Bright Earth:
The Invention of Colour

Philip Ball
Science writer and Consultant Editor, Nature
Talk at the Royal Institution, 16 March 2001

Mailing address: *Nature*
4-6 Crinan St
London N1 9XW
UK
p.ball@nature.com

Science and art

There are many good reasons to talk about art at the Royal Institution. When Michael Faraday lectured here, art and science were still on speaking terms, and J. M. W. Turner came to consult with him about pigments. Humphry Davy studied the composition of pigments from Roman wall paintings. James Clerk Maxwell first demonstrated the principles of colour photography at the Royal Institution in 1861; and when the Institution was founded in 1799, it appointed the Yorkshireman William Savage to address the needs of the nascent colour printing technology, in particular by remedying the shortage of coloured inks.

How nice it is that art and science have once again come to represent a respectable combination. The Creating Sparks festival, hosted by the British Association last September in South Kensington, acknowledged this by looking at some of the many ways in which art and science overlap. But I notice a tendency to talk about this conjunction in abstract terms, such as whether or not the two activities draw from the same wellspring of human creativity. We hear about how scientific themes appear in art, and how art might be used to help convey scientific ideas. This is all very good; but I want to talk about connections far more concrete. I will talk about advances in art that could not have happened without science – and conversely, and perhaps more surprisingly, advances in science that stemmed from art. And let me be clear that by science, I mean both pure and applied science, because I think that the distinction often made between science and technology is a false one. The science of my talk is chemical science, which has always been an eminently useful and practical business.

The topic I shall address stems from a very simple question: from where do artists get their colours? Figure 1 shows a painting by Wassily Kandinsky, in which we can see a fantastic range and brilliance of colour. We tend to take these colours for granted now: one finds racks upon racks of bright paint tubes in any art shop. Look closely at the labels, and you will find that many of them contain complex synthetic chemicals. How long have they been available? Did Kandinsky have them? How about Monet, or Turner, or Rembrandt? In short, just how did art get its colours, and how has the invention of new colour affected the paths that art has taken?

It might seem a little strange to study art by looking at its materials. But it would not have seemed strange at all to painters of the Middle Ages or the Renaissance. They were deeply engaged with their materials, out of sheer necessity - for they made their own paints from the raw materials. These painters knew that the quality of their art depended vitally on the quality of these materials. Although that is still true today, few contemporary artists have a comparable relationship with the physical characteristics of their medium. One suspects there is a perception almost of something vulgar about such tangible aspects of art. This means not only that some artists have undertaken ill-informed and disastrous experiments with paints, but that art itself is in danger of losing touch with its roots as a practical craft – a craft that happens to have produced some of the most glorious expressions of the human spirit.

Colour in antiquity

It might have been more appropriate if Creating Sparks had happened this year, for this is the 150th anniversary of the Great Exhibition in Hyde Park, a truly monumental intersection of art and science. The Exhibition was housed in Joseph Paxton's Crystal Palace. The man responsible for decorating it was a designer named Owen Jones, and Jones decided that his colour scheme would emulate that of ancient times. The stereotypical image of the buildings and temples of classical Greece shows sun-bleached, bone-white stone. But Jones knew better. The Victorians had discovered to their astonishment that not only the walls of these buildings but the statues too were once painted in bright colours. Jones planned for the Crystal Palace to be painted in primary red, yellow and blue.

As it happened, his plan was thwarted, because interior-decorating paints at that time did not have the brightness he desired, and the results were a paler, watered-down version of his aspirations. But what about the paints of the classical world? What were they really like?

The most ancient art we know of, such as that painted fifteen millennia ago in the caves of Lascaux (Figure 2), employed pigments dug straight from the earth: ground-up minerals such as red and yellow ochre and chalk. These ‘earth’ colours are generally quite dull. The ochres are iron-rich minerals, akin to rust. For black, cave artists usually used charcoal. And so the most common colours were those that nature offered most abundantly: black, white, red and yellow.

In 1969, two anthropologists named Brent Berlin and Paul Kay claimed that colour words appear in all languages in the same sequence. Some aboriginal languages distinguish only two colours: black and white. Others have three: black, white and red. When a fourth term is added to the language, it is always either yellow or green, followed by the other of these two. So the quartet of black, white, red and yellow corresponds to a kind of universal four-colour scheme – you never find languages with, say, terms for only red, yellow, blue and orange, or just red and blue. Can it be just coincidence that these four basic colours are the ones that nature offers most readily?

The Egyptians used these pigments too; but they had a broader palette. Egypt in the third millennium BC had a surprisingly sophisticated chemical technology, some of which was learnt from Mesopotamian culture. Moreover, in Egypt the artists were priests, and art was a devotional practice. Artworks were awarded supernatural power through religious ceremonies. So the production of pigments was a socially important task.

