7 Digital colour reproduction

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Abstract: With the advent of digital computers colour reproduction systems have been very quick to adopt digital image processing in every field of image reproduction. Digital information is based on digits representing data in physical quantities of binary digits of 0 and 1. In any colour image reproduction in any system the fundamental logic is based on balancing basic colours to produce 'grey balance', producing pleasant shades of basic colours called 'tone reproduction' and reproduce as clean colours as possible to avoid muddy colours in final reproduction is called 'colour correction'.

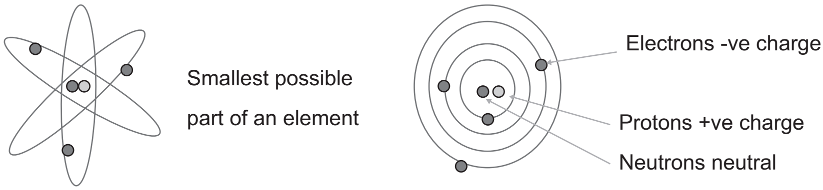
Key words: digital, bit depth, grey levels, additive, substractive, grey balance, tone reproduction.

7.1 Introduction

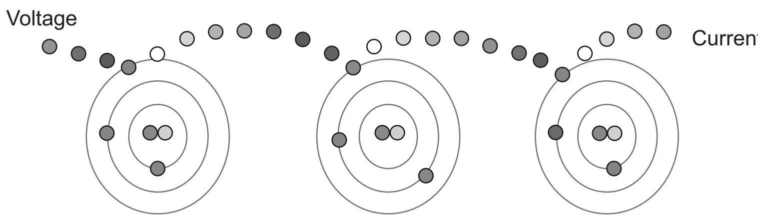
In reproduction systems most analogue methods have given way to the digital technology, whether in photography, printing on various substrates or textiles, television, or computer graphics. Analogue methods refer to all manual methods where no computers are used, but with the advent of digital computers the term *analogue* is also used for analogue methods of computing data. An analogue signal varies continuously, according to information, and thereby the data are represented in a continuous form. The device that converts this continuous representation into mathematical calculations using electrical voltages is called an *analogue computer*. The final output is a continuous form analogue signal. Digital information is based on digits representing data in physical quantities of binary digits of 0 and 1. A digital signal is a discrete or discontinuous electrical signal.

7.2 Digital imaging fundamentals

The basic raw materials that are the building blocks of our world, such as carbon, aluminium, copper, etc., are known as *elements* and are the most basic form of material, difficult to break down any further. If



7.1 Structure of an atom.



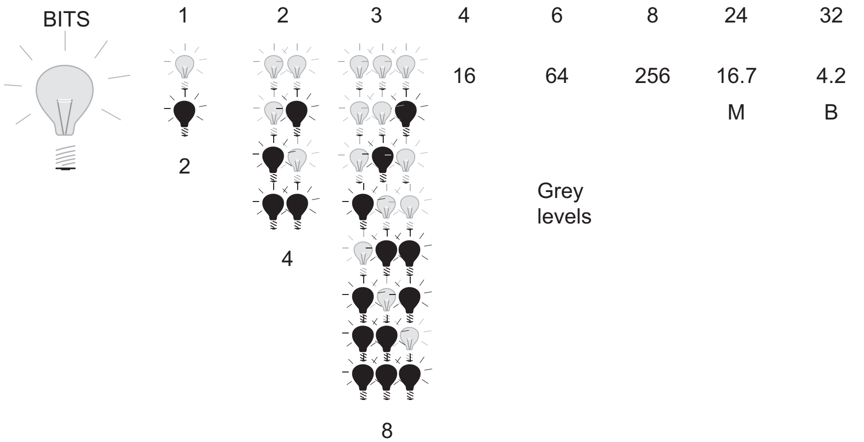
7.2 Flow of electrons.

elements are broken down, then the smallest possible part of an element is called an *atom*. Atoms are very fine, e.g. one gram of copper contains 10 000 000 000 000 000 000 000 atoms (Young, 1975, p. 1). Further breakdown of atom yields *electrons*, *protons*, and *neutrons*. Electrons carry negative charge while orbiting around the nucleus. The nucleus consists of protons carrying positive charge, and neutrons are neutral. An atom is normally in a neutral state, as negatively charged electrons and positively charged protons balance out each other. See Fig. 7.1.

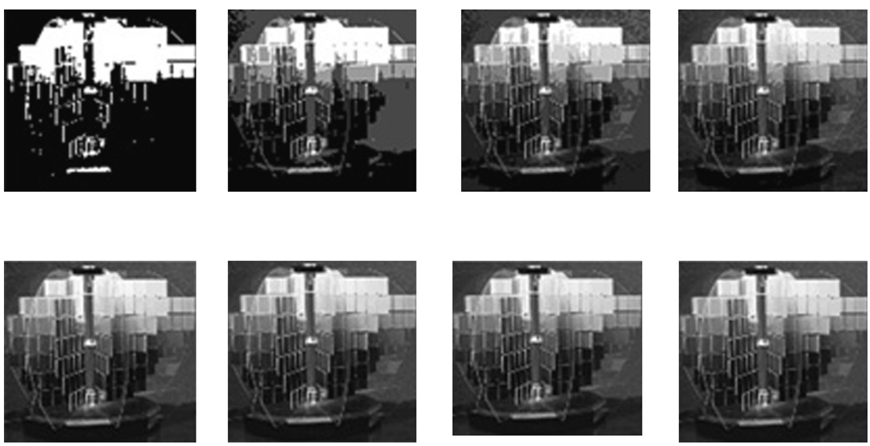
When an electromotive force, *voltage*, is applied, an electron from the outermost orbit is dislodged and travels to the next atom. In this process, the atom from which electron is dislodged becomes positively charged, due to loss of the electron, and the next atom that gains the dislodged electron becomes negatively charged. In this process, atoms have a natural tendency to become electrically neutral and, therefore, the flow of electrons, called *current*, will continue as long as voltage is applied. See Fig. 7.2.

In digital computers, only two digits, 0 and 1, rule the world of computers. 0 is assigned when no current flows, and 1 is assigned when current flows. Various combinations of 0 and 1 constitute a signal, and because the information is represented in two digits they are called *binary digits* or, in short, *bits*. For meaningful information, a minimum of eight digits or bits, called a *byte*, are required.

0 = no current flows
1 = current flows



7.3 Bits and grey levels, result of possible on–off conditions.

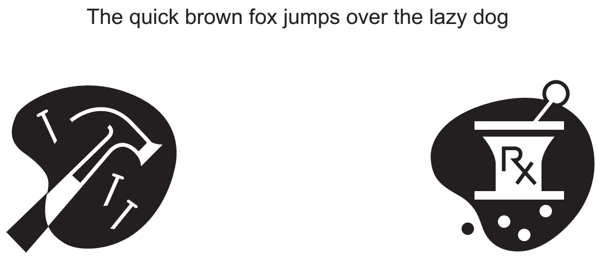


7.4 Grey levels and visual effect in pictures.

A = 01000001 *a = 01100001*
B = 01000010 *b = 01100010*
1 = 00110001 *2 = 00110010*

The same principle, when applied to pictures and graphics, works as follows. One bit of information can have two shades, i.e. when current flows the impression obtained is white, and when no current flows the impression is black. With 1 bit, the possible combinations are 2 shades, 2 bits give 4 shades, 3 bits give 8 shades, 4 bits give 16 shades, and so on. Twenty-four bits give 16.7 million shades, and 32 bits give 4.2 billion shades. These shades

7.5 Bits, grey levels and tonal separation in single colour.



7.6 One bit images giving two grey levels appearance.

are called *grey levels*. See Figs 7.3 and 7.4. Grey levels affect the separation of tones, and its smoothness in the picture. For good smoothness of tones without banding, i.e. without any harsh jump of tones, a minimum of 256 grey levels is required – see Fig. 7.5.

In colour reproduction there are two possibilities. In computer and television graphics three colours, red, green, and blue are used, whereas in printed pictures cyan, magenta, and yellow are used in analogue photography, and cyan, magenta, yellow, and black in photomechanical printing processes. In such cases, 256 grey levels of each of the component colours are necessary for good tonal effect. See Plates XXVII, XLI, and XLII (see colour section between pages 146 and 147).

