

Part II

Printer software

9.1 Introduction

In factories, offices, homes and outdoors the past two decades have seen a revolution in the use of digital devices which are now commonplace for audio and video capture, data transmission and playback. The textile printing industry has not been slow to adopt such systems, particularly computer aided design (CAD) to aid pattern production and computer aided manufacture (CAM) to facilitate reproducible machine settings and print paste and screen production.¹ Some 90% of all printed textiles are produced on screen printing machines and despite the advent of ink jet printing machines for textiles the initial application of textile CAD–CAM systems was for conventional printing. However, it was Stork's introduction of the first ink jet printer for textiles, with its associated special reactive dye inks in 1991, which offered printers a much faster means of producing sample and pre-production prints for customer approval. Wide format ink jet printers were already well established in the reprographics industry and still continue to gain market share from more conventional colour printing methods.

Jet printing may be defined as a process by which the desired pattern with its individual colours is built up by projecting tiny drops of ink of different colours, in predetermined micro-arrays onto the substrate surface, each of these arrays representing one picture element (pixel) of the design. Usually a set of inks is used consisting of at least three primary colours, namely cyan (turquoise), magenta, yellow and optionally black, the so-called CMYK inks known in the reprographics industry as 'process colours'. The proportion of each of these primaries in any area of a print determines the perceived overall colour in that particular region. Similar primaries are employed in conventional gravure and offset lithographic printing, although in this case the colours are usually applied as patterns of dots of varying diameter (amplitude modulation) or as uniformly sized dots in various randomised density arrangements (density modulation). As most ink jet printers were originally designed for paper printing, the technical terms encountered such as dots or lines per inch (dpi or lpi) continue to be used,

whereas a textile printer would refer to the screen mesh or raster, and the colours are inks rather than dye liquors or print pastes.

It is essential to appreciate that the technology of ink jet printing is fundamentally different from that of all other textile printing techniques, not only because of the non-contact mechanics of the print head but also in the means by which individual colours of the design are produced. Traditional textile printing uses one screen for each colour in a design for which individual print pastes are prepared to match the desired shade. In jet printing a great deal of computation is necessary to produce each of the millions of pixels in a design and this continues for as long as the machine is printing the fabric. In the past printing machines were adjusted entirely by mechanical means using the operator's experience and judgement, and although modern impact printing machines may nowadays be fitted with more refined electromechanical feedback devices, these are still relatively unsophisticated compared with the electronic controls required for jet printers.

9.2 Computer aided design, editing and data storage systems

Print patterns can be produced on many standard graphics-based programmes but, because of the special editing requirements in textile designs, it is normal practice to employ proprietary software which gives not only full design/editing capabilities but can be augmented with many other features to form an integrated colour management system (CMS). In particular the CMS will assist in achieving accurate and reliable reproduction of the colours of the original design by characterising the scanner, monitor display and the jet printing machine to be used (see Chapter 10). More complex design systems are also available which record not only the colour information for printed designs but also the 3D surface texture effects of woven and knitted fabrics. Table 9.1 gives examples of design software available and the computer systems by which they operate. Traditionally the most popular operating platform used for professional reprographics was the Macintosh computer and operating system and this was also true of several early systems offered for textile jet printing. However, in recent years there have been a number of amalgamations within CAD vendors and PC-based systems, with MS Windows XP operating systems now more common. Some design system software offers 3D modelling features such as viewing the effect of the design as a garment or even draped on a figurine with rendered shading effects.

Although textile patterns may be produced entirely on the colour graphics monitor of a CAD system using a 'Paintbox' or similar software package, with a pressure-sensitive stylus on a digitiser tablet, it is still more common for designers to originate their artwork manually on paper or card with paint- or air-brushes. To obtain a digital image from paper designs suitable for editing, it is

Table 9.1 Some CAD systems suitable for textile print pattern editing

Company (Website)	Design system	Computer/system base
Aleph (Italy) (http://www.alephteam.com)	Smartcolor	MS Windows
B-Tree (Italy) (http://www.btree.net)	TreePaint	Macintosh/MacOS
DGS Dua Graphics (Italy) (www.ceam-group.it/DuaGraphic)	Matchprint II	PC/Linux
DP Innovations (USA) (http://www.DPInnovations.com)	StudioMaster	PC/MS Windows
Lectra (France) (http://www.lectra.com)	Primavision Print	PC/MS Windows
NedGraphics (Holland) (http://www.nedgraphics.com)	Vision Printing Studio	PC/MS Windows
SpeedStep (Germany) (http://www.speedstep.de)	ProPainter 2000	PC/MS Windows
Stork (Holland) (http://stork.com)	Image PC/BestImage	PC/MSWindows

necessary to scan this artwork using a flatbed scanner (up to A3 size) or a rotary drum scanner for the larger A0 sized originals. The larger rotary scanners utilise a xenon light source, red, green and blue (RGB) interference filters and photo-multiplier sensors which give a superior signal to noise response compared with the CCD sensor system in flatbed scanners. Rotary scanners require more skill to operate than flatbed ones as the artwork needs to be carefully attached to the rotary scanning drum.

Scanners can usually capture an image at up to 2000 dpi or more and opinions vary as to the minimum scan definition required for a textile pattern, but 300–600 dpi is usual. Image capture is also possible using high resolution digital cameras but this is less common. The image acquired by the camera or scanner may be captured in digital RGB in 24, 32 or 48 bit colour, although for textile designs these are usually stored as a 24-bit Trucolor images (i.e. with eight bits each for the R, G and B values). The captured image can be displayed on a computer monitor or VDU (visual display unit) but a great deal of editing is then required before a final design whose data is suitable for inputting to the printing machine is obtained.

A scanner records every brushstroke and nuance of shade and even the smallest blemish in the designer's artwork which therefore requires electronic cleaning up and editing. The design will usually need breaking down into a selected number of colours, and further editing so that it has a defined pattern

repeat. This editing is achieved by the use of proprietary CAD programs, the graphics handling being usually based on well-known editing suites such as Adobe Photoshop, Corel Photo-Paint or Jasc Paintshop Pro.

For most textile designs the image then needs to be broken down into a specified number of colours (say a maximum of 8–12), the precise shade of each being then adjusted individually, while stray defects such as isolated small groups of adventitious pixels can also be deleted and outlines cleaned and smoothed. After the colour separation operation the pattern elements of each colour can be displayed as design ‘layers’ which can be examined, rescaled and ‘fitted’ either individually or in any combination with the other layers. By contrast special effects such as tonal photographic designs, shadow and layer effects and those without conventional pattern repeats can all be jet printed and may consist of a very large number of individual shades. Such tonal effects cannot easily be produced by screen printing for which designs are saved as the individual colour separations. If the design is suitable, however, the digital information can also be used to control the making of individual printing screens, either using a conventional photoexposure method with printed film positives or by direct application of special black waxes onto the screen mesh using scanning, piezo-type printheads before the photoexposure stage.¹

9.2.1 Capture of digital design data

Irrespective of the type of scanner used, the graphics industry has adopted a common communication protocol known as TWAIN (not an acronym), a standard devised in the early 1990s by an industry-wide working group called the TWAIN Coalition. The adoption of this standard provides a consistent integration of image data between all input devices and software applications. Most modern flatbed scanners are single-pass devices using cold cathode fluorescent tubes or LEDs to illuminate the design and either a system of dichroic mirrors or special filters to separate the R,G and B signals before they reach the three linear CCD photosensor arrays. Capture of images by digital cameras differs in that the photosensor array consists of a mosaic of red, green and blue cells usually arranged in a so-called Bayer pattern, there being two G cells for every R or B one.² The combined data for the individual sensors (known as RAW format) can be stored and subsequently processed on an external computer, but many cameras perform so-called demosaicing calculations ‘on board’, using algorithms of varying complexity, to interpolate the two missing values (e.g. the R and B values at a G cell location) for each pixel. Recently a camera chip has been developed by Foveon and Texas Instruments in which each individual cell gives an RGB response and this obviates the need for demosaicing calculations.

9.2.2 Encoding, compression and storage of pattern data

Over the years various methods of encoding digital images have been devised.³ Many systems record the RGB values of each pixel location in a specific order (e.g. all MS Windows displays are based on the Bitmap (BMP) display system for pixel data, the RGB values requiring three bytes of data per pixel, being read, line by line, from left to right of a displayed image starting at the bottom). For high definition and large pattern repeats this results in very large files which, apart from requiring a large memory, may result in slower times of access, display or transmission. Another basic method involves run length encoding (RLE) which reads the data, for example as two bytes, in the form [RGB values][number of consecutive pixels with these values]. This may at first sight appear to be little better than the BMP format and indeed it is not if each pixel differs from its neighbours, but is particularly useful for encoding traditional textile designs which tend to have relatively large areas of uniform colour. Some other methods of encoding allow the data to be compressed but it is important that when the full file is restored the recovered data conforms exactly to the original (i.e. that the compression system is lossless). File compression usually takes place in three stages:

- *Transformation*: Lossless mathematical shifting of image signals (e.g. by applying a discrete cosine transformation)
- *Quantisation*: Simplification of image information (in JPEG the image is processed as 8×8 blocks of pixels, which is the main source of loss)
- *Encoding*: The data is usually then subjected to lossless RLE (run length encoding).

Most data encoding systems carry much additional information (so-called metadata) in the form of file headers. These identify the encoding system type, file and image sizes, the full list of possible colours in the palette, the start and end file address locations for pattern data, the bit/byte order used (which varies between the Motorola and Intel processors used on Macintosh and IBM computers respectively) and, very importantly, characterisation data such as device profiles (see Chapters 10 and 11). For real-time access, data systems tend to be device-dependent, the result of which is a diverse range of data formats to meet different needs. As a result many different image encoding systems have evolved, some of which (such as BMP itself) are becoming obsolete whilst newer methods are still being devised.

Some design and colour management systems employ proprietary file formats which are application-specific, but for maximum flexibility it is preferable to use those (such as TIFF) for which all data is openly readable and therefore usable on a variety of platforms. Some formats allow additional CMS information such as ICC (International Colour Consortium) profile data to be incorporated. Table 9.2 gives some of the commonly used encoding systems with additional comments on their pros and cons.