One of the most renowned pigments of the ancient world was Egyptian blue, which is made by grinding up a copper-containing compound: calcium copper silicate (Figure 3). This substance is made by melting sand together with copper minerals and chalk. It was probably discovered as an offshoot of the manufacture of blue-glazed stones called faience, which were first made in Mesopotamia around 4500 BC. Faience was used for decorative purposes, and stimulated experiments with materials and kiln designs that probably also lead to the discovery of glass and of copper smelting, which ushered in the Bronze Age.

So this blue pigment probably arose by chance as a side-product from a technology developed for making something else entirely. This is a common pattern for pigment discovery, which recurs right through to the twentieth century. Without the social demand for substances such as glass, soap, metals, dyes and plastics, it is unlikely that many of the technologies for pigment manufacture would have evolved, or would have been economically viable. The artist's palette is partly a by-product of industrial technology.

The Egyptians also knew how to use simple chemistry to make artificial whites, yellows, reds and greens, such as verdigris, made by letting vinegar fumes corrode copper. So their colour scheme was really quite rich.

The Greeks knew of all these pigments, but they did not necessarily use them all. Some of the most renowned painters of classical Greece in 600-400 BC, such as Apelles and Nicomachos, chose deliberately to restrict their palettes to just four colours – and sure enough, these were black, white, red and yellow. It is not clear why this four-colour palette was adopted. One idea is that, as the Greeks moved beyond the flat, two-dimensional pictograms of the Egyptians to depict three-dimensional shading, they found it difficult to achieve a harmonious balance of tones with too many colours. Whatever the case, the austere four-colour palette was eventually deemed the dignified and sober choice for serious artists, a prejudice that persisted in Imperial Rome. Pliny in the first century AD condemned artists who used so-called florid colours – even the reds and yellows, he said, ought to be earth colours rather than brighter pigments such as cinnabar which, ever since Alexander the Great's conquests, could be imported from the East. Pliny feared that the sensuousness of Oriental colours would corrupt the supposed purity of artistic expression developed in classical Greece, which manifested itself in art as an elevation of the importance of form over colour. One can find this xenophobic prejudice even in the art theory of the twentieth century.

But unfortunately for Pliny, public taste was more ‘vulgar’, delighting in colour. His injunctions did not stop craftsmen from using bright colours for interior decorating, as we can see from the richly coloured wall fragments and murals that survive at Pompeii (Figure 4). Unfortunately, the mural techniques of the ancient world often don't preserve the colours well. Exposed to sun and air, they fade, discolour or flake off, leaving buildings and statues bare of their original colours and making the classical world seem now like a much more drab, pale place than it really was.

Magic and materials in the Middle Ages

According to the scholars of the Renaissance, the Dark Ages and the Middle Ages interceded between the Golden Age of classical antiquity and the rebirth of learning around the fifteenth century. But not all ancient knowledge was lost or buried with the fall of Rome. Chemical technology positively thrived in the eighth and ninth centuries – not in the Christian West, but in the Islamic Middle East, where Arabic scholars mixed Greek philosophy with the practical skills that flourished in Alexandrian Egypt. These were blended in the art of alchemy.

Even today, alchemy is still widely misunderstood. The popular images are of crazy old men boiling up potions to turn lead to gold, or charlatans getting rich by convincing gullible kings that they can perform this transformation. Some alchemy was like this, but much of it is more aptly regarded as pre-scientific chemical technology. The Italian craftsman Cennino Cennini wrote a craftsman’s manual around 1390 describing the many pigments then available and how they might be obtained, made and used. He mentions alchemy frequently – but not as an esoteric or mystical art. Instead, he regards it simply as a convenient manufacturing method for his colours.

It is no coincidence that alchemists were making colours for artists. Colour is central to alchemy. To make the Philosopher’s Stone, the substance that could allegedly transform base metals to gold, one had to conduct chemical reactions that would take the raw materials through a specified sequence of colour changes. So it is not surprising that the alchemists tended to focus their attention on the substances that offered a wide range of different colours. These turned out to be many of the same materials that artists were using as pigments.

Take lead, for instance. It was known since ancient times that exposing it to the fumes of vinegar and animal dung turned it white, owing to the formation of lead carbonate. This was known as white lead, and was the painter’s finest white pigment right up until the nineteenth century.

But if you roast white lead carefully in air, you can convert it to lead tetroxide, which is red. This pigment, called red lead, was used in the classical world at least since the second century AD. Cennino Cennini simply says of it, "A colour known as red lead is red, and it is manufactured by alchemy." In medieval Latin it was called minium, and its extensive use in medieval illuminated manuscripts gives us the word "miniature", although it is purely coincidental that these works were small (to fit on the page). The Indian and Persian miniatures of the seventeenth to nineteenth centuries, which also feature red lead abundantly, are often finely detailed but not necessarily small at all.

Further roasting of red lead creates a yellow material: lead monoxide, or litharge. This was used in the Middle Ages as a pigment, under the name massicot. To us, there is nothing extraordinary about these reactions of lead with various gases. But to the alchemists, they would have been seen as evidence of some fundamental change that was 'purifying' the lead, bringing it closer to the colour of gold.