In RGB pictures the number of bits are:

8 bits red + 8 bits green + 8 bits blue = 24 bits

and grey levels obtained are:

256 red × 256 green × 256 blue = 16.7 million

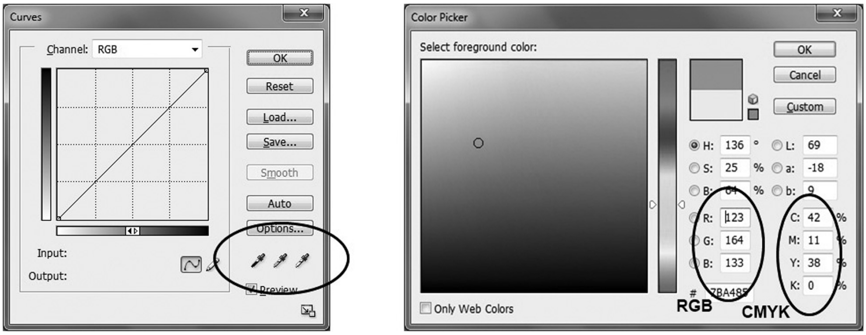
In CMYK pictures the number of bits are:

8 bits cyan + 8 bits magenta + 8 bits yellow + 8 bits black = 32 bits

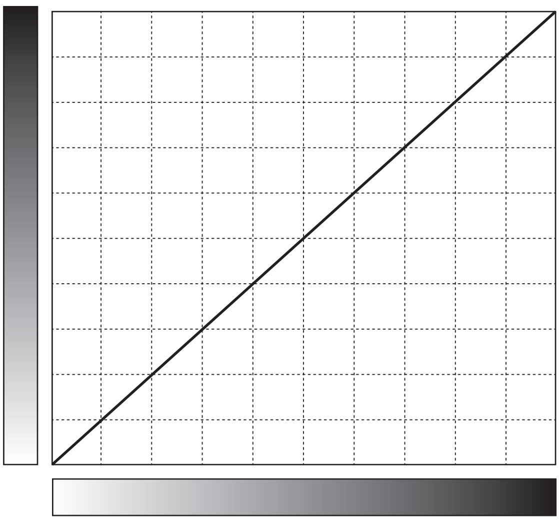
and grey levels obtained are:

256 cyan × 256 magenta × 256 yellow × 256 black = 4.2 billion

The RGB reproduction principles outlined above apply equally well to image capturing by colour scanners and digital cameras. CMYK principles are also applicable to colour scanners where, after capture in RGB, the signals are converted to CMYK, like earlier special purpose graphic arts



7.7 Adobe Photoshop grey balance control for highlight, midtone, shadow available for RGB and CMYK images.



7.8 Facsimile reproduction.

scanners manufactured by Crosfield Electronics, Dr Hell, Itek Graphics, Dianippon Screen, PDI, and Scitex. File size naturally changes depending on the number of component colours, and it is always 25% less in RGB than in CMYK pictures, as number of colour signals changes from 4 to 3.

7.2.1 Digital measurements

As explained earlier a *bit* (binary digit) is a single digit giving only two grey levels. This situation exists in single colour text or line drawings where various shades or tones of the same colour are absent, see Fig. 7.6.

However, to produce these images for meaningful representation, the digital computer needs an eight bit signal, as explained. This eight bit signal is called one byte. Digital measurements are as follows:

One BYTE is eight BITS and represents one character, such as A, B, C, D, ……..

One KILOBYTE is 1000 BYTES or 8000 BITS and represents 1000 characters.

One MEGABYTE is 1000 KBYTES, 1 000 000 BYTES or 8 000 000 BITS. This represents 1 000 000 characters or a single colour 11 square inch picture at an average resolution of 300 pixels per inch. *Pixel* is a short form of picture element.

One GIGABYTE is 1000 MBYTES, 1 000 000 KBYTES or 1 000 000 000 BYTES or 8 000 000 000 BITS. This represents 1 000 000 000 characters or a single colour 111 A4 size, or 27 four colour A4 size pictures at an average resolution of 300 pixels per inch.

For an explanation of picture representation see Section 7.6, 'Image capturing devices'.

7.3 Colour reproduction

Colour reproduction in any system has to satisfy certain basic rules to achieve good colours in a scientific and systematic manner. We have only three basic colours – red, green, and blue – in the case of *additive colours*, or three secondary colours – cyan, magenta, and yellow – in the case of *subtractive colours*. White, grey, and black are only the presence or absence of colours, also sometimes called *psychological primary colours*.

7.3.1 Grey balance

If white, grey, and black are only psychological colours then why look at these or consider greys? In colour reproduction, these *greys* are reproduced using three primary colour phosphors, red, green, and blue on television or computer screen or with sensors in digital camera and, of course, in the human eye, and with three secondary colour dyes, cyan, magenta, and yellow in photographic film or in photo print, or with pigmented inks in photomechanical printing processes. Greys produced with these colours help to exercise good control over the colour reproduction in any process.

Grey is the partial presence of all the colours of the spectrum or three basic colours. In greys, any small imbalance of colours makes it appear coloured towards the shift of the strong colours – see Plate XXVII (see colour section between pages 146 and 147) (good reproduction), Plate XXVIII (red bias), Plate XXIX (green bias), and XXX (blue bias). To illustrate this effect, the colour bias is exaggerated in these examples. It can be seen that grey scale on the right and greys in the picture (ground in the front) show more pronounced effects than the coloured tops worn by the girls, and comparatively much less in the extreme white and black.

In colour television or computer monitors, three major controls are provided: colour, brightness, and contrast. When the colour controls are turned off completely, the monitor looks black and white. These various shades of greys seen are generated from three colour phosphors: red, green, and blue. Any defective or *uncalibrated* monitor shows colour bias towards the presence of the strong colour, generated by a stronger analogue or digital signal.

In digital cameras and colour scanners, whether conventional drum or flatbed, a setting for *white balance* is provided. Some call it *input calibration*, that is white, grey, and black in the picture should be seen by the digital camera or scanner as they are without any bias towards any colour. Unfortunately, this is not paid due attention by many in the reproduction or photography industry, which results in extra colour correction work in *PhotoShop* or similar software and loss of detail.

Like input calibration, *output calibration*, or producing greys with three colour dyes in photography or pigment inks in the printing processes, is very important. For good results, both the calibrations must be achieved; only one on its own is of no use. In photography, the proportion of three colour dyes is balanced to give greys. In gravure printing this is sometimes possible, as the process works on the volume of inks deposited on the substrate. In colour television or computer monitors, the analogue or digital colour signal strength is adjusted to produce equal intensities of the three colour phosphors to produce grey.

In the printing industry the tonal values in the print are achieved with the help of *dots*. These dots vary in size, as in the case of *AM screening*, or form clusters, as in the case of *FM screening* techniques – see Plate XXXI (see colour section between pages 146 and 147). The process of tonal value reproduction is binary, in the sense that all areas carry the same amount of ink, unlike photography or gravure printing. The tonal values perceived by the eye depend on the area covered by the printing ink. In this case, it is the area covered by three secondary colour inks, cyan, magenta, and yellow combined to give *grey* effect, provided these are well balanced in dot size. However, unlike photography or television and computer output, it is not possible to get good greys in dark tonal values in the printing processes, due to its binary nature. This is overcome by the addition of black ink to the three colour inks.

Thus, to reproduce *grey* using coloured dyes and inks, or coloured phosphors, on television monitors is the most basic and first step in colour reproduction. This holds true in conventional drum scanners, flatbed scanners, colour software, and so on – see Fig. 7.7 – or new colour management systems – see Plate XXXII (see colour section). If not done, faulty colour reproduction is inevitable.

As stated earlier, any colour bias is first visible in the neutral grey areas, and not so visible in saturated colour areas. This provides more latitude in colour reproduction for saturated colour areas than grey areas – see Plate XXXIV (see colour section between pages 146 and 147). Ellipses marked show the latitude possible without affecting visual differences in colours. It can readily be seen that saturated colours have wide latitude, whereas greys have very little latitude.

7.3.2 Tone reproduction

The second most important criterion, after *grey balance*, is *tone reproduction*. Tone reproduction affects how the details in the picture are reproduced. For good detail, it is very important that all tonal values or shades in the picture are properly separated.