Table 9.2 Some principal file formats

Acronym for file format	Explanation
BMP	Bitmap. Format for digital images as basis for all Windows-based graphic displays. Large file sizes.
TIF(F)	Tag(ged) image file format. Developed in 1987 as a universal file format based on BMP with data 'tags'. Commonly used in textile design systems. Presently in Revision 6 (1992). 24 or 48 bit colour in RGB or CMYK. Capable of lossless (5 times) compression using the LZW (Lempel-Ziv-Welch) algorithm.
GIF	Graphic interchange format. Compact image format (compression 5–10 times) but limited to 8-bit colour. Widely used on the Internet but being replaced by PNG.
PNG	Portable networks graphics. ISO/IEC 15948; 2003. Supports 24–48 bit colour. Capable of greater lossless compression than standard TIFF.
JPEG	Joint picture experts group. Strictly speaking JPEG (ISO/IEC 10918; 1991) is not a format but a compact picture file encoding system. ⁴ When JPEG compressed files are coded using TIFF this is known as JTIF. Standard JPEG compression greater than 2–3 times is lossy but a lossless (JPEG-L) system exists. The new, more versatile standard, JPEG2000, is now available. ⁵ Best system for photographic images.
TGA	Targa (a trade name). Best known as format for storing quick-reference, 'thumbnail' images. Supports up to 32-bit colour and metadata. RLE compression possible.
EPS	Encapsulated postscript. Common format for text, graphics and desktop publishing systems and also for printer drivers. Now largely replaced by PDF.
PDF	Portable document format (Adobe). Frequently used file compression system for both graphics and text on the Internet.
RAW	Many device-specific RAW file formats have been devised for storing pixel data from camera and scanner sensors but no standards exist, hence proposal for DNG.
DNG	Digital negative format (Adobe). A suggested standardised means of encoding raw data from camera sensors together with metadata recording the basic camera settings.

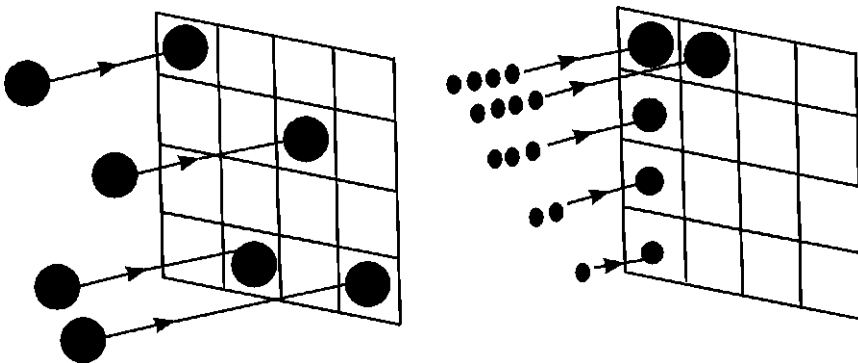
9.3 Pixel and image formation by ink jet printers

The formation of the tiny ink drops produced by jet printers of either the mechanical pulse (piezo) or thermal (bubblejet) type follows a remarkably similar sequence, and the droplets normally form a roughly circular spot when they land on the substrate surface. On leaving the jet orifice the ink initially tends to form a 'tail'. Ideally this collapses into the head of the main droplet which becomes spherical before reaching the substrate. If the applied driving pulse is too strong the tail may be so long as to break up into satellite droplets, a particular tendency with bubblejets. The volume of the droplets varies con-

siderably, but is typically 5–10 picolitres (pl, 10^{-12} litres) depending on the printhead design and the nature of the electrical driving pulse(s).

Each pixel of any design being jet printed is actually composed of multiple droplets deposited onto the substrate as an ordered group called a superpixel, usually on the basis of either a 4×4 , a 6×6 or an 8×8 matrix, and each of the coloured ink drops can be directed within these matrices. Hexagonal matrix configurations are also used on some printers. Most basic jet printers can project only one drop of each colour into any one or more of the 16, 36 or 64 matrix locations. This is known as a binary system. More sophisticated printers, particularly the continuous ink jet type, can modulate the total amount of ink in any one location within the superpixel matrix by projecting several drops. Some modern thermal and piezo-type printers can also produce such halftone effects by projecting multiple ink drops into each superpixel location. An example of this is the Hewlett-Packard C-REt (Color Resolution Enhancement technology). Binary and multi-level halftoning is shown diagrammatically in Fig. 9.1. Table 9.3 shows the relationship between the matrix size and the number of individual shades that can theoretically be produced with a binary system printer using just cyan, magenta and yellow inks.

Jet printers used in reprographic applications can print at up to 1200/1440 dpi but those used for textile printing are normally 300/360 or 600/720 dpi models. There is often confusion between the stated dpi of a printer and the actual definition of the printed design, measured in pixels per inch (ppi), the value of which depends on the size of the superpixel matrix. Thus the printed image definition of a 300 dpi printer using a 4×4 matrix is the same as that of a 600 dpi printing machine using an 8×8 matrix, namely 75 ppi. By comparison the finest screen mesh size (lpi; lines per inch) used for conventional printing is usually 120 lpi (48 raster) and for an average design 80–100 lpi (32–40 raster), which can theoretically be equalled with a jet printer operating at 600 dpi and a 6×6 superpixel matrix.



9.1 Binary and multi-level halftoning.

Table 9.3 Grey levels and colours from CMY inks

Superpixel matrix	Grey levels (including white)	Number of colours
4 × 4	17	4 913
6 × 6 (or 6 × 4 sided hexagon)	37	50 653
8 × 8	65	274 625
16 × 16 (or 4 × 4 with 16 halftone levels per location)	257	16.7 million

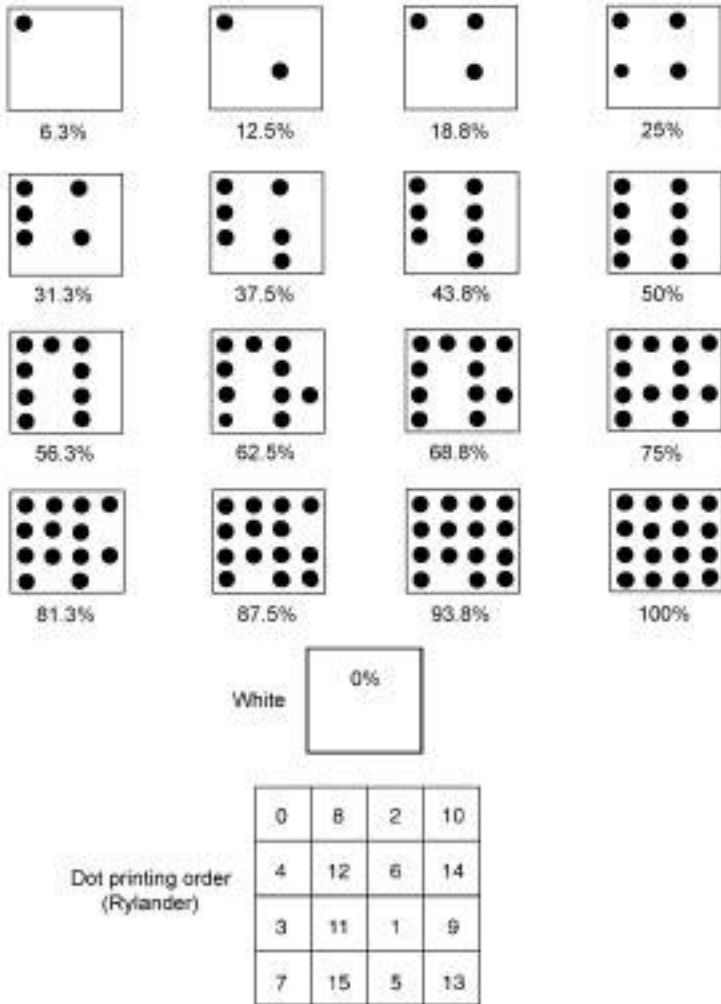
The linear speed at which textiles can be jet printed depends on:

- The maximum frequency response of the printheads as they are scanned across the width of the textile fabric (typically 12–25 kHz; modern piezo systems tend to be faster than bubblejets) and whether the print scanning is single-pass or bidirectional
- The width of the strip of fabric covered in each scan and hence the distance the fabric is moved forward under the heads after each pass of the printhead
- The width of the fabric
- The print definition and superpixel matrix size (the greater these are the slower the production rate).

Thus high production rates and optimum print quality are mutually exclusive. Although improvements have been achieved, the production speed of the smaller jet printers is still only 0.1–0.3 m/min and for the larger, more costly, units 0.5–1.0 m/min, as compared with say 30–50 m/min for a rotary screen machine. Ultimately the printing speed can be also adversely affected by the rate at which the drive data can be computed and transmitted. It is usual therefore to control one or more jet printers with a dedicated high-specification PC or workstation unit, pattern design and editing being carried out elsewhere.

9.3.1 Drop placement within a superpixel (dithering)

To avoid undesirable chevron, moiré or mottled colour effects in digital prints, the placing of individual droplets within the superpixels is carefully controlled to give smooth gradations of shade. Figure 9.2 illustrates the simpler case of a monochrome printer where the black ink spots may be placed systematically in an ordered 4 × 4 matrix arrangement to achieve 17 shade gradations, or grey levels. However, the placing of individual ink drops is usually ‘dithered’ i.e. randomised from pixel to pixel within the matrix. In the case of a colour image each of the R, G and B pixel components are dithered independently. Dithering algorithms vary considerably from one proprietary system to another, but are



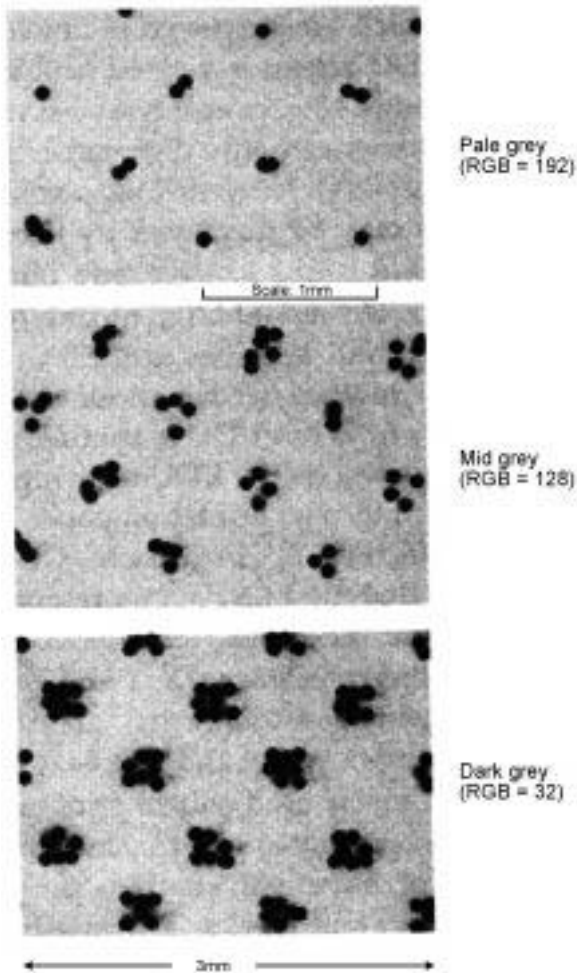
9.2 Illustrates the simpler case of a monochrome printer.

