Part One
Fundamentals

1
Spectral Colour Reproduction

1.1 INTRODUCTION

Three hundred and fifty years ago, a physics student at Cambridge University would have been told that

> White is that which discharges a copious light equally clear in every direction. Black is that which does not emit light at all or which does it very sparingly. Red is that which emits a light more clear than usual, but interrupted by shady interstices. Blue is that which discharges a rarefied light, as in bodies which consist of white and black particles arranged alternatively. . . . The blue colour of the sea arises from the whiteness of the salt it contains mixed with the blackness of the pure water in which the salt is dissolved (Houston, 1923).[1]

No wonder that Pope wrote:

'Nature and Nature's Laws lay hid in night
God said "Let Newton be!" and all was light.'

In 1666 Newton laid the foundation-stone of colour science, when he discovered that white sunlight was composed of a mixture of all the colours of the spectrum, and this discovery is also the natural starting point to a consideration of the fundamentals of colour reproduction.

1.2 THE SPECTRUM

Suppose we are taking a colour photograph of a street in daylight. All the light falling on the street comes from the sun, either directly when the sky is clear, or after diffusion by clouds if the sky is overcast, or after scattering in the atmosphere if there is blue sky. Since sunlight is a mixture of all the colours of the spectrum, our street scene is being illuminated by such a mixture, and some of the components of this mixture will be revealed by certain natural objects. Foliage contains a dye called chlorophyll which has the property of absorbing reddish, yellowish and bluish light, but transmits greenish light; hence, when foliage is illuminated by

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[1] References will be found at the end of each Chapter, and, in the text, are identified by the author's name and the year of publication of the work referred to.

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daylight, it suppresses the reddish, yellowish and bluish components of the light so that only the greenish components are seen by the eye, and we say that the foliage looks green. Similarly, if the street contains a greengrocer's shop and tomatoes are displayed, the tomatoes look red, because they absorb most of the bluish, greenish, and yellowish components of the daylight, and reflect mainly the reddish components. It is thus clear that both the quality of the illuminant and the nature of the objects contribute towards the colour seen. If we return to the street after dark, and find that it is lit by sodium lamps, we shall find that the leaves and the tomatoes now look brown because the illuminant contains only yellow light and this is absorbed by the foliage and tomatoes; there being no green light for the foliage to reflect, and no red light for the tomatoes to reflect, these colours cannot be seen.

However, the sodium lamp is very exceptional as far as its colour is concerned, and most sources of light are similar to the sun in that they usually emit a mixture of all the colours of the spectrum. This is true of electric filament lamps, electronic flash, and most fluorescent lamps. This being so, the extent to which an object reflects the different colours of the spectrum provides a very useful measure of its colour properties.

So far we have only spoken loosely of reddish, yellowish, greenish, and bluish light without defining exactly to which part of the spectrum it belongs. Since all light has wave-like properties, and light in different parts of the spectrum corresponds to waves of different length, it is convenient to define each spectral colour by the wavelength of its light. The wavelengths are all extremely short, and convenient units of measurement are: the micron or micro-metre (µm) which is a millionth of a metre, the milli-micron (mµ) which is one thousandth of a micron or, which is the same thing, the nano-metre (nm) which is one thousand-millionth (10^{-9}) of a metre, and the Ångström (Å) which is one ten-thousandth of a micron. In the rest of this book we shall mostly use the nano-metre. The main spectral colours occupy approximately the following wavelength bands: violet 450 nm and less; blue 450 to 480 nm; blue-green 480 to 510 nm; green 510 to 550 nm; yellow-green 550 to 570 nm; yellow 570 to 590 nm; orange 590

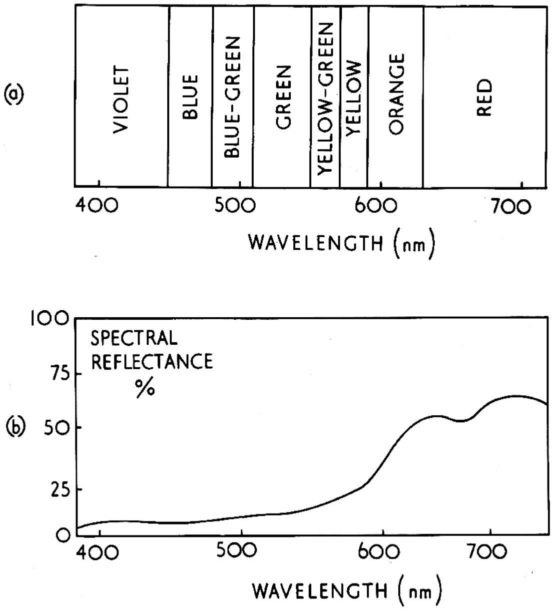

Fig. 1.1. (a) The distribution of colours in the spectrum. (b) The spectral reflectance curve of a red colour.

to 630 nm; red 630 nm and greater. These regions are shown in Fig. 1.1(a). There is a gradual transition from one colour to another throughout the spectrum, and the viewing conditions affect where one colour ends, and the next begins.

