amount of energy proportional to the frequency. These quanta of light are called photons. Albert Einstein proposed this heretical notion in 1905, and it later won him his Nobel prize.

A substance's colour may be generated by absorption of light, a

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phenomenon governed by the material's resonant frequencies. Think of an undamped piano wire humming in sympathy with a sung note; in the same way, matter sings along with sunlight. The resonant vibration absorbs the energy of the light at that frequency, and so it strips out a particular colour from the spectrum of the light. Those rays whose frequencies do not correspond with some resonant frequency of the material either pass right through it (if the material is transparent or translucent) or are reflected (if it is opaque). Only these 'rejected' rays reach our eye. So, paradoxically, it is on the basis of their frequencies – their position in the visible spectrum – that we award the material a colour.

For absorption of visible light, these resonances involve the clouds of electrons that surround the tiny, dense nuclei of atoms like bees swarming around the hive. The light may be absorbed if it can boost the electrons from one energy state to another, just as the piano wire's energy is increased when it is stimulated into resonant vibration by sound waves. Because the electrons' energies are governed by the rules of quantum physics and increase in discrete steps like the gear shifts in a car, only rays of certain frequencies have the right energy to stimulate these colour-inducing 'electronic transitions'.

Not all colour is generated in this way. The rainbow's variegated arc, for instance, is not the result of light absorption by the raindrops, but of refraction: the bending of rays of different wavelength through differing angles (Figure 2.1). This is an example of light scattering, which is the major *physical* way in which colour can be produced. Light absorption, in contrast, depends on the *chemical* composition of the substance.

As light enters a raindrop, the ray is bent (refracted). The angle of bending depends on the wavelength of the light, being sharper for shorter wavelengths. So blue light is deflected more than red light, and the various colours in sunlight are unravelled. Each colour reaches your eye from a slightly different region in the rainbow's arc. The scattering of light can therefore separate colours according to their wavelength. The sky is blue because blue light is scattered by the molecules and dust in the atmosphere more strongly than red light, and so seems to come from all directions. Distant hills acquire a blueness for the same reason: the reflected light is