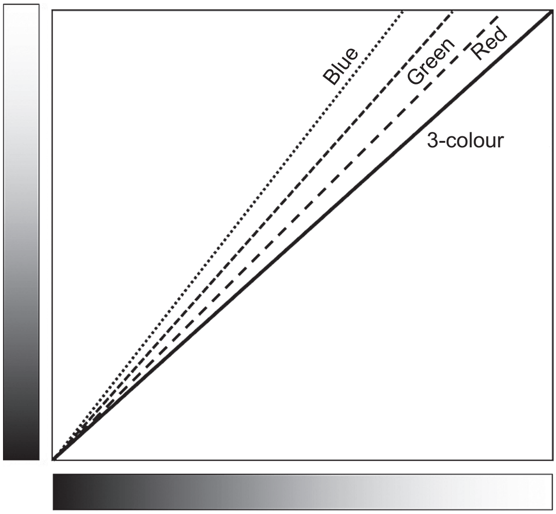
Any perception in the human eye of the outside world is produced by various intensities of light entering in the eye. Light shades reflect a more intense light than dark shades, and thus different intensities produce different shades and consequently the picture detail. A scale of *greys* used by the photographers or in the printing processes helps to indicate proper rendition of tones. Similarly, on colour televisions or computer monitors, *brightness* and *contrast control* settings are used to adjust tonal values.

To illustrate, it is best to first understand single colour black and white reproduction. Any two identical pictures reflecting same amount of light from any point of the picture will appear exactly the same as far as their visual reception is concerned. This means that original and reproduction will match exactly (Yule, 1967, p. 85). This can be represented by a 45° straight line on a graph – see Fig. 7.8. This is called *facsimile reproduction*.

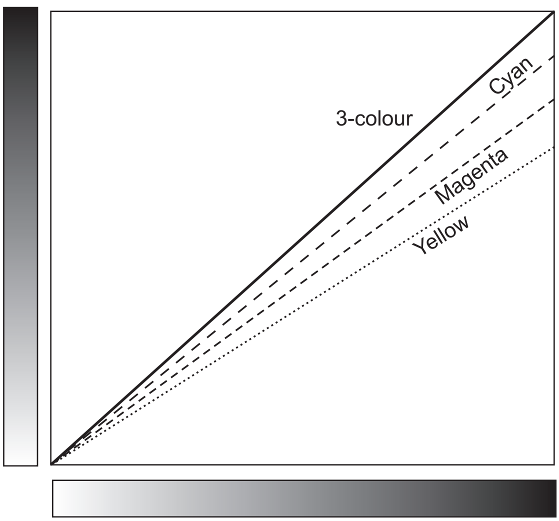
In black-and-white reproduction, one is dealing with a single colour curve to achieve an exact match. In the case of colour, however, there are three or four colour curves which, when combined, the intensities should match the single colour black-and-white curve, in terms of greys as well as tonal values – see Fig. 7.9, RGB process, and Fig. 7.10, CMY process.

Figure 7.9 is for television, computer monitors, and digital cameras (all RGB reproduction systems), and Fig. 7.10 is for analogue photography and printing processes (CMY reproduction systems). In both, to achieve 45° line reproduction the individual three colour curves are required to be set approximately as indicated for good detail in the picture. The difference in the three curves is due to certain faults in the dyes and pigments, and setting this way is to achieve 'grey balance'.

Due to the binary nature of the printing processes, three colours, cyan, magenta, and yellow, do not produce greys throughout the tonal scale and, therefore, black ink is required to convert the brownish tone in the deep



7.9 RGB grey balance and tone.



7.10 CMY grey balance and tone.

shadows to greys as well to improve its details – see Fig. 7.11. This is not necessary in the photographic processes, as the proportions of the three colour dyes can be changed to print greys in the shadow areas. The same is sometimes done in gravure printing processes. *A word of caution – in practice tonal curves are rarely 45° lines, but are usually 'S' shaped.*

Plates XXXIV, XXXV, and XXXVI (see colour section) show the effect on colour pictures when the tone curve changes. Plate XXXIII is the reproduction of original picture, kindly supplied by Paritosh Prayagi. Plate XXXIV almost eliminates all tones between highlight and shadow, giving line drawing effect, also called posterization. Plate XXXV is similar, but extreme highlight and shadow details are lost and mid-tones are more contrasty. Plate XXXVI has dirty highlights and lighter shadows, low contrast mid-tones.

Plates XXXVII, XXXVIII, and XXXIX (see colour section between pages 146 and 147) have only one of the colours changed in tone. Plate XXXVII has cyan tone change, Plate XXXVIII magenta tone change, and Plate XXXIX yellow tone change, giving a visual effect of reddish, greenish, and bluish bias respectively.

For special effects, sometimes tone value changes are effected deliberately, or to improve on bad originals.

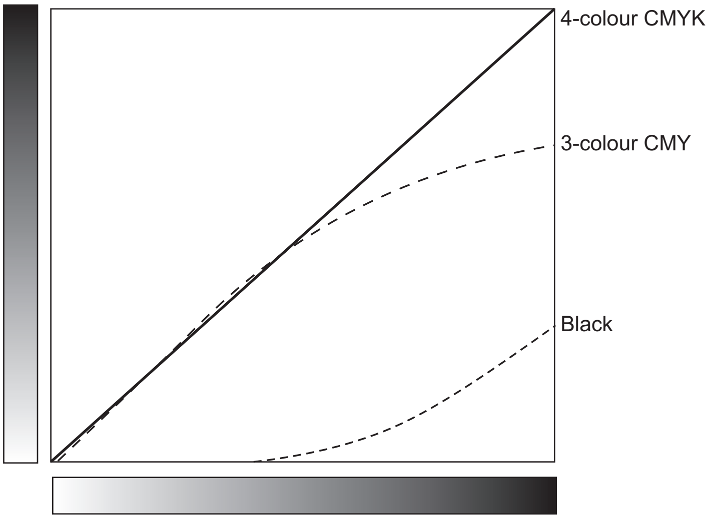
7.3.3 Relationship between grey balance and tones

Once the importance of *greys* and *tone* is understood, it is very important to establish the relation between the two. To achieve this, it is necessary to take a scientific and systematic approach to the subject. For clear understanding, as mentioned earlier, it is better to look at black and white first, and then at colour reproduction.

Figure 7.8 indicates the black-and-white reproduction, where the original (x axis) is plotted against the reproduction (y axis). The original can be a black-and-white artist drawing, photograph, digital file, etc. When graph is at 45°, every tone in the original is matched in the reproduction. This is called *facsimile reproduction*. This is best studied from the *grey scale* reproduction. (The term grey scale used here is in its original meaning a *scale of greys,* e.g. Kodak scale, and not the new terminology where it means black-and-white pictures.)

In practice, due to limitations in achieving high print densities because of ink, substrates, halftones, and printing processes, the densities achieved are somewhere from 1.60 to 1.80 without losing detail in the deep shadows, under good printing conditions. Newly available high pigmented inks may print 2.2–2.5 densities.

In colour reproduction, these greys are reproduced using three primary colours red, green, and blue in additive systems or three secondary colours cyan, magenta, and yellow in subtractive systems. Greys produced with these colours help to exercise good control over the colour reproduction in any process. The greys are reproduced as indicated in Figs 7.9 and 7.10, if reproduction is facsimile. It is very important that greys are formed throughout the scale, from extreme highlights to deep shadows, for good colour reproduction of the entire picture. Figure 7.11 shows how the actual reproduction may take place in printing processes where 3-colour combined density is raised using a black printing ink. Note that black ink printing starts where the three colour combination can no longer produce greys, thus adding black to convert the brownish tinge in the shadow to produce grey.



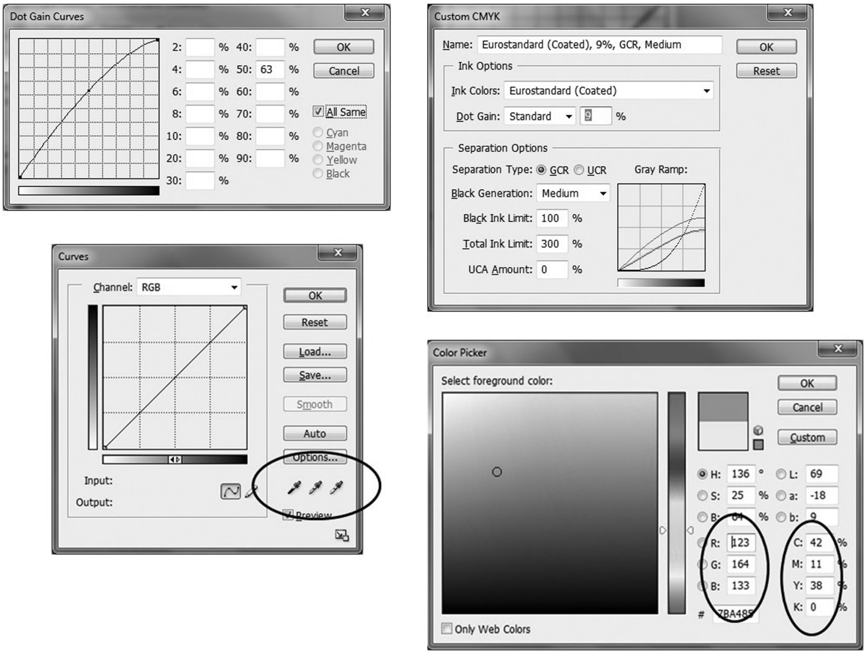
7.11 CMY, black, and CMYK tone curve.

