COLOUR MATCHING AND MIXING WITH PARTICULAR REFERENCE TO MAXWELL'S DISC

Allan Mills

Retired from Dept. of Physics, University of Leicester, U.K.

allanmills1@hotmail.co.uk

Abstract

The theory of colour mixing is divided into additive mixing of coloured lights and subtractive mixing of pigments. It is shown how the young James Clerk Maxwell attempted to quantify colour nomenclature and additive mixing with his spinning 'colour disc', made up of adjustable sectors of the three 'primary' colours red, green and blue, plus black or white. Some experimental demonstrations are suggested.

Mankind everywhere is very fond of colour, but nevertheless we commonly experience great difficulty in accurately describing or naming a given tint. Therefore, we frequently resort to comparing it with a widespread natural colour, e.g. 'sky blue' or 'leaf green'. However, in the 19th century, commercial development resulted in attempts to quantify the description and replication of colours. Two distinct schemes arose – one applied to the additive combination of beams of coloured light, the other to the subtractive mixing of pigments and paints.

I : Additive mixing of coloured lights

White light may be split by a prism or grating into a *spectrum,* conventionally divided into red, orange, yellow, green, blue and violet. It was found that a patch of light of a given colour could often be matched by additively mixing light beams of three frequencies or colours, one from each end of the spectrum plus one from the middle. Clerk Maxwell[1] found that for humans with normal colour vision this third colour is *green,* which when combined with *red* and *blue* lights produces the sensation of white. Red, green and blue lights are therefore termed PRIMARY colours; research with the spectroscope has shown that they centre around:

	nm
RED	650
GREEN	510
BLUE	475

They are shown (within the limitations of the colour printing process) in Fig. 1. They may be approximated by plastic colour filters[2] held within three independent projecting systems. Carefully controlled interference filters are much better defined, and are used by the Lovibond Tintometer Company in their colour-matching and testing instruments.[3]

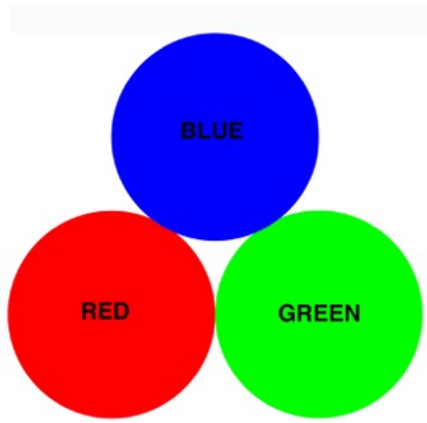


Fig. 1 Primary colours for additive mixing of coloured lights.

Projected adjacent to one another on a white wall we would in principle see Fig. 1 and, if positioned to overlap, true primary colours would combine additively to give the result represented in Fig. 2. It may be surprising to note that red and green beams combine to give a

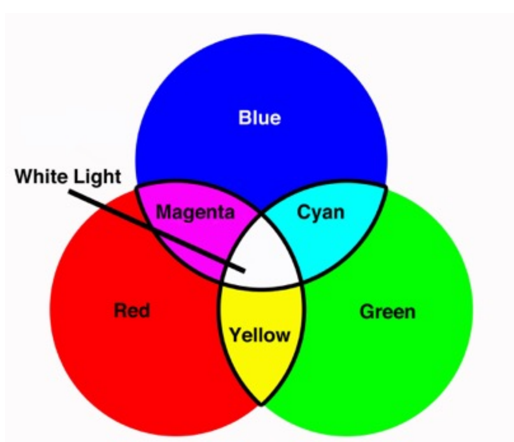


Fig. 2 Results of additive mixing of overlapping primaries.

sensation of *yellow,* just like the monochromatic yellow light in a spectrum. Red plus blue gives *magenta,* while blue plus green gives a blue-green best labelled *cyan.*

The mixing of coloured lights is diagrammatically represented by the additive colour triangle, shown here in Fig. 3.

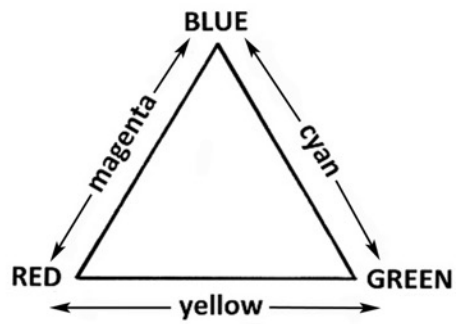


Fig. 3 The additive colour triangle.