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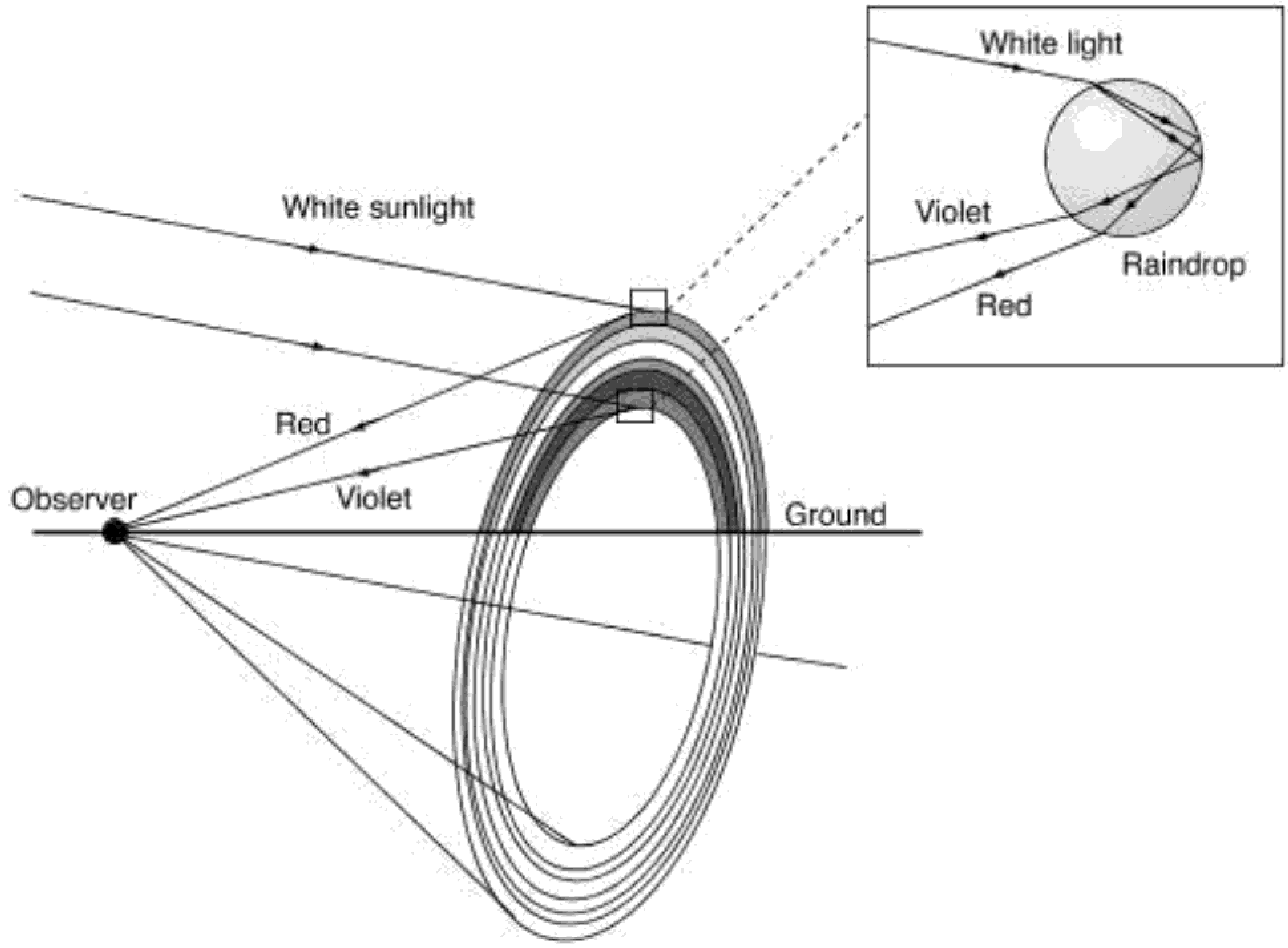

Figure 2.1
How the rainbow is formed. Light of different wavelengths is refracted by raindrops through different angles, and so beams of white light are separated into their spectral components.

augmented by the omnidirectional blue before reaching the eye. (In art this blueing of distant landscape, described by Leonardo, is called aerial perspective.) As the sun sinks low in the sky, its rays travel through a thicker slice of the atmosphere before reaching the observer, and the blue component of the light may be scattered so strongly that it never gets to the eye. Goethe had but a hazy intimation of this: 'as the sun at last was about to set . . . its rays, greatly mitigated by the thicker vapours, began to diffuse a most beautiful red colour over the whole scene around me'.[3]

Natural pigments obtain their colours by absorption of light. But some colours in nature result from physical scattering processes. In particular, no vertebrate animals contain blue pigments: their blue markings are produced by light scattering. The blues on butterfly wings are the result of a microscopic ribbed structure of individual scales on the wing (Figure 2.2). These ridges have a spacing that

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induces preferential scattering of blue light. But the scattering, and thus the hue, varies somewhat depending on the angle of reflection (or equivalently, the viewing angle). So the colour is iridescent, seeming to shimmer and shift as the wing moves. The same is true of blue insect cuticle, and of the kaleidoscopic colours of a peacock's tail: the peacock's feathers are laced with a tiny grid of pigmented black bars that scatter light like the ribs of butterfly wing scales. The rainbow-like colour changes of these feathers have long fascinated artists; a Byzantine writer of the seventh century AD asked:

> How could anyone who sees the peacock not be amazed at the gold interwoven with sapphire, at the purple and emerald-green feathers, at the composition of the colours of many patterns, all mingled together but not confused with one another?[4]

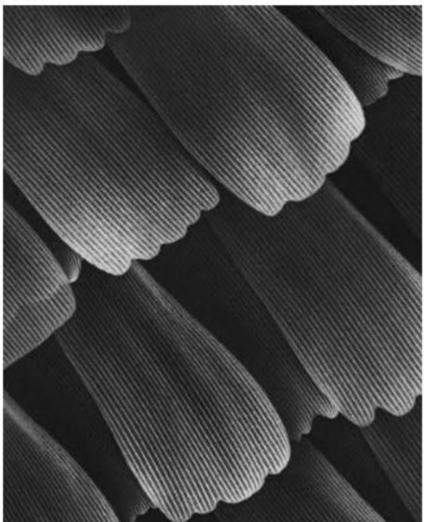

Figure 2.2

The iridescent blues and greens of a butterfly's wings are formed by light scattering from microscopic ribs on the wing scales.