In Fig. 1.1(b) the amount of light reflected at each wavelength by a particular red surface is plotted as a percentage of the amount of light falling on the surface at each wavelength. The curve thus obtained is called the spectral reflectance curve of the sample, and provides a detailed description of the colour properties of the surface. In the case of this red colour it is clear that about 65 per cent of the red light is reflected, 55 per cent of the orange, 30 per cent of the yellow, 15 per cent of the yellow-green, 10 per cent of the green, 10 per cent of the blue-green, 5 per cent of the blue, and 5 per cent of the violet. And these reflectances result in the particular red colour of this surface, actually that of a red tomato.

Now suppose we take a colour photograph of a scene containing this particular tomato. We shall reproduce it as a patch of colour, perhaps on paper, and it is obvious that if our patch of colour has the same spectral reflectance curve as the original tomato, then it can produce the same effect; for, physically, the two colours will be identical. And since they are physically identical they will look alike in identical circumstances. Thus if the original and the reproduction are viewed in the same surrounds first in sunlight, then in electric filament light, and then in sodium light, they will always look alike, although of course they will both change colour as the illuminant is changed. Moreover, they will look alike in colour to animals and to colour-blind persons.

1.3 THE MICRO-DISPERSION METHOD OF COLOUR PHOTOGRAPHY

Such colour reproduction would be spectrally correct but can only be achieved in practice by methods that are far too inconvenient for general use. There are two methods that have been suggested and they are both photographic: the micro-dispersion method, and the Lippmann method. The former is shown diagrammatically in Fig. 1.2. The camera lens focuses the image on a coarse grating, consisting of parallel slits, alternately opaque and transparent, about 1/300th of an inch apart. A large plano-convex field lens then collects the light from all the slits and passes it through a narrow-angle prism. Lenses on both sides of the prism focus images of the slits on a photographic plate, and the image of each slit is drawn out into a small spectrum by the prism. Thus the light from each part of the picture is spread out into a spectrum and hence the spectral reflectance curve of every part of the picture is recorded on the plate. The plate is then developed and fixed in the normal way and a positive print made on another plate (or alternatively the original plate can be reversed), and the positive thus obtained is replaced in the plane of the spectra in exact registration. By passing white light through the system in the reverse direction (from right to left in the diagram), and by using the camera lens as a projection lens, a colour reproduction is obtained in which each part of the picture has the same spectral reflectance curve as that of the original.

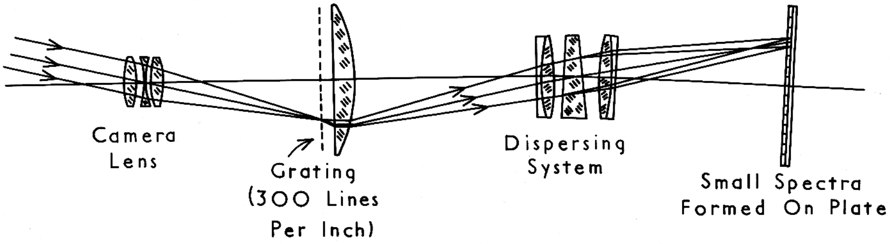

Fig. 1.2. The micro-dispersion method of colour photography (diagrammatic only).

However, the difficulties of the method will at once be appreciated. The more important are: the equipment required is bulky and costly, the grating reduces the amount of light, and an extremely fine-grain (and therefore slow) emulsion has to be used in order to record the minute spectra. But the method is of interest in that it provides colour reproduction that is spectrally correct.

1.4 THE LIPPMANN METHOD

The other method of colour photography that can give spectrally correct colour reproduction is one of the most fascinating photographic inventions ever made. In 1891 Professor Gabriel Lippmann of Paris, by special techniques, made a photographic emulsion with grains (silver-halide crystals) only 0.01 to 0.04 μm in diameter. This emulsion he coated on plates, which he exposed in an ordinary camera, except that the emulsion side of the plate was turned away from the lens, and a layer of mercury was poured against it, as shown in Fig. 1.3(a). The emulsion-mercury interface then acted as a mirror, and the reflected and on-coming waves interfered with one another to produce standing waves in the emulsion. This standing wave pattern was duly recorded in the emulsion as latent image, and, upon development, parallel plates of silver were produced, the distance between successive plates being equal to half the wavelength of the light used in making the exposure. Thus in Fig 1.3(a), the beam perpendicular to the plate represents green light, and the oblique beam, red light. Since red light is of longer wavelength than green light, the plates of silver are more widely spaced for the oblique beam than for the perpendicular beam. The emulsions were made sensitive throughout the spectrum by the use of a sensitizing dye (Eder, 1945).