usually classed as ‘ordered’ (such as the Bayer system) or as ‘randomised’, or ‘irregular dispersed’ dithering, which uses error diffusion computation methods (as in the Stücki and Floyd Steinberg methods).⁶

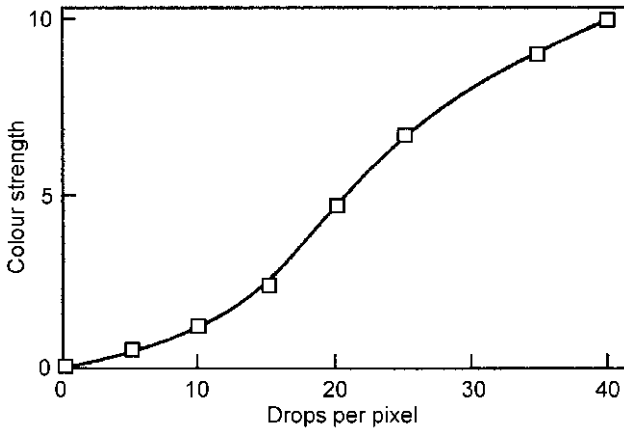
Originated in 1975, the Floyd Steinberg method is simple and in the public domain, being based on a system in which the input signal intensity of each pixel is compared to a fixed threshold (e.g. a grey level of 50%) and the output signal is generated according to this comparison, with the difference between input and threshold values being distributed to the nearest four neighbouring pixels in predetermined proportions (in the original version these were one-, three-, five- and seven-sixteenths).⁷ Several improved versions of Floyd Steinberg have been

evolved, but error diffusion methods in general are slower to compute than ordered dithering, although they yield better quality results with smoother tonal gradations required for photorealistic prints. Without further modification, ordered and some error diffusion dithering methods do, however, tend to produce banded effects at certain grey level values.

Figure 9.3 shows a magnified photographic image of a succession of printed superpixels, for four different grey levels in a simple 4×4 matrix, 300 dpi print, with large unprinted areas between each pixel for the sake of clarity. Note the variations in both the placing and the total number of the ink spots between adjacent superpixels resulting from dithering. The greater the number of drops



9.3 A magnified photographic image of a succession of printed superpixels.



9.4 Selected dyes to extend the limit of the colour gamut of reactive dye printing inks.

of ink placed into each superpixel the deeper the depth of shade, but the relationship between these is not linear, and it is observed that when the drops saturate the total area of the superpixel so that no white substrate remains, there is little further increase in the strength of the print (see Fig. 9.4) It therefore follows that to attain optimum build-up of colour the drops should be small and should suffer minimum lateral spreading on the fabric surface, whilst at the same time being absorbed to a limited extent into the substrate to aid drying, all of which are helped considerably by pretreating the fabric (see Chapter 12). As the number of drops in each pixel increases some in effect fall on areas prewetted by other ink drops, which leads to the overall area covered by the superpixel increasing, giving rise to a so-called dot gain effect with a consequent increase in depth of shade.

When CMY inks are used to produce neutral grey shades (i.e. when $R = G = B$) it might be supposed that the number of spots of each ink present in the superpixel matrix would be equal, but this is not so because of differences in the manner in which colour values of the cyan, magenta and yellow increase with increasing depth of shade which is allowed for by the printer driver software.

9.3.2 Colour gamuts that can be attained using CMY inks

The range of shades in a design that can be perceived on a VDU display (where the colour mixing of light from the RGB phosphors is additive) is much wider than can be achieved by dyeing or printing a fabric and wider still when compared to the colours that can be jet printed. The extent of a colour gamut should not be confused with the number of individual shades that can, at least theoretically, be produced that lie within the confines of that gamut. Thus the use of standard CMY inks with a black ink or a weaker strength cyan or magenta

ink (e.g. when using so-called photo ink cartridges) does not increase the extent or boundary of the colour gamut, only the number of possible individual colours from within the gamut.

With a suitably pretreated fabric and in pale shades, the ink drops deposited in a superpixel remain separate and distinct and the colours produced are governed by the proportional area of the matrix covered by each of the primaries, which is the principle of colour production in reprographics printing and is known as partitive colour mixing. As the depth of shade increases and more drops of ink fall into any one superpixel the spots from each of the primary shade inks tend to impinge on one another and to spread. The range or gamut of shades attainable by the same three primaries in partitive colour mixing is rather more limited than that of subtractive mixing, which, of course, occurs in all conventional textile printing where colours are premixed.

The mixing process within a matrix of ink spots has been studied on paper substrates and a unifying predictive theory developed. A practical trial of this theory showed good correlation between predicted colour values and those actually produced on two commercial paper printers, the software for which employed two dithering methods.⁸ As the depth of shade increases, individual ink spots spread increasingly as they impinge on locations occupied by other spots, leading to the formation of increasingly large superpixels. This can, however, be allowed for in mathematical calculations of the colours attained.⁹ On textile substrates, even when pretreated, ink drops tend to spread more than they would on a coated paper, and on woven fabrics the spread is most pronounced in the warp and weft directions due to capillary action in the fibre bundles.

Where a jet printer also has a black ink supply this may be used in two ways, namely purely to produce dense black shades or as a fourth component, along with the CMY inks, for the duller shades. In fact a combination of CMY inks alone usually produces a poor brownish-black shade. As explained in Chapter 10, it is necessary to introduce still further colours to extend the gamut limits, by providing *inter alia* bright orange, red, blue and green inks. Most wide printers for textiles can now operate with up to seven or eight different inks, thereby attaining a gamut which is considerably extended in three critical directions, namely blue/violet/purple, turquoise/green/yellowish-green and red/scarlet/orange. This places an additional burden on the printer driver software (RIP or CMS) as it is necessary, depending on the target shade characteristics, for the appropriate ink combination to be selected.¹⁰

The theoretical extent of the colour gamut for any combination of colour primaries can be determined by a number of mathematical methods of varying complexity.¹¹ Suitable algorithms can therefore be incorporated into graphics editing software and proprietary CMSs which automatically indicate when an 'out of gamut' shade in a design is selected and the nearest shade match (depending on the desired rendering intent) can be illustrated on the computer

VDU, usually as either a 2D or 3D display. The extent of any achievable gamut depends on the colour characteristics of the primaries chosen, which varies with the class of dye used in the inks. In general reactive and acid dyes tend to yield a wider gamut than disperse and pigment formulations.

9.4 Control of the printing machine

The control of even the simplest computer-driven printer is achieved by software known as a printer driver, supplied via either the computer's software (usually IBM or Macintosh) or printer manufacturer or vendor. A printer driver takes the alpha-numeric or graphics file data and together with other user-specified information (e.g. required definition, single or multi-pass printing options and substrate settings) converts it into output data, which are 'spooled' and when desired transmitted for further processing to the printer's microprocessor/memory. The final instructions from the onboard processor and its memory module then control the electromechanical devices and the printhead firing systems within the printer. Although the drive software supplied by the printer manufacturer can often produce acceptable results, it is more common to use a proprietary RIP (raster image processor) package which offers much faster pre-processing and transmission of image data – indeed some can translate the data 'on the fly' as printing proceeds. Such systems require a correspondingly fast computer/printer communication for which an IEEE-1394 'Firewire' serial link usually replaces the more conventional parallel or serial USB (universal serial bus) printer connection. RIPs also include many other control features which to some degree duplicate those offered by CMSs.

Whatever the software used there are usually a number of options that can be selected before printing begins, chief among which is to choose settings appropriate to the substrate, for its nature has a strong influence on the results. Particularly when using inks based on soluble (acid and reactive) dyes, the fabric needs pretreatment with certain chemicals, such as acids and alkalis, which are necessary for efficient dye fixation, yielding finished prints having optimum fastness properties. Film-forming agents are also applied at the pretreatment stage so that the best colour yield on a particular fibre is achieved, particularly in heavy shades. Thus colour yield can be almost doubled when compared to the use of an untreated substrate.¹² The most universally applicable jet printing coloration system involves the use of pigments, but the colour yields attained depend very much on the choice of the binder and on the processing sequence selected.¹³

9.5 Machine performance monitoring

In general machines with thermal inkjet printheads (e.g. Canon, Encad, ColorSpan) can be made with a closer packing density of the jet orifices than

is possible with piezo heads such as are used in Mimaki, Ichinose, Reggiani and Robustelli machines, but in all jet printers it is clearly essential that they should run with minimum trouble from jets becoming inoperative.

All machines incorporate an automatic flushing cycle for the jets at the start of a run and also at intervals during print runs to avoid problems of unsatisfactory performance which may, for example, arise because loose fibre lints from the fabric have adhered to the jet orifice plates. More seriously, individual jets in a thermal printer can eventually suffer total failure when the tiny heaters (which reach peak temperatures around 400°C) burn out or become blocked by solid burnt-on deposits from an ink. Some manufacturers give their printheads a guaranteed minimum life, e.g. Stork guarantee the jets in the Amber and Zircon printers for 3000 hours (say 6–12 months), although the replacement of the piezo printheads would require a technician. By contrast Encad (Lexmark) print cartridges can be quickly replaced by the machine operator and are guaranteed to deliver 500 ml of ink. Some bubblejet cartridges are fitted with an attached supervisory electronic chip which signals when this point has been reached. When changing from one ink type to another, piezo printheads can be flushed with a special cleaning fluid and the ink supply bottles changed quickly, whilst on bubblejet printers each printhead cartridge/reservoir system is unclipped and changed.

Inoperative jets, which are usually seen to produce stripiness in the weft direction of the printed fabric, are most noticeable when printing dark shades at higher production/lower definition machine settings and when two or more adjacent jets are faulty.¹¹ It may seem rather surprising that such faults can be seen with a printer having a minimum drop definition of 300 dpi, but it must be remembered that such a printer may be giving a true pattern definition of only about 75 ppi. It is therefore prudent at convenient intervals to print special test patterns which will highlight any such jetting failures. The test patterns, which are usually made available as part of the printer driver software, may either be examined visually or be used as part of an automated system check on some machines such as the ColorSpan Fabrijet XII and Encad 700 series. In general such faults are less likely to be observed with 600/720 dpi printers which also have the advantage of showing less colour mottling with some dithering methods.