Yet the finest red pigment of the Middle Ages was, to the alchemists, perhaps the most fascinating substance of all. The Islamic alchemists instigated the notion that all metals are composed of two basic substances or 'principles': sulphur and mercury. Alchemical or 'sophic' sulphur and mercury were considered to be somewhat abstract substances, different from the real sulphur and mercury one could extract from the earth. But nevertheless, if you mix these two raw elements together and heat them, something miraculous happens. The dirty yellow sulphur and the silvery mercury combine to form a hard, blackish red material: mercury sulphide, which turns bright red when finely ground. Painters knew it as vermilion.

The eleventh-century Benedictine monk Theophilus describes the synthesis of vermilion in his own craftsman's manual:

> ...take sulphur (of which there are three kinds: white, black, and yellow), break it up on a dry stone, and add to it two equal parts of mercury, weighed out on the scales. When you have mixed them carefully, put them into a glass jar. Cover it all over with clay, block up the mouth so that no fumes can escape, and put it near the fire to dry. Then bury it in blazing coals and as soon as it begins to get hot, you will hear a crashing inside, as the mercury unites with the blazing sulphur. When the noise stops, immediately remove the jar, open it, and take out the pigment.

This is surely as detailed as any later description of a standard laboratory synthesis, although it bears tell-tale signs of alchemical origins.

Cennino simply advises the painter to get it ready-made from the alchemists – but not ready-ground, because some of them had a tendency to adulterate it with brick dust, to make it go further.

The art historian Daniel Thompson has claimed that the invention of vermilion was the central innovation of medieval art:

> No other scientific invention has had so great and lasting an effect upon painting practice as the invention of this colour… Given abundant vermilion, the standard of intensity in the painter's palette automatically rises. Equally brilliant blues and greens and yellows were required to go with it… If the Middle Ages had not had

> this brilliant red, they could hardly have developed the standards of colouring which they upheld; and there would have been less use for the inventions of the other brilliant colours which came on the scene in and after the twelfth century.

We can see how much medieval artists loved vermilion by the way they would apply it in flat swathes, for everyone to marvel at (Figure 5).

To us, these blocks of unshaded colour look odd, a little cartoon-like. But the aim of the medieval artist was not to paint realistically. The subjects are almost always religious, and the artists themselves were often monks, or at least were hired by monasteries. They believed, like the Egyptians, that paintings had a symbolic religious power, which was enhanced if one used the finest materials and displayed them unmixed. So medieval works are rich in vermilion and gold leaf – and, in the later Middle Ages, in a still more wondrous pigment: ultramarine.

There had never been a blue like ultramarine, and I don't think there ever has been since. Cennino says,

> Ultramarine blue is a colour illustrious, beautiful, and most perfect, beyond all other colours; one could not say anything about it, or do anything with it, that its quality would not still surpass.

As its name implied, it came from 'over the seas', because the mineral from which it is made was not known in the West. Ultramarine is prepared from lapis lazuli (Figure 6), a blue stone found in Afghanistan. For centuries, all of Europe depended on the Afghan mines for their most precious pigment, which cost more than its weight in gold.

Ultramarine was precious not just because it was a rare import, but because it was extremely laborious to make. Most mineral pigments were made simply by grinding them up: this was how a green was made from the copper ore malachite, for instance. But if you grind up lapis lazuli, it turns a disappointing grey colour because of the impurities it contains. These impurities have to be separated, which is done by kneading the powdered mineral with wax and washing the wax in water – the blue pigment flushes out into the water. This has to be done again and again to purify the pigment fully.

In most of the altarpieces of the Middle Ages, the Virgin Mary is shown in blue robes (Figure 7). Various art theorists, even into modern times, have attempted to explain the symbolic significance of the blue: that it conveys humility, virtue or whatever. But the main reason for this choice of colour is that the artist would naturally have lavished the most precious pigment on the most holy aspect of the painting. That would have been the way to make the image best serve the greater glory of God. So you see, art can become harder to interpret if you ignore its materials.

Ultramarine, vermilion and gold leaf: these were the primary blue, red and yellow of the Middle Ages, the most precious colours a painter could acquire, and some altarpieces seem to use little else. But by the fifteenth century, as we approach the period of the High Renaissance, things were different.

The glorious Renaissance

Figure 8 shows Titian's *Bacchus and Ariadne*, painted in 1523. It is one of the most radiant images in Western art, and shows why Titian is considered to be one of the finest colourists of all time.

You can see at once that this is a completely different type of painting than those of the Middle Ages. There are various reasons for this. Most importantly, we are now seeing people and places depicted 'realistically', which is to say, in an attempt to show them as they would appear to a real observer of the scene. Light and shade, perspective, proportion and anatomy are all accurately observed. This is the key feature of the Renaissance Humanism: actual human experience became the central concern of artists and writers, so that it was no longer sufficient to produce stylized, iconic works of art that paid only lip service to the shapes and forms of the world we live in. Renaissance artists put the viewer right in the picture. This new style is often traced back to the Italian painter Giotto di Bondone, who worked in the early fourteenth century.