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Alexander Pope's sylphs in *The Rape of the Lock* clearly share with insects an iridescence caused by light scattering:

> While ev'ry beam new transient colour flings,
> Colours that change whene'er they wave their wings.

Light is scattered most strongly when the scattering objects are of comparable size to the wavelength of the radiation. Water droplets in clouds are the right size to scatter all visible light, creating the sky's milky billows. Glass wool and ground glass, made of the same fabric as windows, look white and opaque for the same reason. Ground-up stained glass becomes paler with prolonged grinding: smaller particles have a greater total surface area to scatter from, and so scattering (which is indiscriminate about wavelength across the visible range) dominates over absorption (which picks out certain wavelengths). This is why grinding a coloured powder may affect its hue – a phenomenon exploited by the artists of the Middle Ages, who controlled the shade of a pigment by the degree of grinding.

Colour from the earth

Until the advent of 'modern' synthetic pigments in the nineteenth century, many artists' colours were finely ground minerals: metal-containing compounds pulled from the earth. Their colours are usually determined by the nature of the metal atoms they contain; and this much is true of many of the new synthetic colours too, among which chromium, cobalt and cadmium compounds feature prominently. Strongly coloured minerals commonly contain so-called transition metals, which occupy the centre of the Periodic Table, chemistry's group portrait of the elements.

Ancient and medieval scholars played a fruitless game in trying to assign particular colours to the four Aristotelian 'elements'. We now know that an element's colour depends on its context. Nevertheless, some of them exhibit recurring chromatic themes. Ask a chemist to assign colours to the most common transition metals and he or she will know the game at once. Red is for iron,

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The colour of some important mineral pigments arises through a very long-ranged rearrangement of electrons: absorption of light liberates electrons entirely from their orbits around particular ions and sets them free to wander through the solid. When this happens, the material becomes more electrically conducting. Semiconductors are substances that need only a little extra energy to boost electrons into such a mobile state. Among them is cadmium sulphide, introduced as a pigment in the nineteenth century. It absorbs violet and blue light, and can range in colour from yellow to orange depending on how it is prepared. The deeper hue of 'cadmium red' is produced by replacing some of the sulphur with selenium. Mercury sulphide, which occurs naturally as the mineral cinnabar, is also a red-tinted semiconductor. A synthetic version corresponds to the renowned pigment vermilion. One hazard of vermilion is that its constituent ions can reshuffle from their usual positions to new locations in a form of the compound called metacinnabar. This absorbs red light as well as blue and green, and so it appears black – fatal, of course, if it happens on the canvas.

In pure metals, such as iron, copper, silver and gold, some electrons are intrinsically mobile; this is why metals are good electrical conductors. The interaction of these mobile electrons with light creates a reflective, metallic sheen. The light is not absorbed but is instead reflected without much scattering, resulting in a mirror-like appearance. But metals like copper and gold do absorb some of the short-wavelength (bluish) rays that strike them, and so they take on a reddish tinge. To medieval artists, this allied pure gold leaf with red pigments.

Organic colour

While rose quartz acquires its colour from titanium or manganese impurities, no such metals tint the rose itself. The colourants in living organisms are organic compounds: discrete molecules containing perhaps several dozen atoms each, with backbones of interlinked carbon atoms. Until the nineteenth century nearly all dyes were 'natural products', which is to say, organic substances

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derived from animals or plants. As well as being used for colouring textiles, they tinted inks and, fixed to particles of a colourless inorganic powder, were the colouring agents of so-called lake pigments.