9.6 Future trends

Any major improvements in digital printing of textiles are likely to come from machinery developments rather than from the design, encoding or operating software. From the electronic operating point of view modern computers have very fast processors and large memory (random access and fixed disc) capabilities, and can be fitted with high capacity colour processing cards and fast external communication systems. On the other hand, those jet printers offering

improved production capabilities (1–3 m/min) that have been introduced, such as the Canon TPU (multihead bubblejet system), the Reggiani DReAM (Scitex/Aprion piezo technology) and Zimmer Chromotex 2003 (with Jemtex continuous ink jet printheads) appear to be less economically attractive than lower productivity machines, such as the Mimaki and Ichinose, originally developed for the reprographics market. In general ink jet printing still continues to exploit only niche markets (sampling, strike-off, *haute couture* and customisation) rather than the short run/rapid response printing business for which the technology could be ideally suited. Unfortunately the ‘weaving shed’ concept of a factory filled with relatively low cost/productivity machines does not appear to have proved sufficiently attractive to any manufacturer, with the exception of Seiren in Japan. Non-contact, white light phase body measuring systems are now available which, with suitable software and in conjunction with improved pigment jet printing and automated garment panel cutting technology, may yet see the ultimate dream of totally in-store customisation of garments realised.¹⁴

From a purely design point of view digital printing methods will continue to give a new freedom to designers who are no longer shackled with the conventions and mechanical constraints of screen printing. Thus, quite apart from the lack of colour and pattern repeat constraints and the ability to produce photorealistic effects, designers can now introduce novel shadow, moiré, textured, blurred and layered effects and in general greater individualism.

9.7 Sources of further information and advice

File formats

<http://www.jpeg.org>

<http://partners.adobe.com/public/developer/en/tiff/TIFFphotoshop.pdf>

<http://www.faqs.org/faqs/graphics/fileformat-faqs>

Dithering techniques

<http://photo.epfl.ch/workshop/wks96>

<http://www.wellesley.edu/pmetaxas/pck50-metaxas.pdf>

Colour reproduction

http://www.poynton.com/PDFs/Guided_tour.pdf

<http://www.nmnh.si.edu/cris/techrpts/imagopts>

Gamut mapping

<http://www.cie.co.at/publ/abst/156-04.html>

<http://www.colour.org/tc8-03>

Books

- C.W. Brown and B.J. Shepherd, *Graphics file formats: Reference and guide*, Greenwich, Manning Publishing, 1995.
- R.W.G. Hunt, *The reproduction of colour*, 6th edn, Bognor Regis, John Wiley, 2004.
- A. McNamara and P. Snelling, *Design and practice for printed textiles*, Oxford, Oxford University Press, 1996.
- J.D. Murray and W. van Ryper, *Encyclopedia of graphic file formats*, 2nd edn, Boston, Addison-Wesley Professional, 1999.

9.8 References

1. T.L. Dawson, 'The use of digital systems in textile printing', in L.W.C. Miles (ed.), *Textile printing*, Bradford, Society of Dyers and Colourists, 2003, 301.
2. B.E. Bayer (Eastman Kodak), US Patent 3,971,065 (1973), 'Color imaging array'.
3. T.L. Dawson, 'Ink-jet printing of textiles under the microscope', *JSDC*, **116** (2000), 52.
4. W.B. Pennebaker and J.L. Mitchell, *JPEG image compression standard*, New York, Van Nostrand, 1992.
5. D. Santa-Cruz, R. Grosbois and T. Ebrahimi, in T. Ebrahimi, C. Christopoulos and D. Lee (eds.), *Signal processing: Image communication*, New York, Elsevier, 2002, 113.
6. I. Kabir, *High performance computer imaging*, Greenwich, Manning Publications, 1996, 446.
7. R.W. Floyd and L. Steinberg, 'An adaptive algorithm for spacial grey scale', *Proc. Soc. Inf. Display*, **17** (1976), 75.
8. P. Emmel and R.D. Hersch, 'A unified model for color prediction of halftoned prints', *J. Imag. Sci. Technol.*, **44** (2000), 351.
9. P. Emmel and R.D. Hersch, *J. Imag. Sci. Technol.*, **46** (2002), 237.
10. V. Ostromoukhov, 'Chromaticity gamut enhancement by heptatone multi-color printing', *SPIE Proc.*, **1909** (1993), 139.
11. J. Morovic and M.R. Luo, 'The fundamentals of gamut mapping: A survey', *J. Imag. Sci. Technol.*, **45** (2001), 283.
12. T.L. Dawson, 'Spots before the eyes: Can ink jet printers match expectations?', *Color Technol.*, **117** (2001), 185.
13. U. Hees, M. Frechte, J. Provost, M. Kluge and J. Weiser, 'Ink-textile interactions in ink jet printing – The role of pretreatments', in T.L. Dawson and B. Glover (eds), *Textile ink jet printing*, Bradford, Society of Dyers and Colourists, 2004, 57.
14. D. Bruner, 'An introduction to the body measurement system for mass customised clothing', <http://techexchange.com/thelibrary/bmsdes.html>.

10.1 Introduction

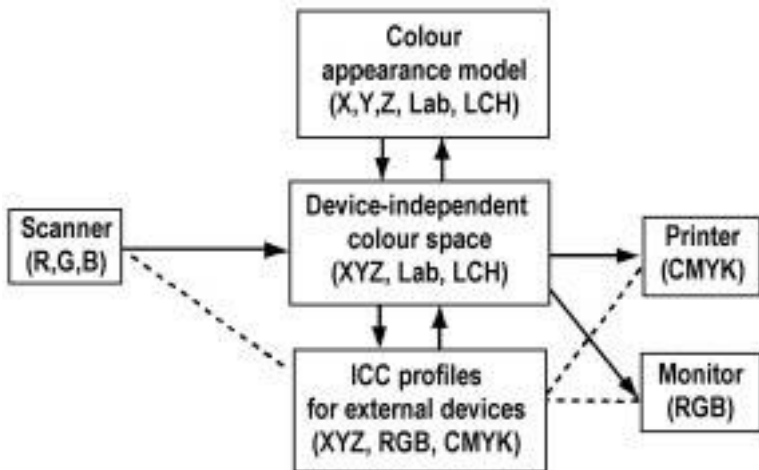
When digital colour processing was first introduced into the reprographics industry it soon became evident that some means was required of controlling the process by which digital data from original artwork which had been computer generated or scanned could be transferred reproducibly to paper by the printing process, other than by using a tedious trial and error procedure. Equally colours viewed on a computer monitor were often a very poor guide to those finally achieved in the printed material. The basic reason for this problem lies in the fact that each of the complex physical processes involved in perceiving, capturing, displaying and reproducing colours varies, hence the difficulty in attaining a result which is consistently acceptable to the viewer. The problem may be summarised as follows:

- *The observer's vision.* Light (reflected from the pattern/print or transmitted from a monitor) is focused on the retina which sends electrical responses to the brain from the red, green and blue cone receptors, although it is nowadays more correct to refer to the cones having a response to long, medium and short wavelength radiation.
- *Digital image capture.* Image is captured as a series of RGB (red, green and blue) cell responses forming a matrix (digital camera) or raster pattern (scanner).
- *Computer monitor display.* Conventional CRT (cathode ray tube) display screens have triads of RGB phosphor dots which are activated by three modulated electron beams. A TFT LCD (thin film transistor liquid crystal display) monitor screen is composed of a matrix of individually addressable translucent cells with RGB filters and has a white backlighting system.
- *Digital colour printer.* Uses CMYK (cyan, magenta, yellow and optionally black) printing ink primaries which, in most digital printers, are jetted onto the substrate as a 'superpixel' matrix of ink spots (see Chapter 9).

In all the above cases there will probably also be differences in ambient illumination, its intensity and colour temperature required (CIE Illuminant D_{65} for textile and D_{50} for reprographic applications) and in the backgrounds against which patterns or monitor screens are viewed.

Computer systems for acquiring, displaying and printing colours digitally normally employ an overall colour management system (CMS) to assist the transfer of colour data from image capture through to the final printing system, a need which was first recognised by the reprographics industry and a number of photographic companies (Kodak, Agfa, Fuji), computer hardware/software providers (Microsoft, IBM, Apple Macintosh), print machinery manufacturers (Heidelberg, LinoColor, Scitex) and suppliers of colour control equipment (Barco, X-Rite, GretagMacbeth) amongst others, each of whom have marketed software which allows cross-system transfer of data. In recent years modified versions of the reprographic CMSs have been further adapted and incorporated into textile inkjet printing control software. Table 10.1 gives some examples of CMSs of varying degrees of sophistication. Most systems require the user to carry out their own measurements with a suitable spectrophotometer whilst others offer measurement and profiling services.

The main purpose of the CMS is to provide a control system by which the measured colour data of a design may be reliably and accurately transformed into output data for display on a monitor or as input to a printer, so that the appearance of these outputs reliably represents that of the input design to the observer. This involves a number of colour data transpositions which are summarised in Fig. 10.1. In addition to ensuring colour consistency between the various input and output devices and providing software to drive a range of digital printers, a CMS will often provide other useful features such as



10.1 Summary of colour data transpositions.

Table 10.1 Colour management systems

Manufacturer (Website: http://)	Product	Platform
Agfa (www.agfa.com/graphics)	ColorTune CMM	MacOS
Aleph (www.alephteam.com)	Newton	MS Windows
Chromix (www.chromix.com)	ColorValet	MS Windows/MacOS
ColorSavvy (www.colorsavvy.com)	SavvyProfile suite	MS Windows/MacOS
Color Solutions (www.color.com)	ColorBlind Prove-It	MacOS
Colorburst Systems (www.colorburstip.com)	Colorburst Pro	MS Windows
Colorvision/Datacolor (www.colorcal.com)	ProfilerPRO, DoctorPRO	MS Windows/MacOS
Ergosoft (www.ergosoftus.com)	TexPrint	MS Windows
Fujifilm (www.colorprofiling.com)	ColorKit profiler	MS Windows/MacOS
GretagMacbeth (www.gretagmacbeth.com/il)	NetProfiler, Profilemaker	MS Windows
Heidelberg (www.heidelbergusa.com)	Prinect Calibrator/Profiler	MS Windows
Kodak Polychrome (www.kpgraphics.com)	Matchprint	MacOS
Pantone (www.pantone.com)	ColorVision and ColorPlus	MS Windows/MacOS
X-rite/Monaco (www.xrite.com)	MonacoEZcolor & Profiler	MS Windows/MacOS

organising the ‘queue’ of print jobs. The CMS may also provide means for communicating design and colour data via the Internet.

It is often the case, particularly with longer print runs, that the digital design, having been sampled/proofed on a digital printer, is then screen printed with print pastes containing completely different dyes. In such cases, having already obtained spectrophotometric data on each colour in the design, an additional feature of the CMS may be to provide recipe predictions for the conventional print production. To be able to do this the system needs to be provided with

colorimetric data for a range of calibration prints for each dye which may be used. The spectrophotometer used for device calibrations can, of course, be used for this purpose.

To further understand the need for colour management systems and how they operate, it is first necessary to appreciate the various ways by which any colour may be unequivocally specified and what functions the various proprietary CMSs can carry out to ensure reliable colour reproduction.