The values obtained are different for different printing conditions and different printing processes, whether AM or FM screening. *This is a pre-requisite for any process of colour reproduction in the printing processes, whether analogue or new digital printing processes using new colour management concepts.* Without this *UCR – under colour removal* and *GCR – grey component replacement* (nowadays called *ink optimization*) do not work effectively.

In analogue photography, the same principle applies for grey balance. However, Kodak based their colour balance not on greys but on 'flesh tones' or 'skin tones', mostly European. The reasoning given is that 80% of photographs have people included, so the dyes are balanced for skin tones. Agfa and Fuji follow grey balance principles. This can be seen in *IT8 test target* prints and transparencies used for colour management work. Grey scale in Kodak IT8 target appears warmer than in Agfa and Fuji – see Plate LXX in colour section.

Plate XXVII is a grey-balanced picture and Plates XXVIII–XXX have upset grey balance – also Plates XXXVII–XXXIX. Sometimes grey balance and tonal values are purposely thrown off balance to improve imperfections or colour cast in the original pictures, or to create special effects, such as posterization – see Plate XXXIV.

Where the black printer starts to convert the brownish tinge in the shadow area to grey, it is called a *skeleton black*, and this does not dirty the light, or light pastel, colours in the print. In the case of *UCR* and *GCR (ink optimization)*, black starts right from the highlight areas and is called a *full scale black*. Plate XLIII is normal 3-colour and skeleton black, and Plate XLIV is



7.12 Adobe Photoshop settings.

(see colour section between pages 146 and 147) 3-colour GCR and full scale black. The GCR technique is based on complementary vision of human eye.

Adobe PhotoShop has possibility for programming both the grey balance and tone reproduction – see Fig. 7.12. When an *ICC colour management* profile is made, it is advisable to embed this information as part of the profile.

7.4 Additive and subtractive processes

In an additive process, three *basic colours*, red, green, and blue, mixed with light beams produce white, and any two combined produce *secondary colours* cyan, magenta, or yellow and white where all three basic colours are combined, thus going from black (no light) to white (all basic colours) as shown in Table 7.1 and Plate XL (see colour section between pages 146 and 147). In a subtractive process cyan, magenta, yellow secondary colours (*printing primaries*) combined on white substrates produce black (actually dark muddy colour due to imperfect pigments and dyes), and any two combined produce *primary colours* red, green, blue (printing secondary), thus going from white to black – see Table 7.2 and Plate XL. An additive example is a television or a computer monitor.

Reproduction problems begin when there is not enough colour, or other colours start interfering with these fundamentals.

Table 7.1 Additive principle

Visual impression	Colour components	Colour combination
White	Red + Green + Blue	Red + Green + Blue
Cyan	White – Red	Green + Blue
Magenta	White – Green	Red + Blue
Yellow	White – Blue	Red + Green
Red	White – Green – Blue	Red
Green	White – Red – Blue	Green
Blue	White – Red – Green	Blue
Black	White – Red – Green – Blue	No light

Table 7.2 Subtractive principle

Visual impression	Colour components
Black	Cyan + Magenta + Yellow
Red	Magenta + Yellow
Green	Cyan + Yellow
Blue	Cyan + Magenta
Cyan	Cyan
Magenta	Magenta
Yellow	Yellow
White	Base substrate

This brings us to what may be called a rule of five for colour reproduction. Consider the following simple primary and secondary colours with full coverage. See Plates XLV, XLVI, XLVII, and XLVIII (see colour section).

Reproduction colours are the primary and secondary colours expected to achieve any colour reproduction whether photography, television, or printing. How this is achieved is shown in Plate XLVI for television, Plate XLVII for analogue photography, and Plate XLVIII for photomechanical printing processes. The situation shown here is ideal, and is not fully realized in practice, hence the need for colour correction at some stage in the process.

7.4.1 Television, computer, and digital photography systems

A television system is additive, and works with only three channel images, i.e. red, green, and blue. To reproduce colours as indicated in Plate XLV, each of the three channels should excite the phosphors as shown in Plate XLVI. For example, the red channel image should excite red phosphors in white, red, magenta, yellow, and 3-colour area (same as white). Red phosphors in the remaining colours should not be excited. Similarly in the case of green and blue phosphors. This means that each of the channels has five colours where phosphors are excited. These may be called *wanted colours*, and where phosphors should not be excited can be called *unwanted colours*. In the case of television, these will be without excited phosphors and hence no light, therefore, black.

7.4.2 Analogue photography system

Analogue photographic systems are subtractive and again work with only three channel images, i.e. cyan, magenta, and yellow. To reproduce colours as indicated in Plate XLV (see colour section), each of the three channel images should again have dye contained in the five *wanted colours* and leave *unwanted colours* without colour dye – see Plate XLVII. In photo prints, these will be without dyes and hence white paper is uncovered.

7.4.3 Photomechanical printing system

Photomechanical printing systems such as analogue photographic systems are subtractive but work with four colours, including black, to extend the tonal range and add depth to the dark colours. To reproduce colours as indicated in Plate XLV the colour printers should print in the five *wanted colours* and leave *unwanted colours* without ink on the substrate. Black ink is printed only where required – see Plate XLVIII.

Colour reproduction problems start creeping in when some colours appear in the *unwanted colour* areas, making the reproduction dark and muddy. In the colour correction process, these are removed to approach ideal colour channels or separations as outlined above. When wanted colours do not carry enough colours, then reproduction appears lighter.

In the case of television systems, image channels are strictly kept separate to avoid interference with other channels, and phosphor quality and area occupied determine the brightness.

In analogue colour photography, colour correction is achieved by the photographic masking method (colour negatives carry orange mask) or special filters while exposing the colour prints. With digital technology digital signals are modified on a print exposing machine.

In the printing processes, colour correction is achieved by:

1. Manual correction (not practised now)
2. Photographic masking (obsolete process)
3. Electronic methods (used with colour scanners and related software)

In spite of all this, one must remember that colour phosphors, dyes, and pigments all suffer with deficiencies, classed as *hue errors* and *grey errors.*

7.5 Colour changes in reproduction processes and colour correction systems

There are various reasons for colour changes in the reproduction processes, and these can be described as follows. In the reproduction systems, the various components used, such as lenses, mirrors, dyes, digital camera sensors, colour monitors and television phosphors, printing inks, etc., have certain characteristics for light and colour transmission and response. To reproduce colour as the human eye perceives it, these various components should match the corresponding parts of the human visual system, such as cornea, lens, aqueous humour, iris, vitreous humour, retina, cones, etc. This is not so. This is the first stage where faulty colours began to appear in the reproduction systems. The second most important problem comes from the pigments and dyes used. All suffer from some deficiencies, which result in faulty colours unless some corrections are applied in the process. In analogue photography and in photomechanical printing processes, CMY and CMYK colourants are used, respectively. The ideal colourants are as shown in Plate XLIX (see colour section).

Looking at the visual colour *spectrum* divided into three sections of roughly 100 nm each: the first third appears blue, the middle third green, and the last third red. These correspond to the basic colours of additive colour reproduction. When two-thirds of the visible spectrum is perceived, the two basic colours combine to give one secondary colour corresponding to cyan, magenta or yellow. With ideal colourants shown in Plate XLIX the reflecting colours have full energy and are transmitted or reflected 100%, while remaining third is fully absorbed. The same is indicated in Plate L (see colour section), though in a different way. Plate L shows full reflection of red, green, and blue colours from a white surface. The same amount of reflection of two primary colours is obtained from ideal cyan, magenta, yellow colourants. If all colourants behaved in ideal fashion, the problems in colour reproduction would be solved to a great extent. Unfortunately, this is not the case. In the real world the colourants behave as shown in Plates LI and LII (see colour section).

Plate LII indicates the deficiencies of cyan, magenta, yellow colourants as *hue errors* and *grey errors*. To understand this better the following explanation may help. Compare Plates XLIX and L with Plates LI and LII.

Cyan colourant absorbs red light magenta and yellow absorb green and blue, respectively. Absorption of this one third of the spectrum gives the visual appearance of colour to dyes and pigments, see plate XLIX.

If the ideal colourant cyan is added with some quantity of ideal magenta and a little quantity of ideal yellow, then in this combination the cyan colourant will absorb red, some quantity of magenta will absorb green, and a little quantity of yellow will absorb blue. The available cyan colourant behaves as if it had been contaminated by magenta and yellow colourants (Yule, 1967, pp. 34–36).