This change meant that the materials of the painter no longer had the symbolic values of the Middle Ages. Ultramarine was still greatly prized - but because it was a beautiful and pleasing colour and because it showed off the wealth of the painter's patron, not because its expense makes it akin to a devotional offering to God. Gold leaf gradually disappears from use during the fifteenth century, since its costliness counted for nothing if it didn't produce a realistic effect. Painters preferred to mimic gold using yellow, white and brown pigments instead.

And furthermore, Titian's paints are totally different to those of medieval artists. Pigments have to be mixed with some fluid binding medium to make a paint, and in the Middle Ages egg yolk was used as the binder. But Titian and his contemporaries mixed their colours with oils. Oil painting was perfected in Northern Europe in the early fifteenth century by the Flemish artist Jan van Eyck, and was gradually adopted by the Italians from around 1460. In the so-called egg tempera method, the paints dry almost instantly; but oils are much slower in drying. This meant that colours could be blended and mixed, permitting the soft shadows and subtle shading that we see in Renaissance art.

The use of oils also brought about some changes in pigment use, because some colours look different when bound in oil from when bound in water or egg yolk. In particular, both ultramarine and vermilion are more transparent and less brilliant in oil. This forced painters to adulterate ultramarine by mixing it with a little lead white to keep it strong and opaque, which helped to erode its mystique. As a result, artists began to feel more free to use a whole range of lighter blues in their works. The art historian Paul Hills says that "Blue by the fifteenth century was moving away from its association with starry night, the vault of the heavens, to the changeful sky of day." This, then, was a change in colour use instigated by the physics and chemistry of the artists' materials.

But there were other reasons why Titian and his contemporaries had a wider range of colours available than most medieval artists. Titian lived and worked in Venice, which along with Florence was the artistic capital of Renaissance Italy. Venice was a major port, where many of the rare spices, foods, textiles and pigments from the East first arrived. So the Venetian artists had first pick of the best colours, and they made abundant use of materials such as ultramarine and yellow orpiment which came from the Arabic nations. This made Venetian art extremely colourful. In Florence, on the other hand, where Leonardo da Vinci and Michelangelo worked, there was greater emphasis on line – on drawing skills – than on colour. The art world of the Renaissance initiated a long-lasting debate on the relative merits of colour and line in art, which resolved itself around the seventeenth century in favour of skill at drawing as the artist's most important attribute, with colour being merely the icing on the cake. This cast a shadow (literally) over the use of colour in art until the nineteenth century.

But during the fifteenth and early sixteenth centuries, Venetian art was full of bright colour. In *Bacchus and Ariadne* Titian uses just about every one of the pigments then available, and in doing so he provides us with a map of the state of sixteenth-century chemistry.

The brilliant blue sky is ultramarine, as is Ariadne's robe. But the sea, which has a greenish tint, is painted in azurite, a blue copper mineral known since ancient times. This is a cheaper pigment, although the best grades were still quite expensive. There were azurite deposits in several places in Europe, including France, Hungary, Germany and Spain. Imported ultramarine rarely made it all the way to Northern Europe, at least at an affordable price, and so most of the blues in the works of German and Dutch artists in the Renaissance are azurite.

There's vermilion here too, in Ariadne's scarf, but also another kind of red pigment: red lake. This is made from red dyes, which are organic materials. Some red dyes were extracted from plants, such as brazil wood and madder root. Others came from animals: cochineal was made in the sixteenth century from ground-up dried beetles, and *lac* or *lacca*, from which lake gets its name, was a resin secreted by certain tree-dwelling insects from Asia and the Middle East. These dyes were converted to lake pigments by dissolving the colouring agents in water and fixing them onto the surface of fine particles of an inorganic white mineral-like substance such as aluminium oxide. This procedure was known in the Middle Ages, but was not really perfected until the Renaissance. Red lakes are darker and richer than vermilion; there was a common red lake known as kermes, derived from a Sanskrit word meaning "taken from a worm", which is the root of our word crimson. Lakes are translucent when used in oils, and Renaissance painters often used them as translucent glazes to give rich flesh tones or to make purples by red glazing over blue.

Renaissance yellows were typically compounds of lead, tin and antimony, which the Egyptians had known how to make. But in *Bacchus and Ariadne* there is also a brighter, richer golden yellow called orpiment, which is arsenic sulphide: the name means "pigment of gold". It can be found naturally in mineral form, but a better-quality pigment could be had by making orpiment synthetically. Its manufacture was surely an alchemical discovery, as Cennino hints. It is highly poisonous, and some painters avoided it for this reason. Cennino warned: "Beware of soiling your mouth with it, lest you suffer personal injury". In view of this and its high cost, orpiment is quite rare in Renaissance art, particularly in Northern Europe. One Northern painter who did make use of it is Lucas Cranach, who had better access to it than most others because he also ran a pharmacy, and was therefore knowledgeable in the materials and methods of alchemy.