10.2 General numerical colour specifications

Any colour may be specified by three coordinates that locate its position in a three-dimensional colour space, which is, however, often represented graphically in two dimensions or as a planar projection. There are a number of standard CIE (Commission Internationale de l'Éclairage) colour spaces, each varying in its overall uniformity and each having its own coordinates.^{1,2} Three commonly used colour spaces are determined as follows:

- CIE xy colour coordinates: XYZ or xyY (usually depicted as a 2-D, x/y plot). The total range of this colour space represents the limits of human vision.
- CIELAB colour coordinates: $L^*a^*b^*$, a visually more uniform colour space usually displayed as a 2-D, a^*/b^* plot.
- CIELCH colour coordinates: LCH (lightness, chroma, hue) sometimes used as an L/C plot to show the chromatic build-up of a particular colour.

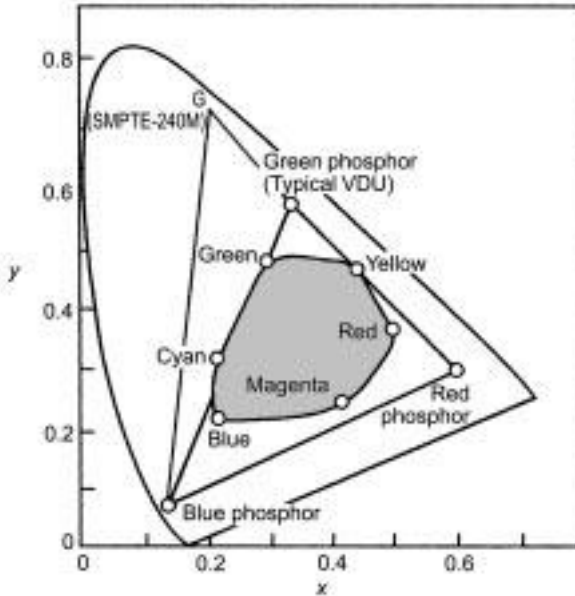
Figure 10.2 is an illustration of the use of the 1931 CIE x/y chromaticity diagram to illustrate that the range or gamut of shades which can be produced on a typical monitor screen and especially an HDTV (high definition television; SMPTE 240M) display is considerably wider than that which can be achieved by an inkjet printing device, particularly if the printer is using only CMY primaries.

When processing device-dependent colour data it is usual to compute with 8 bits per channel even though the colours may have been measured with as many as 16 bits per channel. Thus with 8 bits each for RGB (24-bit colour) and CMYK (32-bit colour), there are 256 grey levels for each primary. This yields a theoretically possible 16.7 million (2^{24}) colours but human observers cannot in fact distinguish differences between all these colours.

The simple relationships between RGB and CMY in terms of their digital values are:

$$R = 255 - C \quad G = 255 - M \quad B = 255 - Y$$

Thus R, G and $B = 0$ and C, M and Y (or K) = 255 represents black and reversing these values gives white or, in a print, the colour of the substrate. Such a simple translation from the RGB values of the colours in a design which has been captured by a scanner into CMY values for a printed image would, however, produce a very unsatisfactory reproduction of the shades of the



10.2 An illustration of the use of the 1931 CIE x/y chromaticity diagram.

original image owing to the wide variations in the colour reproduction characteristics that always exist between any input and output device. Thus in an ink jet printer there is no simple linear relationship between the digital RGB or CMY values and the hue or intensity of the printed colour. In practice conversion from RGB to CMY values is by the use of complex polynomial equations or other non-linear transformations³ and is therefore usually achieved indirectly from colour measurement of target shades which allow a three-dimensional, reference LUT (look-up table) to be constructed.

If in addition there is a requirement that any colour images displayed on a monitor should appear the same on a different display and should also accurately represent those that will eventually be achieved by printing, still further calibration and characterisation of the equipment will be required. All such controls of scanners, cameras, displays and printers require mathematical computation of varying degrees of complexity and it is the critical role of the CMS to facilitate this. Each type of colour-capture, display or reproduction device processes colour in its own particular colour space, and in order to be able to accurately transform every colour (or know that a particular colour is 'out of gamut') it is necessary to devise a common, device-independent, colour space. Over the years a number of colour spaces have been proposed, some of which are quite extensive (such as Adobe sRGB) relative to those sometimes used in CMSs. Thus the sRGB (IEC1966-2.1) colour space⁴ which has been adopted internationally is used in the ICC Profile format specification⁵ which is

discussed in Chapter 11. The extent of the sRGB colour space is very similar to that of a typical computer monitor, or a standard European system TV display, illustrated in Fig. 10.2. When employing ICC Profiles the device-independent colour space is referred to as a Profile Connection Space (PCS) and the software which processes the data is a Colour Matching Module (CMM) or the Colour Engine. For their part the two major computer software suppliers, Microsoft and Apple, provide their own internal colour management controls as part of the operating systems, namely ICM (image colour management) and ColorSync, respectively, but if a third party CMS is to be used successfully these native management systems must be disabled. The extent of the sRGB colour gamut is very similar to that of a typical colour monitor whether it be a conventional CRT (cathode ray tube) or LCD (liquid crystal display) type (Fig. 10.2).

The transformation of RGB values from either the monitor or scanner responses into the XYZ values of the sRGB colour space is carried out in two stages, firstly by using non-linear gamma corrections (power functions of the type R^γ , G^γ and B^γ) for each R, G and B response and then applying a linear 3×3 matrix transform to these linearised RGB values of the following general type:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Note that the RGB values in this matrix are 'normalised', so, for example, a linearised digital value of 200 corresponds to $200/255$, i.e. 0.78.

In this type of matrix some of the coefficients, a to i , can be negative and XYZ colours will be out of gamut when one or more of the calculated RGB values is negative or greater than unity. If there are differences in the viewing conditions relating to the input and output (such as the reference white point of the display and that which relates to the print on textile) then a chromatic adaptation transform must be applied to the data. Chromatic adaptation and other appearance-modelling transforms usually take a similar mathematical matrix form.⁶ In practice the calculations can either be run in real time by the computer or be stored as LUTs containing, for example, a matrix of RGB values for a particular device which can be read off as the corresponding device-independent $L^*a^*b^*$ values. LUTs do not usually comprise the full 16.7 million colour combinations, so the software computes some colours by a process of interpolation.⁷

10.3 Characterising display, input and output devices

In order to achieve consistent display, acquisition and reproduction of textile designs, it is essential to both calibrate and characterise the various pieces of equipment and thereafter to repeat these controls at regular intervals because of

the changes that may occur, for example, in sensor responses, light source emissions and for printers, in the standardisation of the ink supplies and particularly the properties of the textile substrates. The three types of device require a somewhat different approach in the manner in which they are controlled.

10.3.1 Control of colour display monitors

The screen of a CRT (cathode ray tube) monitor consists of tiny R, G and B phosphor spots which are caused to fluoresce when hit by the scanning electron beam, the intensity of light emitted being related to the drive voltages applied to the grid of each electron gun. These voltages in turn are generated according to digital values fed via a DAC (digital to analogue converter chip) and video amplifier on the computer's video card. The relationship between the light intensity obtained on the screen and the initial digital RGB inputs is not linear but, apart from an initial offset, follows a mathematical power relationship defined as the gamma value. The term gamma value can be confusing since it is also used in computer operating systems where the standard colour space gammas are usually set at 1.8 (MacOS) or 2.2 (MS Windows). The 'native' gamma (γ) of a CRT, which usually lies between 2.5 and 3.0, is intrinsic to a particular tube and relates the gun voltage DAC level (D) to the resulting screen luminance (L), as defined by the following relationship:

$$L = KD^\gamma$$

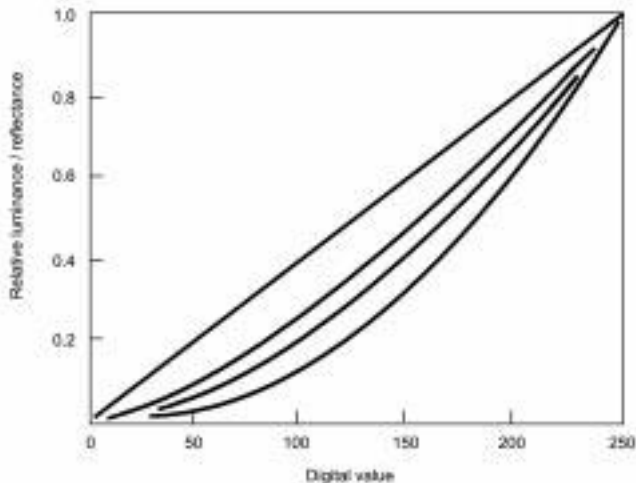
To add to the confusion over gamma values, gamma corrections can be applied at other stages, for example when a scanner acquires an image or when data is processed by a video card. When an image is saved it is possible for the gamma which has been applied to be stored within the file, but this is possible only for certain formats such as TIF, TGA and PNG (see Chapter 9, Table 9.2).

The mathematical basis for the characterisation and standardisation of a conventional monitor based on a CRT display has been well established⁸ but requires additional equipment and may appear at first sight to be a somewhat laborious operation. Accordingly some simpler systems have been devised, such as Adobe Gamma, Praxisoft WiziWYG, ColorWizzard and GretagMacbeth WebSync, which allow visual setting of contrast/brightness and the red/green colour signals by quick, on-screen adjustments. Similarly 'generic' colour profiles for individual monitors are available from the manufacturers. It is also possible to adjust the individual RGB gamma settings using the videocard software control system but this is a very trial and error method. All such visual adjustments give at best only a limited improvement in the accuracy of the display, but in fact for some users there appears to be little need for the computer's display to be closely controlled. On the other hand, some firms employ colour communication software which ensures that their customers can

specify and approve shades digitally from on-screen appearance (using systems such as Datacolor International's ImageMaster), and for such requirements there is no alternative but to use full colorimetric characterisation of all displays used in the communication network.

Initially the monitor, having been left on for a considerable time to become stable, is calibrated, before the characterisation stage. Calibration is carried out by adjusting the contrast control (setting the gun amplifier's offset so that a zero digital D value produces zero luminance of the screen) and the brightness control (which paradoxically sets the black level). The gamma level affects mid tones to the greatest degree as the black and white settings now become fixed points in the gamma curves (see Fig. 10.3). The final calibration requires that the colour temperature of the white point (when R, G and B = 255) corresponds to 6500K (Illuminant D_{65}) which is nowadays the standard for most general-purpose VDUs. With some of the more expensive monitors there are built-in measuring devices and associated software which can achieve these measurements automatically, whilst with other systems the spectrophotometer is interfaced directly via a USB (universal serial bus) connection to the computer, allowing direct control of the monitor display.