Tyrian purple, the imperial colour of Rome, was drawn out of shellfish. Blue indigo was the frothy extract of a weed. Madder red came from a root, cochineal from an insect. Today virtually all dyes are synthetic organic molecules, their carbon skeletons custom-built by industrial chemists. While barely a dozen natural dyestuffs proved stable enough to be useful in the ancient and medieval world, over 4,000 synthetic dyes now bring colour to our industrialized societies.

Nature owes its verdancy to the most abundant of natural pigments: chlorophyll, which imbibes the red and blue of the sun's rays and channels the energy into the biochemical processes of the cell. At the heart of the chlorophyll molecule sits a magnesium ion, which undergoes electronic transitions under the glare of the sun. The oxygen-binding part of the haemoglobin molecule in blood has a similar molecular architecture to chlorophyll's light-harvesting eye, except that iron in all its ruddiness substitutes for magnesium. And much the same structure crops up, studded with a copper ion, in the synthetic blue dye known as monastral blue, familiar from its use on the covers of old Pelican books. 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, though the answer must invoke different species of pigment. The yellows, oranges and reds of many flowers, as well as of carrots, tomatoes and sweetcorn, are produced by molecules called carotenoids. Plant pigments called flavonoids are responsible for blues, purples and reds. Carotenoids are also found in some animals. In lobsters these pigments are nearly black; boiling degrades them to redness, as Samuel Butler avers in his satire *Hudibras*:

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And, like a lobster boil'd, the morn
From black to red began to turn.

Light absorption by organic pigments is fundamentally no different to that by inorganic minerals: it involves a rearrangement of electrons. Often this takes place within floppy electron clouds smeared out across the carbon backbone. This is the case, for example, in the aniline dyes synthesized in the mid-nineteenth century, where the electrons are distributed in doughnut-shaped clouds around 'benzene rings' of six carbon atoms.

The medium matters

That colour is a treacherous thing is a lesson learned in childhood. The pebbles that glittered so richly when plucked from a seaside pool turn to unremarkable greyish lumps when pulled dry from the bag at home.

This change is due to the fact that light is affected by its passage from one transmitting medium – air, say – to another, such as water. Light travels more slowly in water than in air, which is why light rays bend as they pass into limpid rock pools, deceiving us about the depth.[5] This change in speed, characterized by a quantity called the refractive index of the material, determines the strength of light scattering: the greater the change in refractive index, the greater the scattering. So because light passing from air to rock at the surface of a dry pebble experiences a greater change in refractive index than light passing from water to rock when the pebble is wet, more of it is scattered rather than being reflected directly to our eye. This makes the dry pebble look paler and chalkier than the wet pebble.

Sadly, the same effect can undo the bright promise of pigments: glorious as dry powders, they might become dark or semi-transparent when mixed with a binding agent such as linseed oil. This degradation of brilliance when a pigment meets the liquid medium of a paint is what dismayed Yves Klein and led him on his chemical quest for a new binder that honoured the vibrancy of the raw pigment. The principal binding media before the fifteenth

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century were water (in frescos), gum or egg white (in manuscript illumination) and egg yolk (in tempera painting on panels). When artists began to use oils, which have a higher refractive index, they found that some of their most treasured pigments were no longer so beautiful. Ultramarine is darker, vermilion less opaque, chalk white is almost transparent. Other changes were for the better. In oils, translucent colours such as red lakes become not only more transparent but warmer, and give rich results when glazed in thin layers over other colours.

So the colour of a paint depends not only on the colour of the pigment but also on the fluid binding medium – as well as the reflective properties and absorbency of the surface to which it is applied, the texture of the finish, and the shape and size of the particles themselves, not to mention the effects of ageing (which are discussed in Chapter 11). This is why, although I shall be concerned primarily with the substances that have been dug up, synthesized, pulverized and purified to lend colour to paint, I cannot survey the topic of colour manufacture for painting without also occasionally considering the technology of paints as a whole – including the binder.