Also in this picture is the only pure orange pigment known until the nineteenth century – painters otherwise had to make orange by mixing red and yellow. The orange here is realgar, a different form of arsenic sulphide. It also occurs naturally, and was imported to Europe through Venice from Romania and the East. Because it was so poisonous, it wasn't very popular – Cennino warns painters who use it to "look out for yourself".

The fall and rise of colour

Something happened to colour during the seventeenth and eighteenth centuries. Rubens often painted as brightly as Titian, but we remember this period mostly for the more subdued palettes of Rembrandt, van Dyck and Poussin. European art went through a period of subdued colour. There wasn't much innovation in pigment manufacture during this time, and it is interesting that several of the new pigments that did appear were in the autumnal colours typical of Rembrandt. The prevailing attitude of the connoisseurs in the early nineteenth century was summed up by Sir George Beaumont, an artist and a patron of John Constable, who said "A good picture, like a good fiddle, should be brown" (Figure 9).

Here is Constable being dutifully brown. If pictures weren't brown enough, Victorian conservators often made them so with a coat of muddy varnish. In Constable's defence, he is said to have protested by taking a violin and placing it on grass to show how different the two colours were. But nevertheless he observed the convention that expected artists to tone down their colours. The fact that he was actually considered an innovator with an unusually bright palette tells us how truly murky colour had become by the early nineteenth century.

Let's have a look at these autumnal colours. For Baroque painters who liked their works dark and golden, there was Cassel earth, a peaty substance with a warm brown colour that Van Dyck liked so much that it later became known as Vandyke brown. And there was bitumen, an appalling brown pigment that never dried and ended up ruining several nineteenth-century paintings. There was Indian yellow, a mysterious, smelly yellow substance imported from India by the Dutch and used by Rembrandt, which turned out to be made from the urine of cows fed exclusively on mangos. And there was a new yellow pigment, strangely enough called pink, which was made from a plant extract in a manner similar to lake pigments. It was only because a rose-red version of the same pigment persisted in use for longer that the word "pink" became associated instead with a pale red hue.

But in the late eighteenth century, a new rainbow began to spread across the artist's palette. This was the golden age of chemistry, when new elements were being discovered by the handful and Antoine Lavoisier was starting to make sense of chemical transformations such as burning. The question of who discovered oxygen has three contenders: Lavoisier, who named it, and Joseph Priestley and Carl Wilhelm Scheele, both of whom still believed in the old phlogiston theory of combustion.

Scheele was one of the greatest experimental chemists of his time – he also isolated hydrogen, barium and chlorine, which was soon used by the dyeing industry as a bleach. And in 1775, Scheele discovered a green substance while experimenting on arsenic compounds. This was copper arsenite, which soon became used as a green pigment called Scheele's green. It was brighter than any of the earlier pure green pigments – until then, many painters had made greens instead by mixing blue and yellow. There are some paintings in the National Gallery with blue leaves, where the glaze of yellow lake has faded.

Scheele's green was eclipsed by the discovery in 1814 of a new, more attractive arsenic-based pigment, which became known in England as emerald green. Unfortunately it was also potentially poisonous: if exposed to dampness, it decomposed into arsine, a toxic gas. Because they were quite cheap to manufacture, emerald green and Scheele's green were used not only as artist's paints but as household paints and on patterned wallpaper. This made damp rooms death traps, and in the 1860s there were fears in England that young children were being killed by the deadly fumes emanating from their bedroom walls. It is also believed that Napoleon's death in exile on St Helena was hastened in the same way.

Perhaps the most important innovations in artists' colours in the nineteenth century stemmed from the discovery in the late eighteenth century of a bright red mineral from Siberia, called crocoite or Siberian red lead (Figure 10). In the early nineteenth century the French chemist Nicolas Louis Vauquelin investigated crocoite and discovered that it contained a new metallic element whose compounds were brightly coloured. For this reason he proposed the name *chrome*, from the Greek word for colour. We now know it as chromium.

Crocoite is a mineral form of lead chromate. When Vauquelin made this compound synthetically, he found it had a bright yellow colour. This became used as a pigment called chrome yellow – not just for artist's paints but also for commercial ones. It was widely used to paint coaches, for example, anticipating its use on the yellow taxi cabs of New York.

Vauquelin found he could also make a different form of lead chromate that was orange – the first pure orange pigment since poisonous realgar. And chromium oxide was a green colour. With a little water incorporated into the crystals, this provided the rich green pigment called viridian in England.

The new pigments just kept on coming. In 1817 a German chemist called Friedrich Stromeyer discovered a new element called cadmium, a by-product of zinc smelting. He found that this metal could be combined with sulphur to make bright yellow and orange pigments called cadmium yellow and cadmium orange. In the early twentieth century a deep red version became available too. This cadmium red became very popular; Matisse was particularly fond of it.