For accurate characterisation of a general-purpose CRT or LCD monitor, it is essential to use some type of colorimeter or spectrophotometer which can measure the colour coordinates of areas of colour displayed on the screen. These are usually small portable spectrophotometers such as Spectrolino and Eye-one Pro (GretagMacbeth) and particularly the modestly priced ColorSpyder (Colorvision/Datacolor) and MonacoOPTIX (X-rite) colorimeters that can be placed against an LCD monitor screen without distorting its extremely thin glass sandwich



10.3 Gamma response curves.

construction. The Spyder and Optix devices utilise the output from a series of photodiodes (seven and 22 respectively) each fitted with a filter so as to measure screen luminance over a range of wavelengths when coloured test patches are displayed. In addition to the use of surface contact colorimeters it is also possible to use more sophisticated, remote-sensing spectroradiometers such as the EyeBeamer (GretagMacbeth) and the Bentham TP300. The generation of the test colour patches is controlled by the individual CMS program selected which compares the measured colour coordinates of the test colours with the input values and from this data compiles a monitor profile conforming to the ICC specification.

In recent years the technical performance (with respect to spatial colour uniformity and viewing angle sensitivity) and the price level of TFT LCDs has improved considerably, and LCDs are increasingly replacing the more bulky CRT-based monitors. Initially their calibration and characterisation proved somewhat difficult. TFT LCDs are transmissive devices fitted with a white backlighting system which must ensure that when the RGB filter arrays are set equally ($R = B = G = 255$) the resultant white point corresponds to the D_{65} standard. Several workers have shown that the gamma-correction model which is satisfactory for CRT characterisation is not adequate to describe the response of LCDs, as these follow an S-shaped function curve (as indeed does the output from a printer). The colour reproduction characteristics of LCDs also differ from those of CRTs in that the white point colour temperature increases as luminance decreases, an effect known as 'grey tracking'.⁹ This can be corrected by modifying the video look-up table (LUT) of the display device driver. There are also problems in that the chromaticity of the LC cell display changes with applied voltage, which affects the grey level, and there can also be a cross-talk effect between adjacent cells. Finally, although the performance of LCD displays has been greatly improved, there are still limitations in the screen viewing angle. Despite these problems the range of shades (colour gamut) which can be displayed on an LCD is wider than that of a CRT-based monitor and, by choosing a suitable characterisation model, almost as good colour management of LCDs can now be achieved.¹⁰ Suitable software for LCD characterisation has now been included in most CMSs.

Once characterised, all display devices need checking at regular intervals to overcome time-related 'drift'. Some firms do this every week as a matter of routine whilst a once-a-month control system is advisable. Scanners tend to be more stable but still require checking from time to time, as do printers, particularly as differences will arise if there are any changes in the 'standard' substrates or inks being used.

10.3.2 Characterisation of input devices

For the acquisition of colour design data the most commonly used device is a scanner, usually employing a CCD or CMOS sensor array with RGB filters. Less

commonly the input may be taken from a digital camera, again with an RGB array but the individual pixels are often in a Bayer mosaic arrangement with two G for every R or B cell.¹¹ The colour data can be downloaded in this form as an RAW format file, or alternatively a demosaicing algorithm can be performed to give interpolated RGB data for every pixel.

As with monitors, the scanner should first be calibrated, although these devices do tend to run very consistently over long periods of time and to maintain the settings incorporated by the manufacturer. The most direct and efficient way to characterise a scanner is to scan a special test image comprising both a grey scale and a wide range of colour patches, for each of which the colour coordinates are known or can be measured. The IT8.7/2 to 7/4 series of reflective colour targets are produced by Kodak, Fuji and Agfa to ANSI standards. For example the IT8.7/3 (ISO 12642) card has 928 colour patches and is commonly used rather than the much less extensive 20 shades of the GretagMacbeth ColorChecker card. For an extension of this range of shades (1485) the ECI 2002 (European Color Initiative) colour targets may be used. The colour coordinates of all the colours of the IT8 target as issued are closely controlled and the colour values (in terms of XYZ, $L^*a^*b^*$ and LCH) can be downloaded, for example from the Fuji website (<http://www.colorprofiling.com>). For greater accuracy they may also be measured automatically using a small reflectance spectrophotometer such as the Spectrolino/Spectroscan (GretagMacbeth) or PULSE (X-Rite) devices. Such spectrophotometers may be used either with a software-driven, actuated support table or as a manually operated scanning device in conjunction with a guide frame which fits over the target shade card. Both types of device can complete the scanning and storage of the very extensive test patch data in only a few minutes. Using a sufficiently large number of test colours, an LUT can be constructed relating the captured RGB values to the actual tristimulus values for each shade, with interpolation for intermediate points not included in the LUT data. Clearly the greater the number of test patterns actually measured, the less need there is for interpolated data. Other, often less precise, mathematical methods of characterising both scanners and cameras have been described.^{12,13}

10.3.3 Characterisation of printers

If a suitable scanner has first been characterised, it is possible to characterise a printer indirectly by first scanning an IT8 target card using the scanner profile. This image is then printed with any generic printer profile controls switched off. With suitable software provided from within the CMM it is then possible to amend the values in the LUT for the printer and also relate these values back to $L^*a^*b^*$ values in the sRGB device-independent colour space. Alternatively the data for the IT8 shades can be input to the computer display (which in some

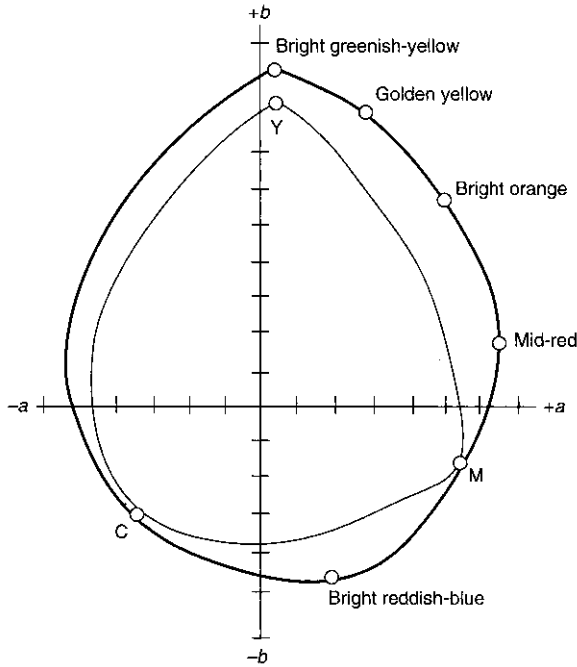
systems may be done by scanning the IT8 target and the test print simultaneously), or the resulting image printed and the colour coordinates for each printed shade then measured spectrophotometrically. Comparing the input and output colorimetric data allows an LUT specific to that printer to be constructed. In all such characterisation work it is essential to record details of the substrates which are printed, because although some degree of control of the total amount of ink which can be applied to the fabric surface can be achieved via the printer driver software, variations in chroma, lightness and sometimes hue will certainly be evident when the substrate is changed. Similarly a different characterisation procedure must be carried out for each dye/fibre type combination and also for the same dye and fibre if, as is sometimes done for convenience, the shade specified may be either for the printed shades before as well as after the dye fixation (and possibly, washing-off) operations, a situation that has no comparison in reprographics printing.

There still remain a variety of mathematical characterisation methods for printers ranging from simple first-order masking systems using linear matrix transforms to higher-order polynomial solutions based on the halftone process whereby the CMY colour spots are treated as producing colour in an additive manner according to the relative area each group covers within each pixel and the light-scattering properties of the substrate, following the colour prediction models of Neugebauer and Kubelka-Munk.¹⁴

10.4 Colour gamut and rendering intent

Figure 10.4 illustrates the overall range of shades (i.e. the gamut) that can be achieved when printing with typical reactive dye based CMY inks, but in this case for clarity the representation is on a CIELAB diagram in which the colour distribution is much more uniform than in a CIE chromaticity plot. The extent of the gamut can be considerably expanded if additional inks, comprising brighter primaries such as orange, yellowish-red, reddish-blue and yellowish-green, are selected. This idea was first promoted with the Pantone Hexachrome and Heptatone colours which utilise an additional bright red, purple and green.¹⁵ Many inkjet printers for textiles can now accommodate up to seven primary shades although the printer driver software is correspondingly more complex.

Irrespective of the primary shades used, but particularly when only CMY inks are involved, it is not uncommon for it to be impossible to match certain shades specified in an original design. This situation is recognised by the colour management software either when input data is converted to sRGB colour space or, somewhat less likely, when it is transformed into the printer colour space. In general the least objectionable gamut remapping is that which preserves the original hue while sacrificing lightness or saturation.¹⁶ If this occurs the user is asked for a 'rendering intent' which can be specified in one of four ways, namely:



10.4 The overall range of shades that can be achieved when printing with typical reactive dye based CMY inks.

- *Perceptual (Picture)*. The method generally recommended for photographic reproduction because it applies the same gamut compression to all images, thus maintaining the same overall relative colour rendering balance.
- *Relative colorimetric (Proof)*. Reproduces out-of-gamut colours to the nearest reproducible hue. Preserves lightness but not saturation.
- *Absolute colorimetric (Match)*. Converts out-of-gamut colours to the nearest hue but sacrifices saturation and lightness.
- *Saturation (Graphic)*. Maps the saturated primary colours in the source to those in the destination irrespective of differences in hue, saturation or lightness. As the name suggests, this intent is used mainly for business display graphics.

The technology of gamut remapping using lightness- and chroma-preserving scaling functions has been studied extensively and several algorithms perform well when printing on paper.¹⁷ The author is, however, not aware of any similar comparisons having been carried out specifically on a textile substrate. Several CMSs offer the possibility of visualising both 2-D and 3-D displays of the colour gamuts that can be achieved with from three to eight primary inks.

10.5 Colour communication

In modern commercial textile environments there is an increasing need for rapid and reliable communication systems both internally (possibly between many geographical sites) and with customers, specifiers and suppliers. This is particularly the case with the trend for suppliers and major retail groups to source globally rather than locally. To facilitate this there needs to be a rapid and reliable data transmission system which should preferably be 'open' (non-proprietary). Examples of colour data that may need to be transmitted are:

- Large, high definition image files, particularly if in 48-bit, uncompressed (e.g. TIF, BMP) colour data format
- Colorimetric measurement data which may, for example be transmitted in XML (eXtensible Markup Language) code exemplified by GretagMacbeth's CxF language for colour data transmission¹⁸
- Colour management data such as equipment characterisation and ICC profile information.

Particular problems can arise when transmitting and viewing colour images over the Internet,¹⁹ where it is desirable that the sender's data can be displayed accurately by the receiver (e.g. for Internet sales of coloured garments), for without suitable monitor characterisation even the 216 so-called 'web-safe' colours may not always correspond. Originally GIF-encoded, 8-bit graphics were used on many websites to assist in rapid download rates, but this has become less common with the increasing adoption of high speed broadband communication and 24-bit 'Trucolor' display. However, 16-bit 'Hicolor' is sometimes used for which none of the individual colours (other than black and white) correspond exactly with those of 8- or 24-bit colour.