If the ideal colourant magenta is added with some quantity of ideal yellow, then in this combination the magenta colourant will absorb green and some quantity of yellow will absorb blue. The available magenta colourant behaves as if it has been contaminated by yellow colourants (Yule, 1967, pp. 34–36).

The yellow colourant is much better and very close to ideal yellow, hence the deficiency can be disregarded for many applications (Yule, 1967, pp. 34–36).

In actual fact, each of the three inks is contaminated with the other two, but to keep explanation simple, only major faults are highlighted. So when only the available cyan colourant is deposited on the white surface it is as if cyan, magenta, and yellow are deposited as follows:

available cyan = Cmy

Similarly, for available magenta and yellow colourants

available magenta = My
available yellow = Y

But the matter is more complicated, as follows:

available magenta = Mcy
available yellow = Ycm

Due to these ink deficiencies, when equal quantities of available cyan, magenta, yellow colourants are mixed, only considering major deficiencies it works as follows:

cyan (Cmy) + magenta (My) + Y = CMmYyy

With equal quantities the combination has a maximum percentage of yellow and a minimum percentage of cyan. This excess of yellow followed by magenta makes the combination appear reddish brown rather than grey. To convert this to grey, a higher quantity of cyan dye is used in the paper print and transparency photographs, and a bigger dot of cyan in the photomechanical printing processes compared to magenta and yellow.

The explanation above relates mostly to the *hue error* of colourants. The *grey error* makes colours appear dirty to some extent, and makes it difficult to obtain clean colours.

To calculate the deficiencies precisely and apply correction, mathematical analysis using measurement instruments is possible and has been used. To successfully apply the rule of five, as mentioned earlier *colour correction* is applied in the process.

When two-thirds of the visible spectrum is perceived the two basic colours combine to give one secondary colour that correspond to cyan, magenta or yellow. When these colourants are deposited on white or transparent substrates, the base substrate is calibrated to read as 100% transmission or reflection for all three basic colours, red-green-blue. If the colourants cyan-magenta-yellow were ideal, as in Plate XLIX, the transmitted or reflected lights would be equal to transmitted or reflected lights by the base substrates, see Plates L and LIII in colour section between pages 146 and 147.

Unfortunately, the colourants cyan-magenta-yellow are not ideal and have some defects, as shown in Plate LI; the transmitted or reflected lights, therefore, are not equal to transmitted or reflected lights by the base substrates. The reflection and transmission figures for the colourants are only indicative, and the actual percentage may vary.

Now, comparing ideal Plate XLIX and available Plate LII given in Plates LIII and LIV, the following deficiencies are evident:

Cyan colourant absorbs red and gives out blue and green:

Blue absorbed is 100–55, therefore, a deficiency of 45%

Green absorbed is 100–30, therefore, a deficiency of 70%

Magenta colourant absorbs green and gives out blue and red:

Blue absorbed is 100–45, therefore, a deficiency of 55%

Red absorbed is 100–80, therefore, a deficiency of 20%

Yellow colourant absorbs blue and gives out green and red:

Green absorbed is 100–85, therefore, a deficiency of 15%

Red absorbed is 100–95, therefore, a deficiency of 5%

It is readily seen that none of the colourants is transmitting or reflecting any of the colours equal to transmission or reflection by the substrates. This deficiency does not give clean colours, and the colours are degraded or greyed to some extent; this is called the *grey error* of colourants, yellow having the least *grey error* and cyan the maximum. This is further exaggerated by substrates, such as matt or structured base or dirty newsprint, but the effect is minimized on glossy coated papers with high optical brightness.

The first stage in colour correction is *grey balance* and the second stage is *tone reproduction*, as explained in Section 7.3. Grey balance optimization brings colourants in balance by changing their proportions in the combination of cyan-magenta-yellow, instead of equal quantity deposition. This is achieved by changing colourant volumes in photography or gravure printing process and dot variations in the other photomechanical printing processes. After this, colour correction is applied to coloured areas.

From the above it is clear that cyan has a blue deficiency of 45% and magenta has a blue deficiency of 55%. Blue absorption is a function of yellow colourant. When it is also absorbed by cyan and magenta it behaves as if these colourants have contamination of yellow colourants. Since nothing can be done about it, to compensate, the amount of yellow colourant is reduced whenever these fall in combination with yellow. In cyan-yellow combination, yellow is reduced by 45%, and in magenta-yellow combination, yellow is reduced by 55% (Yule, 1967, pp. 34–36).

Likewise, cyan has a green deficiency of 70% and yellow has green deficiency of 15%. Green absorption is a function of magenta colourant. When it is also absorbed by cyan and yellow, it behaves as if these colourants have contamination from magenta colourants. Since nothing can be done about it, to compensate, the amount of magenta colourant is reduced whenever these fall in combination with magenta. In magenta-cyan combination, magenta is reduced by 70%, and in magenta-yellow combination, magenta is reduced by 15%.

Similarly, magenta has red deficiency of 20% and yellow has red deficiency of 5%. Red absorption is a function of cyan colourant. When it is also absorbed by magenta and yellow it behaves as if these colourants have contamination from cyan colourants. Since nothing can be done about it, to compensate, the amount of cyan colourant is reduced whenever these fall in combination with cyan. In cyan-magenta combination, cyan is reduced by 20%, and in cyan-yellow combination, cyan is reduced by 5%.

In actual practice, it is far more complicated than described here.

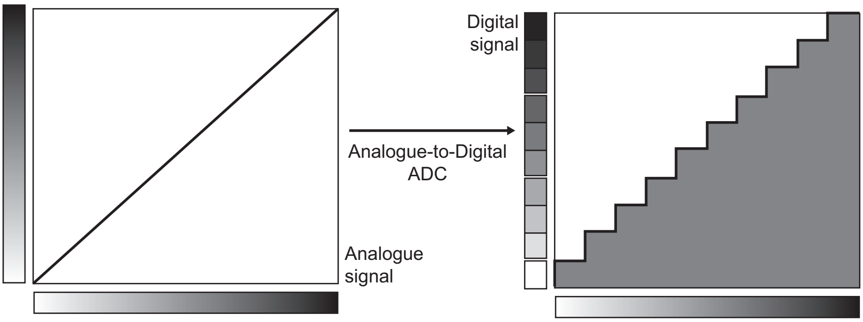
In the manual colour correction method, this is done by reducing densities or dot sizes, referring to the process colour charts or based on experience. Today, unfortunately, most PhotoShop operators work exactly the same way on uncalibrated colour monitors.

In photographic masking methods (now obsolete) this was achieved by exposing final colour separation films through intermediate *photographic masks*. See Plates LV and LVI (see colour section between pages 146 and 147).

The principles of corrected separations in Plate LVI have also been used in the electronic colour scanners to modify the electronic signals.

Another *colour correction* system used in the colour scanners, and now also present in today's *colour management systems*, is based on the Neugebauer equations. The fundamental principle is that in all photomechanical colour reproduction systems using three colour reproduction, there are only eight colour areas: substrate colour, cyan, magenta, yellow, red, green, blue, 3-colour. In four colour reproduction, additionally, these seven colours are combined with black and, in addition, only black area is present, thus making a total of 16 colours including substrate. There are no other colours in the microscopic halftone image structure. So effectively only 16 areas are controlled to get right colour reproduction – see Plate LVII (see colour section).

The *colour correction* example illustrated here is from the photomechanical printing processes for the sake of convenience and easy understanding. The same general principles are applicable for all colour reproduction processes.



7.13 Analogue signal to digital conversion.

The more recent approach of *ICC colour management* will be explained later in this chapter.

7.6 Image-capturing devices

Digital cameras and colour scanners are image-capturing devices. Colour scanners convert the existing analogue two dimensional pictures into digital form. Digital cameras can be considered as three dimensional scanners capturing two or three dimensional objects in digital form. These devices have an *analogue-to-digital* (ADC) converter to convert original analogue light signals of varying light intensities to digital measurable quantities, see Fig. 7.13.

In image-capturing devices, the light sources throwing light on the object has a certain spectral composition, depending on its *Kelvin degree colour temperature*. The lower the temperature the more reddish-yellowish is the light, and the higher the temperature the more bluish is the light. Around 5000° K light is balanced in roughly equal proportions of all the wavelengths of the visible light.

Resolution depends on the resolving power of the lens, its ability to distinguish the details in the subject to be captured – see Fig. 7.14. Depth of field is bringing the objects at front and back of the focusing point into acceptable focus. This depends on the focal length of the lens and its aperture opening.