Maxwell's colour disc

It will be observed that greys and browns are not reproduced in the above schemes, although variations of these colours are common in the natural world. Greys are in fact very low intensity mixtures of all the primaries, while browns are low-intensity yellows produced from red + green in varying ratios.

In order to match colours in a quantitative manner, James Clerk Maxwell[4,5] (while still a student) developed the *colour disc* he is holding in Fig. 4. The only sources of colour available to him were artists' paints, and he chose red, green and blue in (as near as he could get) primary shades. Discs of thin white card were coated with these paints and, when dry, a radial slit cut in each. Inserting a nail through the common centres enabled the discs to be fitted together in such a way that sectors of adjustable angular width could be exposed (Fig. 5). He then attached the assembly to a short wooden rod, held it securely in a wire frame, and spun it by pulling on a thin cord wrapped around the axle.

Fig. 4 The young Clerk Maxwell with his 'colour disc'.

This gave the effect of additive mixing of amounts of primary colours proportional to the angular width of their exposed sectors. (Making a point at the end of the rod and spinning the assembly like a top would not generally have been successful, because of the inherent asymmetry following adjustment.)

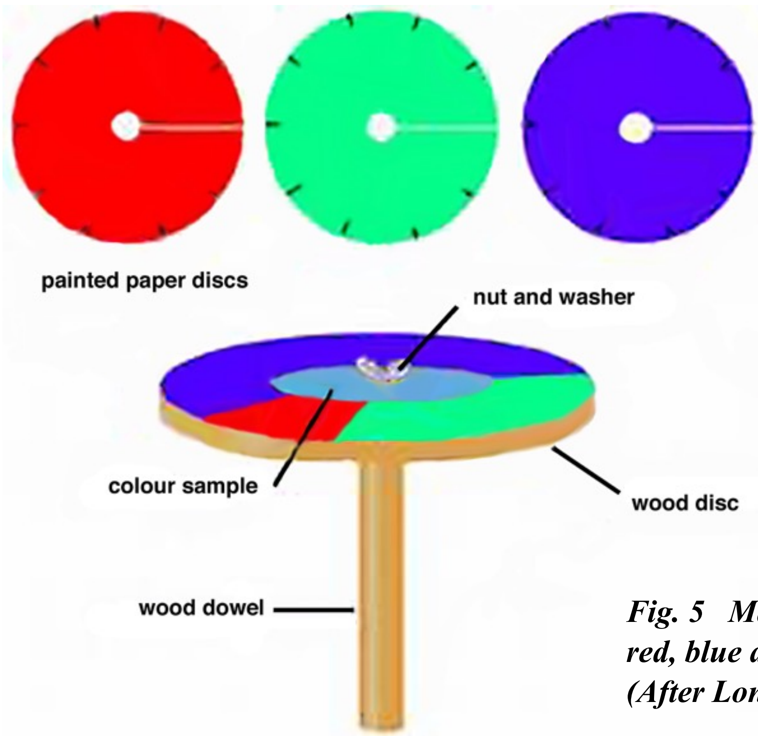


Fig. 5 Maxwell's method for combining red, blue and green in adjustable ratios. (After Longair[6], by permission)

For colour matching experiments a small disc of the coloured material to be analyzed was fixed at the centre, and the assembly spun as before. Illumination by a specified source was essential, for colours can appear to vary with different illuminants. Matching was attempted by adjusting the angular widths of the exposed red, green and blue sectors, but could rarely be achieved with natural colours. To do this, Maxwell added adjustable slit discs of white or black card. White diluted the combined colour and made it lighter, while black card decreased the resultant intensity and made it appear darker. Browns and greys could therefore be synthesized, and assessed quantitatively by measuring the angular width of each constituent sector of the matching tint with a protractor, or inscribing graduation marks on the sectors themselves.[6]

The biggest problems with Maxwell's disc was that it could not be adjusted to a close match while rotating, and only experience guided the choice of sector to be adjusted and by how much. Perhaps this is why it never achieved widespread application.