Depending on the operating and browser systems (e.g. Internet Explorer, Netscape Navigator, Windows, MacOS, Linux, etc.) in use, the software may either choose the nearest colour supported or process the design image by dithering adjacent pixels, using neighbouring colours from the available palette. This type of dithering of whole pixels (as opposed to the dithering of ink spots within a pixel) can produce very objectionable effects, particularly in a textile design with large areas of solid shade. A number of firms offer software which enables web colour management and specification (e.g. GretagMacbeth's NetProfiler and eWarna's Online Colour eXchange).

10.6 Colour reproduction performance of equipment operated with a CMM

A few workers have published results of investigations to compare the repeatability and accuracy with which colours can be reproduced by digital printers,

Table 10.2 Shade reproducibility from scanner to digital print

Substrate	Number of test colours	Mean colour difference (ΔE_{cmc})		Reference
		Not characterised	Characterised	
Paper	24	16.5	6.0	Randall ²⁰
Paper	24	9.6	2.6	Dawson ^{7,21}
Textiles	24	N/A	6.4	Dawson ⁷
Paper	240	29.4	2.6	Sharma and Fleming ²²

with and without CMS control, although most of these studies concerned prints on paper rather than on textiles.

Accuracy of shade matching can be assessed using a suitable spectrophotometer and calculating the total colour difference (ΔE) according to the CMC(2:1) colour difference equation. In general a ΔE of 1 or less represents a very good degree of colour matching for a dyed fabric and possibly a value of up to 3 might be completely acceptable in a textile print.⁷ Some data published for the reproduction of the 24 colours on the GretagMacbeth ColorChecker by inkjet printing on paper without any device characterisation shows that reproduction is poor, but although this is definitely better after device characterisation there still seems to be room for improvement. In a more extensive series of tests using the 240-shade IT8.7/2 test card and six different CMSs, the possibility of attaining much better reproducibility, at least in paper printing, has been demonstrated (Table 10.2).

Day-to-day repeatability has been evaluated for a variety of wide digital printers on textile fabrics and was found to be very good with $\Delta E_{\text{cmc}} = 1.0 \pm 0.6$, slightly better than was found for some office paper printers with $\Delta E_{\text{cmc}} = 1.7 \pm 0.8$.⁷ Practical and economic considerations require that print performance should also be reliable to ensure minimum downtime.

The commonest faults relate to partial or complete malfunctions of individual jets and, if two neighbouring jets are affected, this appears as a stripiness in the print, particularly when printing heavy shades at lower dpi settings. Such effects may arise simply because of the tiny drops being deflected from their normal direct path to the substrate surface. Misalignment defects can be lessened if the distance between the jets and the substrate is minimised, although this increases the likelihood of contamination from loose textile fibres. Fibres adhering to the printhead surface or partial jet blockages because of inadequate filtering of the ink supply can usually be cured by head cleaning or flushing the system. All printers have software which allows a flushing cycle and indeed this is interposed at intervals during printing (another factor which reduces output). In more difficult cases the ink supply can be changed to a special cleaning fluid.

Thermal printers can suffer from jet blockages due to a charring effect, known as kogation, occurring in the region where the tiny, bubble-forming heaters are located, so that a build-up of insoluble matter occurs which affects jetting performance. Careful formulation of the inks minimises the effect. Extreme thermal stress can ultimately cause the electrical interconnects to the heater elements to fail and in this case the ink cartridge must be replaced. To identify jet faults, test patterns can be printed at intervals between production runs, and this can be carried out automatically on some machines such as the latest Encad and ColorSpan units.

10.7 Future trends in colour management

Considerable progress continues to be made by manufacturers and software suppliers in providing integrated solutions which are simple to apply and which utilise small, relatively low cost, calibration/characterisation equipment. In particular, with the trend to the adoption of more extensive colour targets, the advent of simple yet speedy methods of acquiring large amounts of calibration data with minimum effort is commendable. The continuing development of 'entry level' systems will enable even the smallest enterprise to achieve accurately characterised colour displays and reproducible print results without the need for highly skilled technical operatives.

10.8 Sources of further information and advice

Standard RGB colour spaces

<http://www.w3.org/Graphics/Color/sRGB>

<http://www.srgb.com/c55.pdf>

<http://www. www.cl-c.com/Color%20Management.pdf>

IT8.7/3 Color Target

<http://www.clemson.edu/printcon/downloads/series.pdf>

Colour space coordinate calculations/conversions

<http://www.brucelindbloom.com>

<http://www.dgcolour.co.uk>

Colour management

http://www.boscarol.com/pages/cms_eng

<http://normankoren.com/colormanagement.html>

<http://www.measureitrite.com>
<http://www.tasi.ac.uk/advice/creating/colour2.html>
http://www.ipa.org/tech/color_management
<http://www.ewarna.com>

Books

- R.M. Adams and J. Weissberg, *The GATF practical guide to color management*, 2nd edn, Pittsburgh, PA: GATF Press, 1998.
- M.D. Fairchild, *Color appearance models*, 2nd edn, Chichester: John Wiley, 2004.
- E. Gioganni and T. Madden, *Digital colour management: Encoding solutions*, Englewood Cliffs, NJ: Prentice Hall, 1998.
- P. Green, *Understanding digital color*, 2nd edn, Pittsburgh, PA: GATF Press, 1995.
- P. Green and L. MacDonald (eds), *Colour engineering: Achieving device independent colour*, Chichester: John Wiley, 2002.
- A. Sharma, *Understanding color management*, New York: Thomson Delmar Learning, 2003.

10.9 References

1. R. McDonald, *Colour physics for industry*, 2nd edn, Bradford: SDC, 1997.
2. R.S. Berns, *Billmeyer and Saltzman's principles of color technology*, 3rd edn, Bognor Regis: John Wiley, 2000.
3. A. Johnson, 'Methods for characterising colour printers', *Displays*, **16** (1996), 193.
4. M. Stokes, M. Anderson, S. Chandrasekar and R. Motta, *A standard default color space for the Internet – sRGB*, Ver. 1.10, Hewlett-Packard, 1996.
5. *Spec. ICC.1:2001-12*, International Color Consortium (www.color.org).
6. 'A colour appearance model for colour management systems, CIECAM02', TC8-01, CIE159:2004.
7. T.L. Dawson, 'Spots before the eyes: Can ink jet printers match expectations?', *Color Technol.*, **117** (2001), 185.
8. R.S. Berns, 'Methods for characterising CRT displays', *Displays*, **16** (1996), 17.
9. G. Marcu and K. Chen, 'Gray tracking correction for TFT-LCDs', in *IS&T/SID 10th Color Imaging Conf.*, Scottsdale, AZ, 2002, 272.
10. G. Sharma, 'LCD displays vs. CRTs – Color calibration and gamut considerations', *Proc. IEEE*, **90** (2002), 605.
11. T.L. Dawson, 'Light detecting devices: their use for colour measurement and image capture', *Rev. Prog. Col.*, **34** (2004), 72.
12. A. Johnson, 'Methods for standardising colour scanners and digital cameras', *Displays*, **16** (1996), 183.
13. G. Sharma, 'Target-less scanner color calibration', *J. Imag. Sci. Technol.*, **44** (2000), 301.
14. P. Emmel and R.D. Hersch, 'Colour calibration for colour reproduction', *ISCAS 2000 – IEEE Int. Symp. on Circuits and Systems*, Geneva, V-105.
15. V. Ostromoukhov, 'Chromaticity gamut enhancement by heptatone multi-color printing', in *IS&T/SPIE Proc. Conf. on Device-independent Color Imaging and Imaging Systems Integration*, San Jose, CA, SPIE 1905 (1993), 139.

16. E.D. Montag and M.D. Fairchild, 'Psychophysical evaluation of gamut mapping techniques using simple rendered images and artificial gamut boundaries', *IEEE Trans. Image Processing*, **6** (1997), 977.
17. G.J. Braun and M.D. Fairchild, 'Image lightness rescaling using sigmoidal contrast enhancement functions', *J. Electronic Imaging*, **8** (1999), 380.
18. T. Senn, T. Braun, S. Greter and F. Lamy, US 2001004801 (GretagMacbeth, USA), 2001.
19. D. Saunders, J. Cupitt, R. Pillay and K. Martinez, 'Maintaining colour accuracy in images transferred across the Internet', in L. MacDonald and R. Luo (eds), *Colour imaging: Vision and technology*, Chichester: John Wiley, 1999, 215.
20. D.L. Randall, 'Digital images for textiles – next generation', www.techexchange.com/thelibrary/digitalimagingNG.html.
21. T.L. Dawson, 'Ink-jet printing under the microscope', *JSDC*, **116** (2000), 52.
22. A. Sharma and P.D. Fleming, 'Evaluating the quality of commercial ICC color management software', *Proc. TAGA Tech. Conf.*, Asheville, NC, 2000, 336.

11.1 Introduction

What is pink?

To measure and to describe colors is a science of its own. Unlike for time, length or mass, there is no unit for color. In addition, the physical description of a color event needs an infinite number of values: it is the spectrum of the colored light, and since a spectrum is continuous it cannot be described by a discrete number of values. To describe the visual impression of a color event, only three values are necessary: color space is said to be three-dimensional. The international commission on illumination (CIE) has developed some well-established unit systems that can be used to describe a color,¹ for example CIE XYZ, CIE Lab, CIE Lch or CIE Luv. The advantage of these color spaces is that they can describe any visible color, and that they are well defined. They allow one to define a color in absolute values and they do not depend on the device that has been used either to measure or to reproduce the color. They are called ‘device independent color spaces’. Color spaces like RGB or CMYK are different. They depend on the device that has been used for measuring or reproducing the color: for example, an RGB value could be the measurement result of a scanner or the input of a CRT device, while a CMYK value is usually a recipe that is printed with, for example, an ink jet printer.²

The job of color management is to translate between the different color spaces: for example, it takes an RGB value from a scanner and calculates an RGB value that will display exactly the same color on a CRT, or it calculates the CMYK value that can be printed on an ink jet device. While typical RGB devices such as scanners, digital cameras, CRTs or LCDs can be characterized by quite simple formulas, ink jet printing devices are very difficult to characterize. The only way to describe the behavior of an ink jet printer very accurately

1. From now on the expression ‘color’ shall be used to mean ‘visual impression of a color event’.
2. Also RGB color spaces can be device independent: e.g. artificial RGB color spaces like ECI-RGB, sRGB or AdobeRGB are not related to a special device.

is to use big tables, where for many different input colors the appropriate output colors are listed. These formulas or tables are called profiles.