Bit depth gives the number of grey levels obtainable and the smoothness of the tonal values. Digital imaging normally operates with eight bits for each colour, but in deep shadows it tends to give contouring effects and, therefore, a higher number of bits, 10 or more for each colour, are captured by most of the new generation of capture devices (Hunt, 2004, p. 546). Similar higher bit depth is also provided for in new software, such as PhotoShop CS versions.

7.14 Resolution chart.

CCD vs CMOS. The first digital cameras used charged coupled devices (CCD) to convert images from analogue light signals into digital pixels. CCDs require a special manufacturing process, so tend to be more expensive than complementary metal oxide semiconductor (CMOS) sensors.

CCD sensors, upon exposure to light, become charged, and the charges move in line to the next sensor and emerge at the end of line. CMOS chips use transistors at each pixel to move the charge through. See Plate LVIII (colour section between pages 146 and 147). This offers flexibility, as each pixel is treated individually. Table 7.3 is based on lecture series at Centre for Image Analysis at Uppsala Universitet (Bengtsson, 2008).

White balance is important in all image-capturing systems to eliminate colour cast during photographic shooting and colour scanning.

Table 7.3 Comparison of the characteristics of charged couple devices (CCD) and complementary metal oxide semiconductor (CMOS) sensors

Aspect	CCD	CMOS
Sensitivity	High	High
Dynamic range	High	Moderate
Uniformity	High	Low to medium
Speed	Moderate to high	Higher
Windowing	Limited	Extensive
Antiblooming	None to high	High
Energy need	High	Low
Clocks	Multiple	Single
Bias	Multiple, higher voltages	Single, low voltage

Based on lecture series at Centre for Image Analysis at Uppsala Universitet, Sweden, Bengtsson, 2008.

7.6.1 Digital cameras

Digital cameras have all the parts of conventional film cameras except for a film plane. The film plane is replaced by CCD or CMOS sensors that convert light intensities into electrical signals. These electrical signals, after conversion into digital signals through ADC, are then used for display or printing purposes.

CCD and CMOS sensors break up the light coming from the object into its basic components of red, green, and blue, generating three images which are brought together on a display and replicating the colour image of the original object. Green sensors are normally double the number of red and blue sensors, as it also implies the luminosity of the colour – see Plate LX (see colour section between pages 146 and 147). Sensors are arranged in various formats, such as trilinear array, triple matrix, one shot single matrix, three shot single matrix, multi-shot single matrix sub-element shift, and multi-shot single matrix whole element shift.

In digital photography the light sources that illuminate objects vary widely from bright sunlight, to starlight, to a variety of artificial light sources – see Plates LXI and LXII (see colour section).

7.6.2 Colour scanners

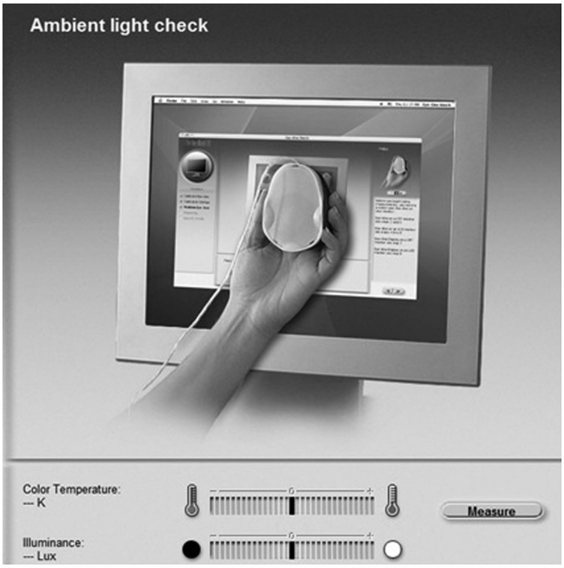
Colour scanners, as we know them today, are mostly flatbed devices. These have fixed light source to illuminate the originals, as opposed to digital photography, to be scanned and some software to produce the desired scanned results, such as size, resolution, tone adjustment, cast and colour correction, etc. The scanned images are transferred to computer for further processing, see Plate LXIII (see colour section); however, in the earlier graphic arts, special purpose colour scanners the final output of films and image carriers (plates and cylinders) was obtained from the output section of the colour scanners, see Plate LXIV (see colour section). In flat bed and drum (both cases), output signals could be RGB or CMYK depending on the system and the programmed software capabilities.

7.7 Colour monitors

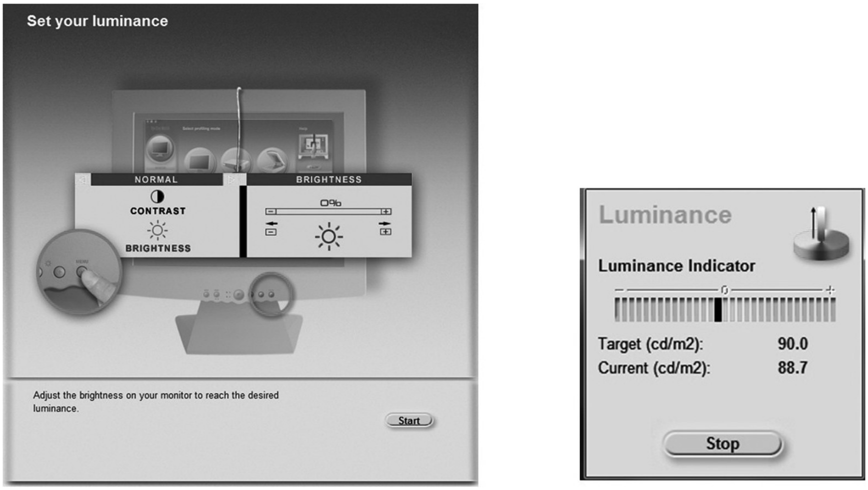
Colour monitors vary very widely in displaying colours. Apart from the variety of monitors available on the market, each one is also affected by its own settings as well as ambient lighting conditions. With the change in monitor surround lighting, colour appearance on monitor changes; therefore, the first step should be to standardize the ambient lighting conditions for colour temperature and intensity of lighting in the studio – see Fig. 7.15. Monitors should be lit evenly and consistently. Today the monitor calibration devices can calibrate all kinds of monitors, whether CRT, LCD, LED, etc. The following settings are adjusted to calibrate monitors. To illustrate, GretagMacbeth (now X-Rite) Eye One Display 2 device, is taken as an example.

7.7.1 White point

This is the whiteness of the monitor that is set based on the *colour temperature* of the three colour controls, red, green, and blue of the monitor. This gives the overall colour of the canvas to display pictures – see Plate LXV (see colour section).



7.15 Ambient light measurement.



7.16 Setting monitor brightness.

7.7.2 Monitor brightness and luminance

Monitors have to have a certain brightness for comfortable working. This is also important for good colour viewing, as monitors that are too bright or too dim will not give correct colour appearance. Brightness and luminance are related. In a network situation, all monitors are set to the same luminance for colour uniformity across the monitors, but individual monitor brightness may differ depending on its architecture and age (Fig. 7.16).

7.7.3 Monitor contrast

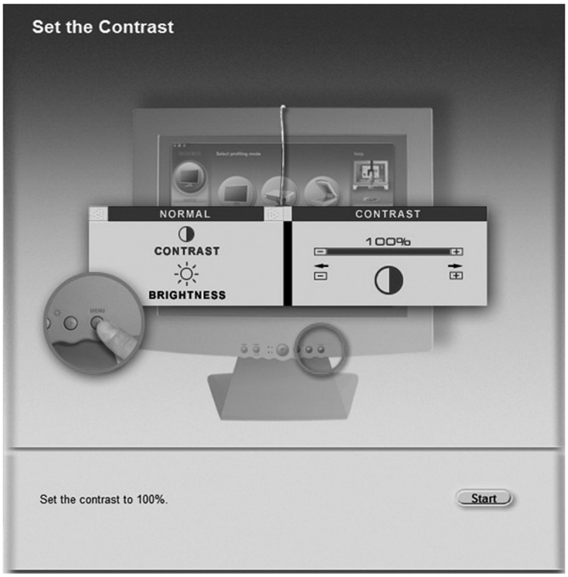
Monitor maximum contrast to give good detail rendering (Fig. 7.17).