Wheels of light

'. . . in the Rays [Colours] are nothing but their Dispositions to propagate this or that Motion into the Sensorium, and in the Sensorium they are Sensations of those Motions under the Forms of Colours'.[6] We can perhaps forgive Newton a little vagueness about how we see colours, given his great achievements in explaining how they are generated. But his detractor Goethe was right to stress that colour is not about light alone. There is also the matter of how we perceive it – and this is the trickiest business of all.

For instance, colour depends on the circumstances under which we look for it. There is a sense in which we can regard leaves as possessing a kind of *latent* greenness, in that they contain a compound (chlorophyll) that absorbs red and blue from white light. But of course green leaves are not 'green' under all circumstances – under

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starlight, for instance, or viewed through a red filter. Colour is a function of the illumination.

This may seem obvious enough; but it would be thoroughly confusing if, like the ancient Greeks, we were to regard colour as an intrinsic property, requiring light only to activate it like electricity activating a light-bulb. This confusion is apparent in Aristotle's views on the relationship between colour and light:

> things appear different according to whether they are seen in shadow or in sunlight, in a hard or soft light, and according to the angle at which they are seen . . . Those which are seen in the light of the fire or the moon, and by the rays of the lamp differ by reason of the light in each case; and also by the mixture of the colours with each other; for in passing through each other they are coloured; for when light falls on another colour, being again mixed by it, it takes on still another mixture of colour.[7]

He claims, in other words, that colour is a property that does something to light. For Descartes and Newton, colour was equated with the light itself and not the illuminated object. Newton's prism experiments helped to clarify that apparently colourless light contains colour within it.

In the nineteenth century the emphasis shifted again. Strictly speaking, there is no such thing as coloured light, but only electromagnetic radiation of different wavelengths. Colour is a matter of perception, a result of the effect of light on the eye and brain. Newton had an inkling of this, commenting that 'the rays . . . are not coloured'. It is astonishing that we perceive such major (and uneven) changes in hue for rather small changes in wavelength – as if the sea were to switch from green to red as the wind drops and the waves lengthen.

Only in the past two centuries has it really been appreciated to what extent colour itself, as opposed to measurable features of materials such as light absorption, is a contingent phenomenon. The many tricks that our visual system plays when 'colours' are presented in different contexts attest to this.

Everyone who has spent early years mixing paints with the child's engaging blend of instinct and empiricism is astonished when they