Only in later life did Maxwell develop the equations of electrodynamics with which he will always be associated.[7]

Experimental demonstration

It is not easy to obtain paints in guaranteed primary colours. Stationers do, however, commonly stock A4 packs of heavy paper ('art card') in assorted colours. Red, green and blue sheets may then be chosen that are sufficiently close to the primary colours of Fig. 1 for demonstration purposes, but must not be expected to give colour values identical with those in reference works.

Cut 6 inch diameter discs of the chosen colours with scissors, and punch small holes in their centres with a sharp cork-borer. Then make a radial slit in each, and interlace the discs together through these slits so that adjustable sectors may be exposed. Secure loosely on a screwed bolt with washers and a nut , and then hold the bolt in, for example, the chuck of a hand drill. (I used the mechanism from a battery-powered novelty fan, but do not use an electric drill or any mains motor – much too hazardous!) Adjust the sectors to 120° each (Fig. 6a), slightly tighten the nut, and rotate rapidly in daylight. The resulting visual appearance will probably be a rather dull white (Fig. 6b).

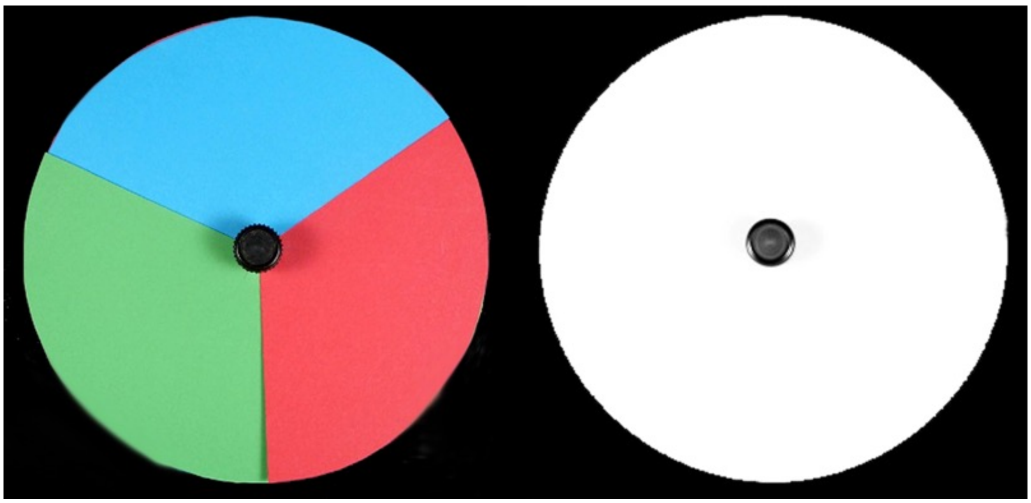


Fig. 6 (a) 120° sectors of red, blue and green.
Fig. 6 (b) Effect of additive mixing by rotation.

5 inch diameter discs of black or white card bearing radial slits may then be added on top of the coloured examples (leaving a border of the unmodified colour) and finally a 2.5 inch diameter disc (no radial slit) of the sample under test. Secure by tightening the nut, and spin with the chosen device when illuminated by daylight. Adjust the amount of each sector exposed until a

reasonable match with the central sample is achieved. A certain small exposure of black or white card will probably be required to adjust the apparent tint to match many natural samples.

I examined samples of brown (kraft) paper (Figs. 7a and b) and an evergreen leaf (Figs. 8a and b). Measuring the angular extent of each sector with a protractor, and calculating the relative areas of each as a percentage of 360^{o}, gave the results below:

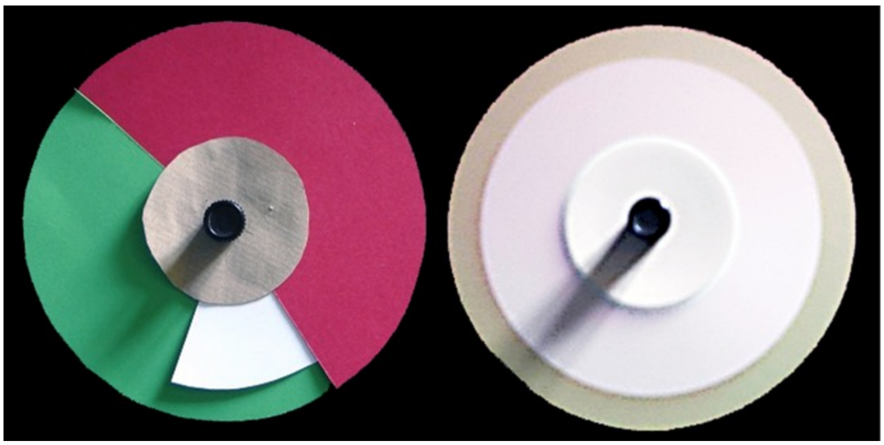


Fig. 7 (a) Disc with additional adjustable white sector, plus a central sample of brown kraft paper. Fig. 7 (b) Appearance on rotation.

<u>Kraft paper</u>

	%
Red	53.9
Green	31.7
Blue	0.0
White	14.4

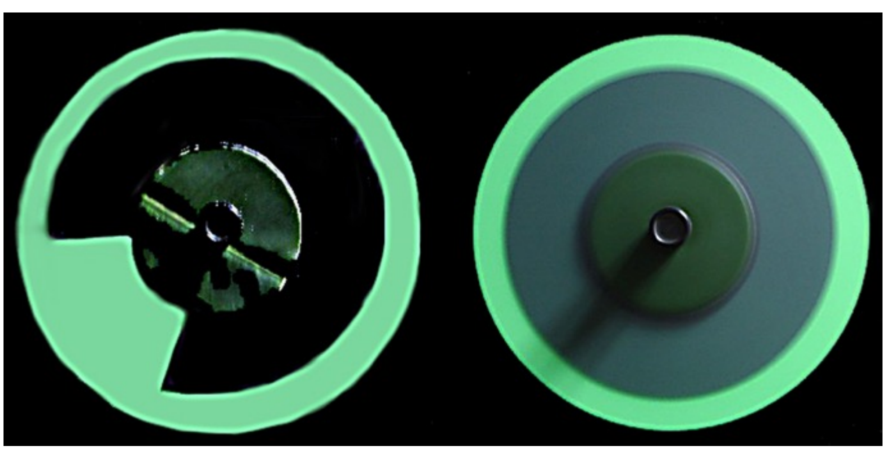


Fig. 8 (a) Disc with additional adjustable black sector, plus a central sample of a dark evergreen leaf. Fig. 8 (b) Appearance on rotation.

Dark evergreen leaf

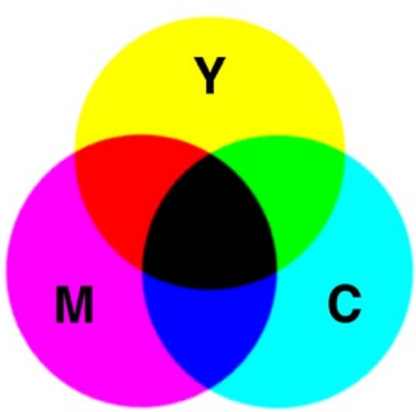
Red	0.0
Green	9.7
Blue	0.0
Black	90.3

Remember that other samples of coloured card and different illuminants may not give identical figures.

II Subtractive mixing of pigments and paints

A coloured pigment is a finely-ground solid that absorbs much of any white light that falls upon it and reflects the rest. A paint is a suspension of pigment(s) in a transparent liquid medium containing either a dissolved resin or a constituent that polymerizes to a resistant solid upon exposure to the oxygen of the air. A classic example is linseed oil. The suspension may be thinned with a volatile solvent (e.g. turpentine) to aid spreading and uniform coating of surfaces. Paints are nowadays available commercially, and commonly used directly from the can. However, artists have always preferred to purchase tubes of concentrated suspensions of pigments in oil, and mix portions by experiment on their palettes until a desired shade has been achieved.

It will be realised that the resulting colour is that which is reflected in common by all the intermingled pigments. By considering the mixing of coloured lights discussed above, the basic colours might be chosen to be magenta, yellow and cyan, mixing in pairs producing red, green and blue (Fig. 9). Mixing all three basic colours would- if they are pure – result in complete absorption of light – i.e. black. This 'scientific' colour triangle is shown in Fig.10.