After processing the plate to a negative, it is viewed by reflected light as shown in Fig. 1.3(b). There is no need to make a positive by reversing the plate, since the developed silver layers of the negative are of such fine grain that they give a positive image when viewed by reflected light. This positive image, moreover, is coloured, for the plates of silver will strongly reflect light of half-wavelength equal to the distance between the plates, and weakly, or not at all,

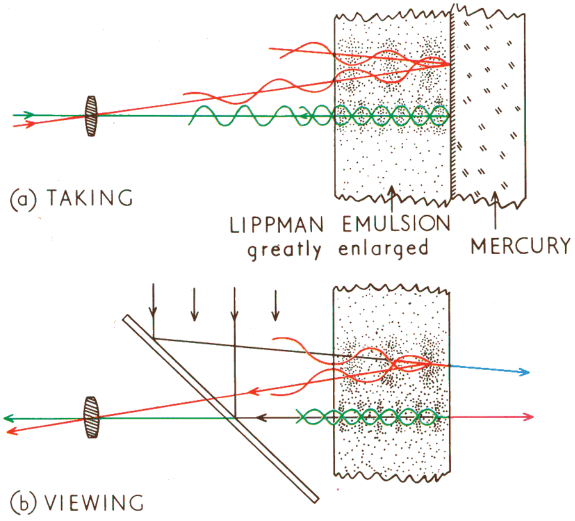

Fig. 1.3. The Lippmann method of colour photography (diagrammatic only).

light of other wavelengths. Hence all spectral colours, and in fact all other colours also, are reproduced with spectrally correct colour rendering.

Professor Lippmann and other later workers have produced many beautiful colour photographs by this method, and it is probably the most elegant method that will ever be devised. Its disadvantages, however, are of a severe nature. First, the Lippmann emulsions, because of their extremely fine grain, are extremely slow, and exposures of several minutes are necessary to make a Lippmann colour photograph even in bright sunlight. It is impossible to use a fast emulsion because the interference pattern that has to be recorded is smaller than the grain-size of fast emulsions. Secondly, the necessity for viewing the results by reflected light means that it is difficult to project Lippmann colour photographs on to a screen with adequate light; and even when viewed directly by reflected light the angle of viewing is critical. (Nareid, 1988.)

1.5 USE OF IDENTICAL DYES

In some circumstances it is possible to reproduce the spectral reflectance curves by using the same dyes as were present in the original objects. A textile manufacturer, when trying to reproduce a given colour on an undyed fabric, will achieve spectrally correct colour reproductions if the same dyes are used in the same amounts as were used on the pattern. In this book, however, we will generally understand the phrase *colour reproduction* to refer to making pictures of original scenes, and the use of identical dyes is then usually possible only in the special case of copying an existing colour photograph or print by means of a process that uses the same dyes or inks (this is discussed in Section 15.7).

1.6 APPROXIMATE SPECTRAL COLOUR REPRODUCTION

By using as many as six differently coloured dyes, inks, or pigments, it is possible to achieve colour reproduction in which the spectral composition appoximates that of many originals (Taplin and Berns, 2001). This procedure can enlarge the gamut of reproducible colours, and this can be useful in copying works of art (see Section 28.16); it can also reduce changes in accuracy of colour rendering when differently coloured illuminants are used, and this is important in the mail-order catalogue business.

1.7 A SIMPLIFIED APPROACH

In view of the difficulties inherent in the micro-dispersion and Lippmann methods of colour photography, it is not surprising that they have never become popularly used, and the feasibility of using as many as six colorants is very limited. Were it not for the fact that when the human eye views colours it simplifies their complexity, none of the present-day methods of colour reproduction would work.

The rest of the book, therefore, is devoted to describing the principles and methods of achieving colour reproduction by an approach that is basically much more simple: instead of all the colours of the spectrum being dealt with wavelength by wavelength, their effects are considered in three groups only, as is the case with the human eye.

Although this approach leads to methods of colour reproduction in photography, television, and printing, which are highly successful in practice, we shall see that a proper understanding of them does sometimes involve some quite complicated considerations. It is therefore suggested that the general reader may prefer to omit Chapters 8, 9, 15, 16, 17, and 22, at the first reading.

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