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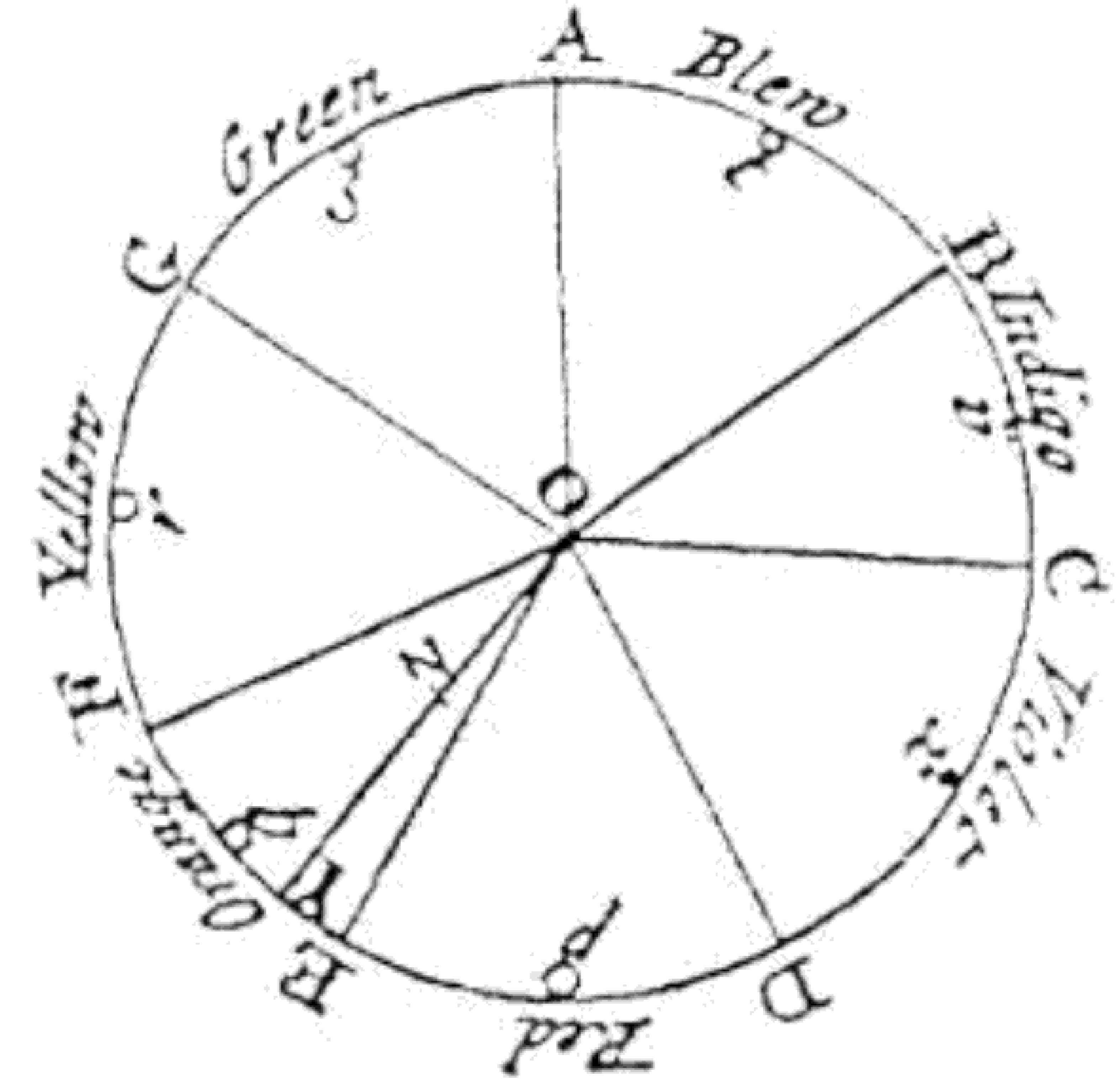

Figure 2.3
Isaac Newton's colour wheel divides the spectral colours according to their proportions in the rainbow.

but it does not help us resolve the apparent discrepancies between the primary colours in pigment mixtures and those in mixtures of light. In the former case, yellow is primary and green secondary; in the latter case, the reverse is true. In addition, red, yellow and blue paints mix to black (or nearly so), whereas Newton claimed that the entire rainbow of hues mixes to white. Goethe and his acolytes were quick to seize on this apparent inconsistency in Newton's theory. Any fool could see that no mixture of pigments gave one pure white, nor anything remotely like it.

James Clerk Maxwell dispelled the confusion – among scientists, at least – by showing in 1855 that three kinds of coloured light suffice to generate almost any colour: orange-red, blue-violet and green. (This triad 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* colour by the addition of various components, which together stimulate the retina in the eye to create a particular colour sensation. This is called *additive* mixing. Instead of using light rays, one can achieve additive mixing by rapidly alternating the separate

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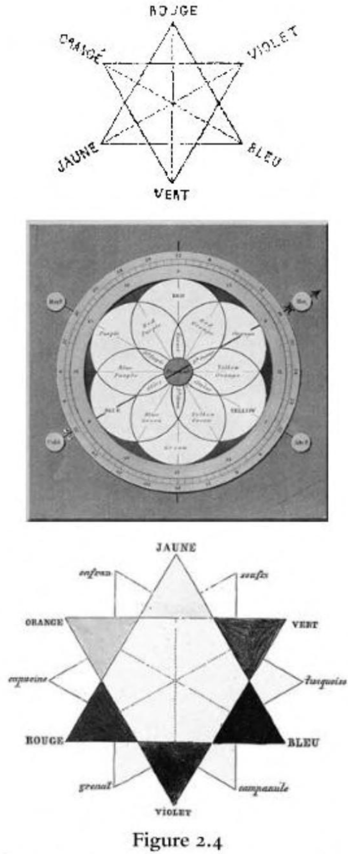

a.

b.

c.