7.7.4 Monitor colour temperature

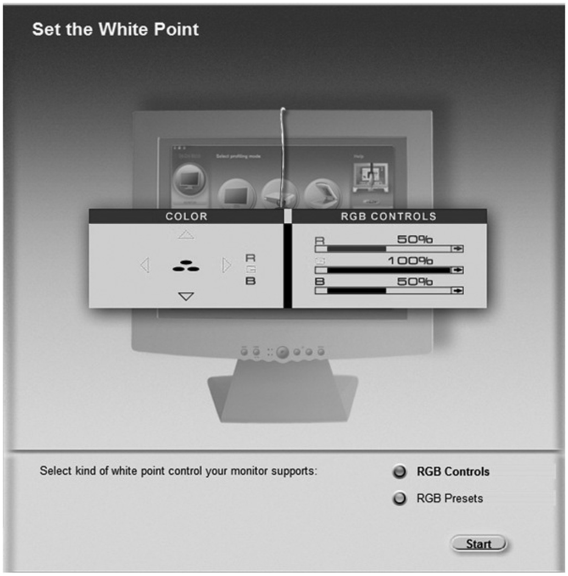
Monitor colour temperature using individual controls for red, green, blue channels; if such controls are not provided then set the colour temperature most appropriate for the kind of application envisaged (Fig. 7.18).

7.7.5 Calibrated monitor

Before undertaking this exercise, make sure following preliminary monitor checks are done (Plate LXVI (see colour section)):



7.17 Setting monitor contrast.



7.18 Setting colour temperature.

1. Evenness of monitor brightness
2. Freedom from chromatic aberrations
3. Freedom from spherical aberrations

4. Light booth for viewing colour samples against display monitor
5. Room wall and furniture colours
6. Monitor light hood.

7.8 Colour management

There are many reasons, based on complex colour science, why the appearance of a colour image is difficult to reproduce consistently on different devices. In many ways, communication in colour has problems similar to those of communication in language. Each device is like a person, speaking its own language. Even the same language has different dialects. The result is a breakdown in communication and misinterpreted messages. What is needed is an interpreter capable of interpreting the language as well as the dialect, to ensure that the message is properly communicated. The same holds true for colour reproduction (Weisberg, 2004, p. 3).

The actual colours produced depend on the characteristics of a particular digital camera, scanner, display monitor, and printer used, and because these characteristics vary from one device to another, the results obtained from the same input on different devices can vary considerably.

The first problem is that R, G, B and C, M, Y, K outputs are device dependent; this means that different digital cameras and scanners give different R, G, B signals from the same scene, or the original, different monitors produce different colours from the same RGB signals, and different printers produce different colours from the same C, M, Y, K dot sizes – see Plate LXVII (see colour section between pages 146 and 147).

The second problem is that different viewing conditions prevail; this means that conventional colorimetry is insufficiently sophisticated to define colours that look alike on two different types of display.

The third problem is that different monitors and printers not only describe colours differently, but also differ in the gamut of colours that they reproduce.

The fourth problem is that characteristics of some parts of the installation may vary with time. This is particularly true of colour monitors, any chemical processing, a printing process, and raw materials used, particularly the substrates and colourants, i.e. inks and toners.

Colour management is the term used where colour reproduction becomes repeatable and reliable, following certain norms and disciplines. Colour management reproduces colours the best possible way within the limits of the colour reproduction systems, using device-dependent colours through the effective use of device-independent colour systems based on human colour vision, (CIE system is described earlier in Chapter 3). Every transformation of colour passes through CIE when exchanging colour information between various devices. CIE may be called an interpreter, synonymous with language translation as mentioned earlier – see Plate LXVIII (see colour section).

Each device in the network has to go through the three Cs of colour management (Sharma, 2004, pp. 34–35):

1. Calibration involves establishing a fixed, repeatable condition for a device: for a display monitor, adjusting contrast and brightness settings; for a printer, deciding on substrates and inks. This establishes a known starting state, and a means of restoring the device to that state.
2. Characterization is studying the behaviour of that device by sampling colour patches and recording the device response – see Plate LXX (see colour section). The colour patches are representatives of the various colour combinations encountered in practical situations, and can be described as compressed colour charts. This response includes the characteristics of the device, colour gamut capability, etc., and this information is stored in a device profile.
3. Conversion is a process in which image is converted from one device profile to another device profile through CIELab conversion – see Plate LXVIII.

Once the calibration and characterization have been carried out, device profiles are ready for regular production. This works as shown in Plate LXXI (see colour section). In the example in Plate LXXI, colour scanner RGB values are obtained by scanning a test chart illustrated in Plate LXX, and Lab values for each colour patch are obtained. These Lab values are converted through the CIELab colour model to the monitor RGB values for display. Display RGB values are converted through the CIELab colour model to printer CMYK dot percentages or print density values. The CIELab colour model works as interpreter, and helps to get nearest colour match within the device capability.

7.8.1 Reproduction processes and gamut mapping

The reproduction processes for a variety of output systems vary very widely and each one has its own limitations in terms of colour fidelity as compared to the original images or designs. Within each process, again, there are innumerable variables, such as substrates, colourants, process variations, CMYK only or CMYK plus special colours, only special colours like Pantone, halftone methods, and so on. Reproduction processes are:

1. Television
2. Computer displays

3. Photo lab systems
4. Litho-Offset
5. Letterpress
6. Flexography
7. Gravure
8. Screen Process
9. Digital printing (electrophotographic and ink jet).

Colour gamut compression is a method of reproducing the colours in the original design to fit the output device's colour gamut capability, whether display or hard copy print by a particular process. It is a method of compressing the colours in the most appropriate and acceptable way. There are different methods of compression.

Perceptual rendering adjustment

Perceptual rendering adjustment reproduces an image taking into account the substrate and colour characteristics of the output system in such a way as to ensure that the human eye will perceive the image in the target colour system as the most faithful reproduction of the original (GretagMacbeth ProfileMaker 5.0, now X-Rite) – see Plate LXXII (a) (see colour section).

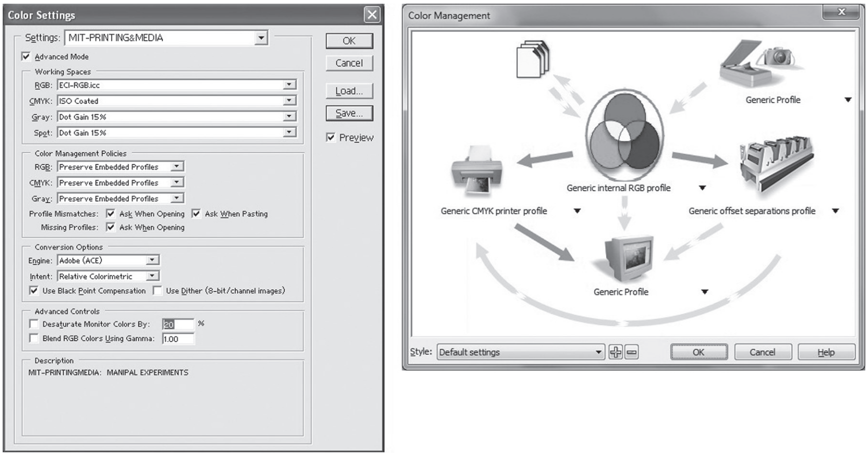
Absolute colorimetric adjustment

Absolute colorimetric adjustment is where the colour data is transferred to the output colour system to provide minimum delta E, i.e. colour difference. In this process, the white point of the source colour system is adopted in the output colour system. For example, to proof a page reproduced for newspaper printing on a proofing printer running a special paper, and at the same time simulate the newsprint colour, the white point of the source system is adopted for digital proofs (GretagMacbeth ProfileMaker 5.0, now X-Rite) – see Plate LXXII (a).

Relative colorimetric adjustment

Relative colorimetric adjustment is intended specifically for proofing printers. Relative colorimetric rendering intent functions essentially in the same way as absolute colorimetric except that the white point of the target colour system is mapped to that of the source colour system. If a newspaper proof is output on the colour printer with the relative colorimetric adjustment, the conversion result would be very similar to the absolute colorimetric interpretation, but the colour printer's white point would be used instead of simulating the paper white of the newspaper printing process (GretagMacbeth ProfileMaker 5.0, now X-Rite).

(a) (b)



7.19 Colour settings in (a) Adobe PhotoShop (b) CorelDraw.

Saturation-preserving adjustment

Saturation-preserving adjustment distinguishes brand colours of corporates on a colour output system; the exact reproduction of the original colours is less crucial than the preservation of the highest possible degree of saturation (GretagMacbeth ProfileMaker 5.0, now X-Rite).