In the late eighteenth century the French government considered pigment manufacture so commercially important that it appointed leading chemists to devise new ones. The government asked Louis-Jacques Thénard to look for a synthetic substitute for expensive ultramarine. In 1802, Thénard found a way to make a rich blue colour from cobalt, which became known as cobalt blue. Cobalt offered several other colours too: in the 1850s a cobalt-based yellow pigment called aureolin became available in France, followed soon after by a purple pigment called cobalt violet, the first ever pure purple pigment. A sky blue pigment called cerulean blue, made from cobalt stannate, was a favourite of some of the post-Impressionists.

What painters really wanted for a blue, however, was a cheaper form of ultramarine itself. In 1824 the French Society for Encouragement of National Industry offered a prize for the first practical synthesis of ultramarine. It is a complicated compound to make – the blue colour comes not from a metal but from the presence of sulphur. In 1828, a Frenchman named Jean Baptiste Guimet claimed the prize, which was immediately disputed by the German pigment manufacturer Christian Gmelin, who argued that he had done it first. Well, the French decided patriotically to stick with Guimet, and synthetic ultramarine is often known as French ultramarine.

So pigment manufacture was now big business, and no longer a cottage industry performed by apothecaries. Factories were set up in the nineteenth century to make and grind pigments. Some sold them in pure form to the artist's suppliers, who would then mix up paints for their customers from pigment and oil. But some pigment manufacturers, such as Reeves and Winsor & Newton in England, provided ready-made oil paints which, from the 1840s, were sold in collapsible tin tubes.

Either way, this meant that painters became ever less familiar with what it was they were buying, and had no way of assessing the quality of this profusion of new paints. And so a new breed of professional began to appear: the colourman, who knew the skills of the painter but also possessed some chemical knowledge that allowed him to test the materials that he supplied to artists. In England, the foremost colourman of the nineteenth century was George Field, who supplied paints to Turner and the Pre-Raphaelites (Figure 11). Notice in particular the vibrant greens here, which some critics called 'unripe enough to cause indigestion'. These painters relied on Field's judgement as to whether or not a colour was reliable – whether, for example, it would rapidly fade or discolour on the canvas.

Thanks to Field, Turner was able to acquire the new colours almost as soon as they were invented, and he was amongst the first painters in England to use cobalt blue, emerald green, viridian, chrome yellow and others. This was a gamble, even with Field’s assistance, because some of these colours might lose their brilliance over a matter of several years. Several of Turner’s works have suffered from the instability of his colours.

All the same, Turner remains one of the greatest innovators in colour, and brought a blaze of Venetian brightness to the dour palettes of most early nineteenth-century art (Figure 12). This was considered shocking by many contemporary critics: one of them said of this picture that it was "a specimen of colouring run mad – positive vermilion – positive indigo; and all the most glaring tints of green, yellow and purple". Joris-Karl Huysmans, a prominent art critic before he gained notoriety as a novelist, saw things differently. With the Oriental love of colour in mind, he compared Turner to "a Rembrandt born in India".

Turner's use of colour was an important influence on the Parisian Impressionists such as Monet, who came to London to see his work. The Impressionists made equally avid use of the new colours. Figure 13 gives an indication of the colours that the Impressionists had at their disposal. The shock of seeing their work was not just that of seeing a new style of painting, without the clear edges and smooth finish favoured by the French Academy of Fine Arts, but also that of seeing colours never before known on canvas. In *Boating on the Seine* (1879-80) by Pierre-Auguste Renoir (Figure 14), apart from the traditional lead white there are just seven pigments, and all but the reds are "modern" synthetic colours: cobalt blue, viridian, chrome yellow, "lemon yellow" (strontium chromate) and chrome orange (basic lead chromate). They are applied almost unmixed, and the impact of the new pure orange is very apparent in the boat's outline. placed against the cobalt blue river. This is Impressionism straight from the tube.

The orange and blue look all the more striking here because they are directly juxtaposed. This was a favourite trick of the Impressionists, who learnt from nineteenth-century colour theorists such as the chemist Michel-Eugene Chevreul that colours look more brilliant when placed next to their complemetary colour: red against green, blue against orange, yellow against purple. One finds a lot of these complementary contrasts in works by Monet.

The Impressionist style shaped the early work of many of the most important painters of the modern age. Paul Cézanne began as an Impressionist, and Vincent van Gogh’s work was transformed when he came to Paris and saw these paintings. They gave him the inspiration to use bold, unmixed new colours with glaring brilliance, such as those in *The Night Café*, painted in 1888 (Figure 15). With the harsh dissonances in this work, Van Gogh said,

> I have tried to show that the café is a place where one can ruin one's self, go mad, or commit a crime.