Figure 2.4

Many systems for organizing colours in the nineteenth century, such as Auguste Laugel's colour star from *L'Optique et les arts* (1869) (*a*), tended to favour symmetrical arrangements in order to emphasize the primary and secondary relationships and the juxtaposition of complementary colours. George Field's colour wheels from *Chromatography* (1835) (*b*) and Charles Blanc's colour star from *Grammaire des arts du dessin* (1867) (*c*) find space for tertiary colours too.

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colours in the visual field. Maxwell's initial experiments, assisted by the Scottish colour theorist and interior decorator D. R. Hay, employed spinning discs painted with the three additive primary colours. The discs were made from interlocking and overlapping segments that allowed Maxwell to vary the proportions until they mixed to an achromatic silvery grey. In 1860 Maxwell devised an instrument that enabled him to synthesize a wide range of colours directly from light by mixing rays of three different wavelengths ('red', 'blue' and 'green') in various ratios.

A blend of pigments, on the other hand, *subtracts* wavelengths from white light. That is to say, the pigments themselves are not the sources of the light that triggers a colour sensation, but are media that act on a separate source of illumination. 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 ofboth materials is not too strong – in the orange part of the spectrum. Each time a pigment is added to a blend, another chunk of the spectrum is subtracted from the reflected light. As a result, the colour gets duller and murkier. Each time a light ray is added to a mixture, on the other hand, more photons are injected into the resulting ray, and the combined light beam gets brighter.[8] Thus making colours by mixing pigments is called *subtractive* mixing.

Subtractive mixing inevitably penalizes the luminosity of the pigments, since more of the illumination is absorbed by the mixture. For example, most red and yellow pigments inevitably absorb a little orange light. So the orange that results from their mixture isn't very brilliant – some of the orange light is lost from the white light that illuminates the image. In contrast, a genuine orange pigment absorbs virtually no light in the 'orange' part of the spectrum and so doesn't suffer from this defect. This is why a genuine orange pigment may be more vibrant than a mixture of red and yellow. The nineteenth-century colour technologist George Field explains this in his book *Chromatography*, at the same time alluding to the chemical hazards of mixing (the possibility that the pigments might react with one another; see Chapter 11):

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Now, the more pigments are mixed, the more they are deteriorated in colour, attenuated, and chemically set at variance. Original pigments, that is, such as are not made up of two or more colours, are purer in hue and generally more durable than those compounded . . . Cadmium orange, for instance, which is *naturally* an orange pigment and not composed of red and yellow, is superior to many mixtures of these colours in a chemical sense, and to all such mixtures in an artistic sense.[9]

So the ancient taboo on mixing (see page 19) was still strong in the nineteenth century; until this time, there was not a single good, pure orange pigment available to artists, nor violet either.

Called-for colours

The six-part colour wheel captures another set of colour relationships that is of vital significance for the artist. Each primary sits opposite the secondary composed of the other two primaries: red against green, blue against orange, yellow against violet. You could say that each of these pairs contains everything, colourwise, that the other does not. They are complements of one another, like the positive and negative prints of a photographic image. (The analogy here is exact, in fact.)

Goethe recognized that strong hues tend to generate an impression of their complementary colour in the surrounding field, like a contrasting halo. The same effect arises in the 'after-image' produced when one stares at a colour for long moments and then looks away. Goethe relates how, in an inn lit by a setting sun, he saw an after-image of a fair-skinned girl in a red dress as a dark-faced figure robed in 'beautiful sea-green'. He called these opposites 'called-for' colours as though each one demands its complement.

The observation was not wholly original: among those who had previously remarked on the phenomenon of after-images in the eighteenth century were the French naturalist Comte de Buffon, the colour theorist Moses Harris, and the scientists Joseph Priestley and Benjamin Thompson (Count Rumford). But Goethe appreciated that this sensation of complementaries is a product of the visual system, and has nothing to do with the light reaching the eye at that

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