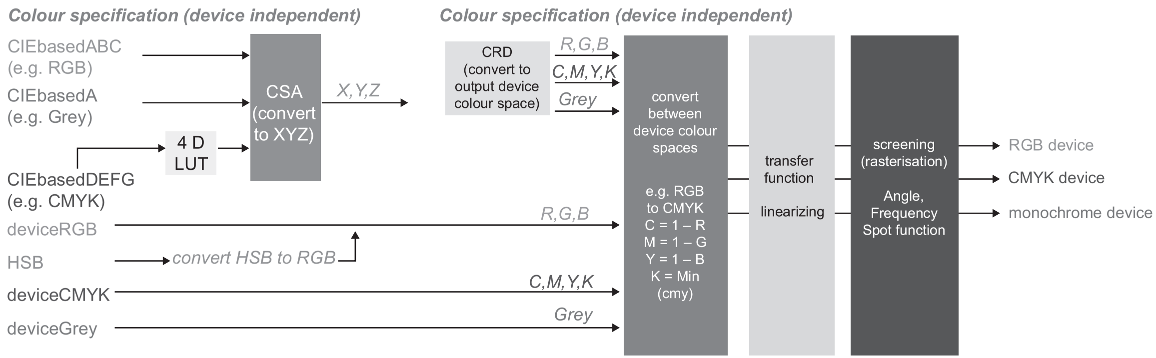
7.8.2 Managing colour in different applications

Once the ICC colour profiles are calculated for the inputting and outputting systems (incorporating rendering intents) then the digital file preparation operations are performed using the appropriate ICC profiles in the application software such as Adobe CS suite, CorelDraw, Quark Xpress, PDF conversion or any other application systems, including ripping software. Figure 7.19 shows the colour settings in Adobe PhotoShop (Fig. 7.19a) and CorelDraw (Fig. 7.19b).

7.9 Managing workflow for consistent colour quality

Following information is provided by GretagMacbeth (now X-Rite) help file for their ProfileMakerPro 5.0 colour management software.

Workflow describes the process by which the information, content or produce flows from one step to the next in the production process. In digital systems, the starting point is an analogue picture or a design scanned on a colour scanner to obtain digital conversion, or alternatively a digital camera for live pictures. Digital originals can be in a variety of file formats for further colour processing in the reproduction systems (Fig. 7.20).



7.20 Digital colour workflow (based on Brues, 2000, p. 89).

In modern digital workflows, from origination to output there are no standardized ways of communicating all aspects of special colours in the whole value chain. This is why **colour exchange format (CxF)** was developed. CxF supports, automates, and simplifies the colour communication of special colours within a digital workflow. CxF is an **Extensible Markup Language (XML)-based data format** which can be seamlessly integrated into an internet-based workflow and can be used independently of platform and programming language. **XML, which is orientated to Standard Generalized Markup Language (SGML), defines how a dataset should be described.**

SGML is sometimes referred to as a metalanguage, because it is a language used to describe other languages. SGML defines the rules of how the logical structures (titles, paragraphs, contents, etc.) of a document should be described.

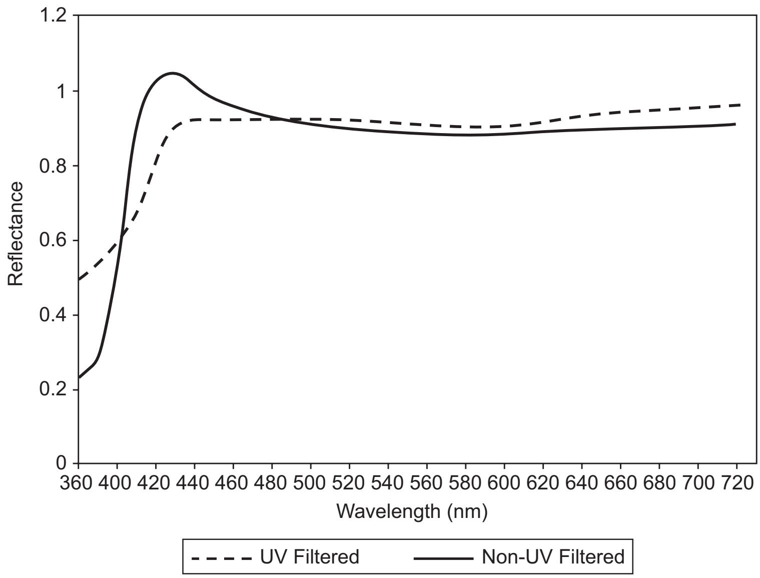
Metalanguage is the definition or description of a language. A metalanguage describes the rules for the generation of a language.

The CxF file contains all the important information that has an influence on the conversion or reproduction of a colour. In this way, each colour in the CxF file can be specified differently, whether or not the colour has been measured, typed manually or defined as a special colour. The user or the application calling the CxF file decides on which attributes to use. The following data are saved in the CxF file:

1. Spectral data
2. Lab
3. Scene lighting
4. Observer angle (2° and 10°)
5. Physical filters (Polarized, D65, UV Cut)
6. Recipes

Using CxF files requires a **CxF composer,** which writes and reads the CxF data. With a CxF viewer one can load special colours in the CxF file and display and print them in true colour. The future goal is to synchronize all involved input/output devices with ICC-based colour management systems and to translate device-dependent colour definitions incorporated with ICC profiles. This will give a hard copy of the colour patches in true colour, as well as a printout of the embedded text and images – platform and software independent.

With the free **Software Development Kit (SDK)** from X-Rite, implementation in other colour management applications, RIPs, proofers, measuring devices, printing processes, and colour applications can be achieved.



7.21 Fluorescent sample measurement: solid line-no filter, dashed line-UV cut filter.

7.10 Measurement and management of special colours

The measurement and management of special colours need special attention and the right kinds of instruments. The light interaction with such colourants is more complex.

7.10.1 Fluorescent materials

Fluorescent materials, such as optical brightening agents, are used in textile, paper manufacturing, etc. These materials absorb light in the ultraviolet region below 380 nm and emit at longer wavelengths in the blue part of the spectrum. This gives the appearance of extra whiteness, as in some cases blue light reflected from the sample is more than the blue light incident on it, due to the conversion of UV radiation into blue light emission. As a result, the fluorescent material looks brighter than the non-fluorescent material. The measurements of fluorescent colours and blue light emission can be compared by measuring without filter and then with a UV cut filter that prevents UV light falling on the sample – see Fig. 7.21.

7.10.2 Metallic and pearlescent colours

Metallic and pearlescent colours are used in many applications, such as packaging printing, and in the products itself, such as cosmetics, automobiles, etc. Metallic flakes reflect specular light when their size is bigger, and diffuse light when their size is smaller (Plate LXXIII (see colour section between pages 146 and 147)). Measuring reflection with normal 45/0 or 0/45 optical instruments gives different values depending on the direction of the measurement instruments while measuring. Therefore, metallic colours are measured with spherical geometry or multi-angle instruments. The instrument is called a goniospectrophotometer when the sample is illuminated at various continuous angles, and a multi-angle spectrophotometer when illuminated only at a few angles (Berns, 2000, p. 13).

7.10.3 Reasons and examples of colour appearances

In daily life it is often the colloquial and poetic expression that supersedes the scientific expression of colour (Yule, 1967, pp. 12–13). These expressions are often used by artists. With scientific measurement of colours using instruments, there is no guarantee that colour appears to the human eye as measured. Discounting instrument limitations and metamerism there is a much larger issue, called *colour appearance*.

A famous visual communication artist in India, Professor Ranjan R. Joshi, describes *ART* as:

A absorption of light rays by the object being perceived
R reflection or refraction of light rays by the object being perceived
T transmission of light rays by the object being perceived

In short, Professor Joshi advocates that ART is nothing but a science of light rays producing colours. Physics, chemistry, physiology, psychology, memory – all in one. Psychology, because it is our brain that interprets the light signals, combines with memory and gives the experience of colour reality. Further he says, perception and reality are both connected with the game of optical illusion.

This is an untapped area, where *colour management* technology needs to make great progress, and hope may one day become reality.

7.11 Conclusion

Digital image processing is based on binary digits in digital computers to represent images, text, and graphics. However, the starting point as well as final perception by the human eye is always in analogue form. There are two basic principles in colour reproduction: additive and subtractive. Both differ in the manner they work, but ultimately achieve the same objective, that is reflection of three basic colours - red, green, and blue. To produce pleasing images, the most important aspects of colour reproduction are grey balance, tone reproduction, and colour correction. Whether conventional methods of managing colours or newly based device independent colour management, such as CIE, the aim is the same. Metallic colours need special instruments to measure and manage colours. With all the limitations of current technology, colour may still appear different to the human eye due to a variety of factors, and this may evolve in the future with new research on *colour appearance modelling*.

7.12 References

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