He relied on the strength of these colours to convey the passion of his visions. In a letter to his brother Theo, he said:

> I have got new ideas and I have new means of expressing what I want, because better brushes will help me, and I am crazy about those two colours, carmine [a red lake, probably made from a synthetic dye] and cobalt. Cobalt is a divine colour, and there is nothing so beautiful for putting atmosphere around things. Carmine is the red of wine, and it is warm and lively like wine. The same with emerald-green. It is bad economy not to use these colours, the same with cadmium.

So you can see how artists found these new colours a direct source of inspiration.

Henri Matisse was also an Impressionist early in his career, but he later used the new pigments to even more stunning effect as the figurehead of the movement known as the Fauves: a French word meaning "wild beast", reflecting the uninhibited use of bright colour (Figure 16). Fauvism made colour a central constructive component of modern art. Kandinsky initially painted in the Fauve style too, and went on to try to discover a kind of universal emotional language of colour. None of this would have been possible without the development of the vibrant new pigments in the nineteenth century.

Dye manufacture

This explosion of colour was not just confined to fine art. As chemistry blossomed, it brought colour into the world at large. In 1766 the Scottish chemist William Cullen outlined the chemist's goal:

> Chemistry is the art of... producing several artificial substances more suitable to the intention of various arts than any natural productions are... Does the dyer want the means of tinging a cloth of a particular colour? Or does the bleacher want the means of discharging all colours? It is the chemical philosopher who must supply these.

A hundred years later, this seemed to be possible. Organic chemists had discovered how to make new dyes from the aromatic hydrocarbons found in coal tar, the black residue from gas-lamp burning. These new dyes engendered fashions in dress that would strike us as garish even today. Women took to the streets in voluminous dresses and gowns of purple, magenta and other rich colours. The 1850s were the Purple Decade, as we can see reflected in *April Love* by the Pre-Raphaelite Arthur Hughes (Figure 17).

It was painted in 1856, and it was in that year that the first coal-tar dye was made by William Perkin, who was just eighteen years old at the time. As a boy, Perkin used to come here to listen to Michael Faraday lecture, and he enrolled at the Royal College of Chemistry in Piccadilly under the German chemist August Wilhelm Hofmann. He discovered the coal-tar dye called mauve while trying to make the anti-malarial drug quinine at Hofmann's instruction, and he immediately quit his studies and set up in business with his father and brother, at a factory in Harrow. The gamble paid off, and half a century later Perkin was a rather shy and reluctant celebrity, and regarded as one of the greatest organic chemists of the age (Figure 18).

Perkin initially tried selling the dye under the name Tyrian purple, harking back to the legendary purple dye of Imperial Rome, extracted from Mediterranean shellfish. But there was more to be gained by association with Parisian high fashion than with Classical antiquity, and the word mauve comes from the French word for mallow.

Coal-tar dyes were followed by synthetic versions of natural dyes: in 1868 chemists made alizarin, the molecule that gives madder red its colour; and in 1877 indigo was synthesized. This led to the collapse of dye-growing industries in Europe and in the British colonies in India. But it also spawned the entire modern chemicals industry. The commercial call for dyes was immense, and dye manufacturers thrived. Towards the end of the century they began to diversify into new areas, particularly pharmaceuticals. In 1909 Paul Ehrlich discovered the first synthetic drug - Salvarsan, a cure for syphilis - after experimenting with staining of cells using synthetic dyes. All the chemicals giants today – Hoescht, BASF, Agfa, Bayer, Ciba-Geigy – began their lives as dye manufacturers. So you could say that not only did chemistry beget colour, but colour begat modern chemistry.

Twentieth-century blues

The pigments of modern times encode their own stories about how art evolved in the twentieth-century. If I had time, I would talk about the influential colour theory of the chemist Wilhelm Ostwald, who was also an amateur artist and made his own pigments. Ostwald exerted a strong influence on the colour scales used by commercial paint manufacturers in Germany. And I would have liked to trace the evolution of the Day-Glo colours of Andy Warhol and Roy Lichtenstein. Or the impact of new synthetic paint media like acrylics and alkyds on the colour choices of the Abstract Expressionists and their successors: in the 1950s US artists like Frank Stella started using household paints made with these new resins, and so their palettes lay at the mercy of the commercial paint companies. Stella took colour into new territory by using metallic paints in some of his works. But I shall conclude with a single modern parable about chemistry and colour in art: the story of the world's most beautiful blue.

Yves Klein was never an artist in the league of Turner, Rembrandt or Titian, but he is remembered for one thing: International Klein Blue, which he used for a series of monochrome paintings in the 1950s (Figure 19).

You can't do this colour justice in a reproduction - you have to see it at first hand to appreciate how lovely and lustrous it is. Klein believed that colour alone was sufficient to say all he wanted to say, without the distraction of line and form. In 1954 he said,

> I believe that in future, people will start painting pictures in one single colour, and nothing else but colour.

And that's just what he did.