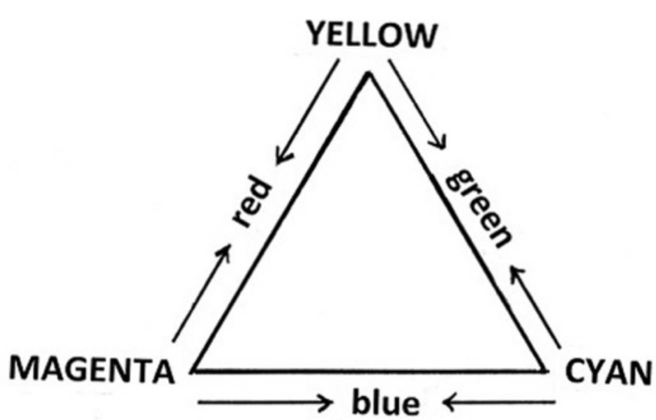


Fig. 9 (left) Magenta, yellow and cyan as primary colours for subtractive mixing.

Fig. 10 The 'scientific' subtractive colour triangle.

However, long ago artists decided that they preferred to designate their strongest red and blue as primary colours, necessitating *yellow* as their third primary if greens were to be obtained by mixing it with blue (Fig. 11). Mixing red and blue paints gives a residual purple, while orange

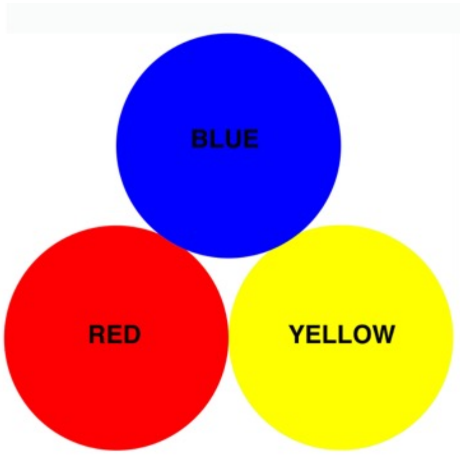
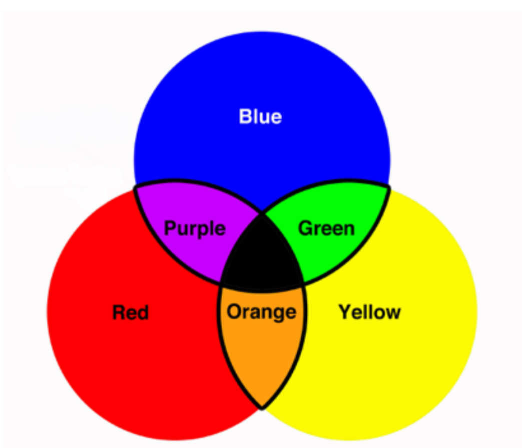


Fig. 11. The traditional primary colours used by artists for subtractive colour mixing of paints.

results from the subtractive mixing of red with yellow (Fig. 12). Combining all three pigments results in general absorption across the spectrum, theoretically producing a black. The 'artists' colour triangle is shown in Fig. 13, and has been extended to entire 'colour wheels'.[8] This system is so firmly established that there is no possibility of replacing it – and no good reason to do so!



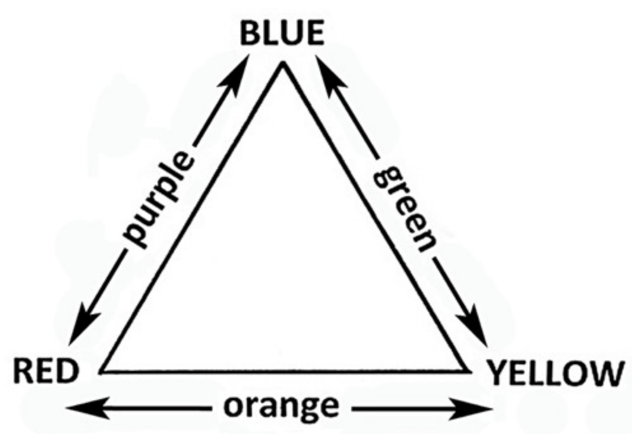


Fig. 12 (left) Subtractive mixing of traditional primary colours.

Fig. 13 The traditional 'artists' subtractive colour triangle.