Klein's blue is in fact none other than ultramarine - that is, the synthetic version of ultramarine devised in the nineteenth century. But ultramarine never looked like this before - at least, not on the canvas. Klein realized that pigments always tended to look richer and more gorgeous as a dry powder than when mixed with a binder, and he wanted to find a way to capture this appearance in a paint. In 1955 he found his answer: a new synthetic fixative resin called Rhodopas M60A, which could be thinned to act as a binder without impairing the chromatic strength of the pigment. This gave the paint surface a matt, velvety texture. Klein collaborated with a Parisian chemical manufacturer and retailer of artists' materials named Edouard Adam to develop a recipe for binding ultramarine in the resin mixed with other organic chemicals. To protect this wonderful new paint from misuse that would compromise the purity of his idea, he patented it in 1960.

The significance of this little episode in art history is to show not only that some artists were still depending on chemical assistance in the modern era, but also that the intimate relationship of painters to their materials has not been entirely severed. Today painting is an unfashionable art. Young artists want to work in sculpture, installation and video. One hears stories of how students at art schools who wish to do something as outmoded as painting automatically risk lower marks. There are still painters who care deeply about colour and paint, but they are few - Howard Hodgkin and Bridget Riley come to mind, and, in a brownish greyish way, Frank Auerbach. In an age when painters have more choice of materials than ever before, this might seem strange. But I wonder whether in a way that surplus of choice might contain the very problem: artists have lost confidence in paint because they no longer feel they understand it. I can't help but feel sad at how different this is from the spirit apparent in an account by the photographer Georges Brassai of a conversation with Picasso (Figure 20). This is what Brassai said:

> 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!

Further reading

P. Ball (2001). *Bright Earth: The Invention of Colour*. Penguin, London.

D. Bomford, J. Kirby, J. Leighton & A. Roy (1990). Art in the Making:

Impressionism. National Gallery Publications, London.

Cennino Cennini (c.1390). *Il Libro dell' Arte*. Translated by D. V. Thompson as *The Craftsman's Handbook* (1960). Dover, New York.

R. L. Feller (ed.) (1986). *Artists' Pigments: A Handbook of Their History and Characteristics* Vol. 1. Oxford University Press.

E. West Fitzhugh (ed.) (1997). *Artists' Pigments: A Handbook of Their History and Characteristics* Vol. 3. Oxford University Press.

J. Gage (1993). *Colour and Culture*. Thames & Hudson, London.

R. D. Harley (1982). *Artists' Pigments c.1600-1836*, 2nd Edn. Butterworths, London.

A. Roy (ed.) (1993). *Artists' Pigments: A Handbook of Their History and Characteristics* Vol. 2. Oxford University Press.

D. V. Thompson (1956). *The Materials and Techniques of Medieval Painting*. Dover, New York.

A. S. Travis (1993). *The Rainbow Makers*. Associated University Presses, Cranbury, NJ.

Figures

Figure 1. Wassily Kandinsky, *Picture with a Red Spot* (1914). Centre Georges Pompidou, Paris.

Figure 2. Cave art from Lascaux, France, painted c.15,000 BC.

Figure 3. *Hunting Birds in a Papyrus Thicket*, wall painting from the tomb of Nebamun, 8th Dynasty (c.1567-1320 BC), Thebes. British Museum, London.

Figure 4. Mural from the Villa of Mysteries, Pompeii, c.50 BC.

Figure 5. Altarpiece attributed to Masaccio and Masolino (c.1423-8). St Jerome's drapery is rendered in vermilion. National Gallery, London.

Figure 6. Lapis lazuli, cut and polished. Natural History Museum, London.

Figure 7. Duccio, *The Virgin and Child with Saints Dominic and Aurea* (c.1315). The Virgin's robes are painted in ultramarine. National Gallery, London.

Figure 8. Titian, *Bacchus and Ariadne* (1523). National Gallery, London.

Figure 9. John Constable, *The Valley Farm* (1835). Tate Gallery, London.

Figure 10. Crocoite (natural lead chromate). National Museum of Natural History, Smithsonian Institution, Washington.

Figure 11. John Everett Millais, *Ophelia* (1852). Tate Gallery, London.

Figure 12. J. M. W. Turner, *Ulysses Deriding Polyphemus* (1829). Tate Gallery, London.

Figure 13. The Impressionist palette. From D. Bomford *et al*. (1990). *Art in the Making: Impressionism*. National Gallery Publications, London.

Figure 14. Pierre-Auguste Renoir, *Boating on the Seine* (1879-80). National Gallery, London.

Figure 15. Vincent van Gogh, *The Night Café* (1888). Yale University Art Museum.

Figure 16. Henri Matisse, *Woman with a Green Hat* (1905).

Figure 17. Arthur Hughes, A*pril Love* (1856). Tate Gallery, London.

Figure 18. Portrait of William Henry Perkin by Arthur Stockdale. National Portrait Gallery, London.

Figure 19. Yves Klein, *IKB 2* (1961). Sammlung Lenz Schoenberg, Munich.

Figure 20. Pablo Picasso, *The Three Dancers* (1925). Tate Gallery, London.