Experimental demonstrations

It has already been remarked that it is difficult to obtain artists' colours in guaranteed primary colours. The best approximations I have located are 'Crafter's Choice' acrylic paints in:

Red :	Scarlet PNTA-119
Yellow:	Pale yellow PNTA-111
Green:	Light green PNTA-132
Blue:	Pale blue PNTA-122

These may be squeezed from their polythene containers, mixed thoroughly, and applied to a white card to illustrate the results of blending coloured paints.

Another method of demonstrating subtractive colour mixing is to hold the transparent primary colour filters specified above in pairs, one above the other, in front of a source of white light. This makes it clear that only the colour common to both filters penetrates the combination. Superimposing all three should result in complete obscuration – i.e. black – but rarely does!

Additive mixing of red, blue and yellow

It was of interest to see what tint Clerk Maxwell would have seen by additively mixing red, blue and *yellow* in equal amounts. Six inch diameter discs of these colours were therefore cut from painted card, slit radially, and interlaced so that 120° of each colour was exposed (Fig. 14a). Rotation in daylight produced the sensation of a buff colour (like a manila folder) as shown in Fig. 14b.

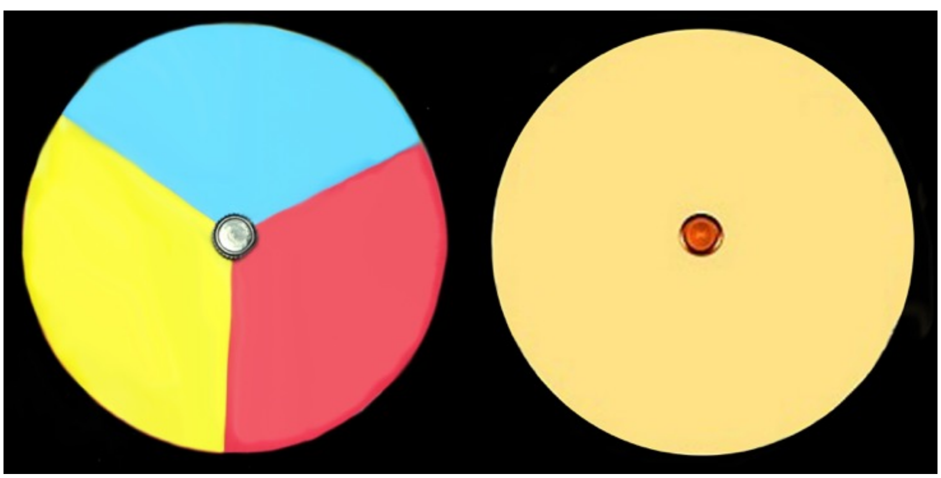


Fig. 14 (a) (left) Disc with 120° sectors of red, blue and yellow.
Fig. 14 (b) Appearance when spinning in daylight.

Acknowledgements

Grateful acknowledgement is made to the editor of *Phil.Trans.* for permission to reproduce the diagram shown here as Fig.5.

References:

1. J. Clerk Maxwell, Experiments on colour as perceived by the eye, with remarks on colour blindness *Trans. Roy. Soc. Edin.*, (1855), **21,** Part II.

2. 'Stagedepot' on the Web. Swatches of Rosco filters for stage lighting are available. Try red E106, dark green E124 and deep blue E120.

3. Lovibond Tintometer Group. See Web. URL???

4. W.D. Niven, *The Scientific Papers of James Clerk Maxwell* (Cambridge, 2 vols) See Vol. I, 1890, pp 126-154 and plate I.

5. B. Mahon, *The Man Who Changed Everything: the Life of James Clerk Maxwell,* 2003, (Wiley). See especially Ch.5.

6. M.S. Longair, "Maxwell and the science of colour", *Phil.Trans.Roy.Soc. A (*2008), **366,** pp. 1685-1696.

7. Ibid. ref. 4.

8. P. Mollica,. *Color Theory,* 2013 (Foster).

Biography

Allan Mills retired 18 years ago from the post of senior lecturer in the Department of Physics and Astronomy of the University of Leicester. Although it is difficult to do research in modern science at home, he has found a vast – and largely untapped – field in experimental and practical studies in the history of science. allanmills1@hotmail.co.uk