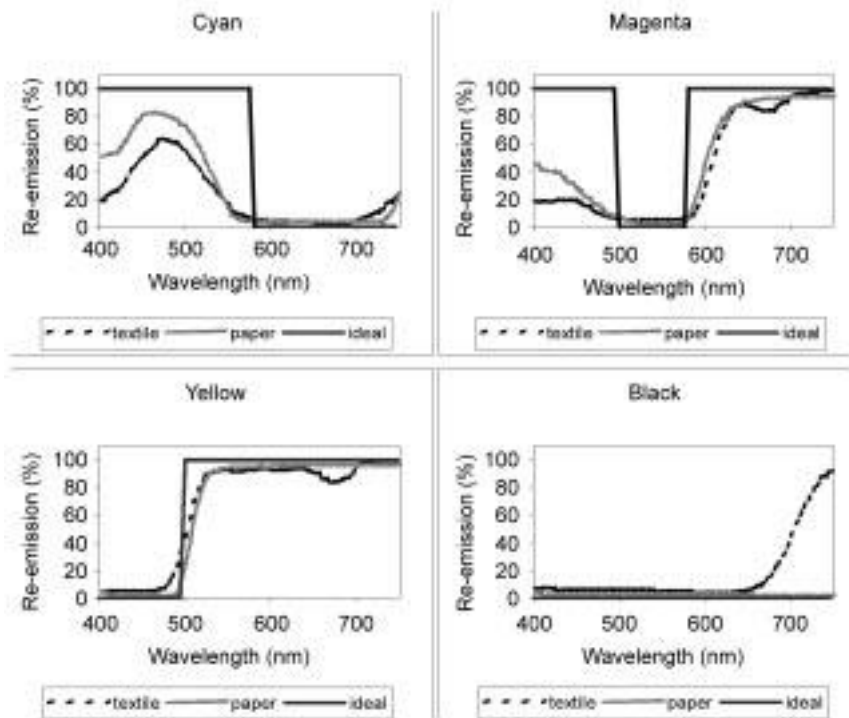
11.2 Overview of textile colors and common color spaces

It is true that a mixture of the three ideal colors cyan_ideal, magenta_ideal, and yellow_ideal, will not cover the whole gamut of visible colors, but it will cover the maximum gamut that can be reached by a mixture of only three colors. The problem is that even today's chemistry is not able to deliver colors that exhibit spectra like the ideal colors: all available colors are far from being ideal. This becomes even more difficult if you want to print not only with ordinary dye inks on glossy paper, but on fabrics with some reactive, disperse, acid, sublimation or other textile inks: the gamut becomes quite small (Fig. 11.1). In addition to this, the colors that are normally used in textile design are quite hard to achieve with a mixture of just three or four³ colors: for example, navy blue is a very common color for textile design and normally you cannot be reached by a combination of normal cyan, magenta, yellow and black (CMYK). If one asks about colors that are hard to get by standard CMYK, the most frequent answer would be saturated red, green or blue. These are only the most impressive colors, but also a dark brown or ocher can be very difficult to print. The only way out is to add several special colors to your textile ink jet printer: for example, Hexachrome uses orange and green as additional colors, or you could add red, green and blue to CMYK. There are many different settings and it's hard to decide which is the best for a special purpose. We will give some advice later in this chapter.

There is another motivation to use even more inks in an ink jet printer: usually even the smallest droplets of black, cyan or magenta will be seen on a substrate as single dots when printing light color shades. To prevent this, these color shades are printed only with the light versions of the inks: light cyan, light magenta and light black.

While calibrating an ink jet printer for paper is generally fairly simple, doing so for textiles is a bit more complicated. Having completed a printout on paper, you just have to wait for the inks to dry before you can start to measure the results.⁴ Textile printing, however, usually needs some post-treatment, such

3. Since just three colors (CMY) don't allow the printing of dark color shades, almost every common printing process uses at least four colors where black (K for black) is added: it is called the CMYK process. Another advantage of CMYK to CMY is that you can save ink: this is not only a financial aspect (K is cheaper than even just a single C, M or Y, and cheaper still than the sum of all three, C+M+Y), but it's also a necessity because some printing substrates don't allow printing with up to 300% of a single ink (100% cyan + 100% magenta + 100% yellow).
4. To get more precise results, you should wait not only until the printout has dried completely, but also some additional hours because during this time the colors (sometimes) change slightly.



11.1 Spectra of different color sets for CMYK printing: inks for textile or paper, and ideal CMYK inks. Black and yellow inks, for both textile and paper, show quite ideal behavior. Especially for magenta and cyan, the textile inks are far away from the ideal spectra. Epson Ultrachrome Inks on paper, and DyStar Jettex R reactive inks on cotton, have been used as samples.

as transferring ink from paper to textile by a sublimation process, or steaming, washing and drying for a reactive ink process. It is not until this final step that the colors are valid and might be used for calibration purposes. Therefore, efficient software for textile printing should not need too many steps with many printouts, which have to be done one after another to do a complete printer calibration. Otherwise you will have to repeat the whole workflow (printing, post-treatment and measuring) too often and this will take too much time.

11.3 ICC basics

Given an environment of 10 different input devices (scanners, etc.) and 10 different output devices (printers, monitors, etc.), either you would need 100 different translation tables (10×10) to translate a color value from any input to a color value of any output device ('closed loop color management'), or you

would use ICC color management instead (Ostromoukov *et al.*, 1994). ICC color management would need only 10 input profiles and 10 output profiles (20 profiles altogether). The idea behind it is to divide the translation from input to output color space into two steps:

1. Translate input color value to a device-independent color value.
2. Translate device-independent color value to output color value.

The ICC standard uses either CIE-Lab or CIE-XYZ values as device-independent color values. This color space is called the ‘profile connection space’ (PCS).

ICC color management can be divided into two tasks:

1. Preparation: build a profile for any input device and any output device. This is done by using a calibrated spectrophotometer (e.g. devices of Gretag, Xrite, Avantes, etc.) and ‘profiling’ software (e.g. ErgoSoft ColorGPS, Monaco Profile Creator, Gretag Profile Maker, etc.).
2. Application: select the appropriate input profile and output profile for every job (printing, or viewing on a monitor). The calculation, i.e. combination of the two profiles and calculation of the correct output color value for every input color value, is done by the so-called color management engine, CME (sometimes also called color management module, CMM, or color management system, CMS), which can be either part of the RIP software or part of the operating system.

The second task is less difficult and much better defined. The CME takes an input and an output profile and calculates a transfer function that delivers for any incoming color value the output color value. Even though the transfer function that has to be created by the CME is not defined absolutely by the ICC standard and in consequence some differences between several CMEs may exist, these differences are quite small and they can be reduced further by using ICC profiles with higher accuracy, i.e. larger profiles. For proofing or simulation, applications such as the simulation of a second output device can be included to the transfer function.

Until now, we have only talked about exact color matching. Actually, this is not the real objective in many cases: one has to be aware of the possibility of different gamuts of input and output color space, and that, for example, a color taken with a camera could not be printed with the ink jet, or the pure white colors are different in input and output. Depending on the subject that has to be printed, the real objective for color translation might be different. Therefore the ICC standard offers several ‘rendering intents’ the user can choose from (see Table 11.1).

Table 11.1 ICC standard, rendering intents

Rendering intent	Description	Typical application
Absolute colorimetric	100% exact color match (colors out of gamut can lose contrast, color gradients might end in posterization)	Exact color reproduction, preview, proofing (including simulation of media white)
Relative colorimetric	Exact color match, but adaptation of media white (colors out of gamut can lose contrast, color gradients might end in posterization)	Simulation, color reproduction, preview, proofing (excluding simulation of media white)
Perceptual	Input colors are compressed; also colors out of gamut offer contrast, smooth color gradients, no posterization	Reproduction of, for example, photographs on a printer with smaller gamut
Saturation	The contrast of the input colors is increased: very pure and saturated colors can be reached	Reproduction of, for example, business graphics

11.4 ICC advantages and disadvantages

11.4.1 Advantages

The major benefit of color management is the adaptation of the colors of any input device and any output device. You are able to print out exactly the same colors you have previously measured with a scanner. The advantage of ICC color management is to do this not only at a single place with just one pair of devices, but to be able to print out exactly the same colors that somebody else has captured in another part of the world: color values in graphics become standardized. You just have to couple your graphic with the corresponding profile and everybody, everywhere, with a profiled printer can print it out in the correct way. ICC color management allows you to define colors in your graphics with standardized values, in the same way as you can define, for example, lengths with standardized values such as centimeters. The ICC standard supports profiling of many different devices such as any kind of printer or printing machine, monitors, scanners, digital cameras, image setters, etc.

The other advantage of ICC color management is the possibility of simulating the behavior of one output device on another output device. For example, you could use your ink jet printer to exactly simulate the output of an offset press, or the output of a textile screen printing machine. This simulation is called proofing. A less expensive method of proofing is soft proofing, where a calibrated monitor is used instead of a printer as output device. This can also be done using

ICC color management. However, it is obvious that for proofing applications the gamut of the proofing device must include the gamut of the simulated device. If the media of proofing and simulation devices are different, the media color of the simulation device can be simulated (by using absolute colorimetric rendering intent) or ignored (by using relative colorimetric rendering intent).

11.4.2 Disadvantages

To convert a color value is not as simple as doing conversions like Celsius to Fahrenheit or meters to inches. Color conversions are usually non-linear and can only be described by multiple values that are organized in tables. Since color spaces are at least three-dimensional, the tables usually must have at least three dimensions. A reasonably accurate description of the color non-linearity would need around 30 different values per dimension, i.e. $30 \times 30 \times 30 = 27,000$ values. For different rendering intents, different multidimensional tables are necessary, and since a profile must be able to do the conversion in both directions, one has to apply another factor of 2. This is the reason why ICC profiles easily become quite big. This gets even more difficult for CMYK colors, where four dimensions are necessary, and it becomes a forbidding task for more than four colors. This is an important aspect because it can become necessary to add an appropriate ICC profile to every graphic or image.

The ICC standard provides only one perceptual rendering intent. As previously described, the perceptual rendering intent should offer the appropriate contrast compression for a special output device. But this contrast compression depends not only on the output device, but also on the actual input profile, or rather on the actual input data, i.e. only one perceptual rendering intent is too coarse.

The ICC standard does not offer dedicated tools to reduce or control metamerism effects or fluorescent colors. Especially, optical brighteners which are used in almost every printing material may cause color shifts.

Usually ICC output profiles are huge multidimensional tables with discrete color recipes at each table position. For values between table positions some interpolation techniques are used, so it may happen that some recipes will not appear anywhere. In other words, profiling an output device will never offer a bigger gamut; on the contrary, in some cases it may reduce a gamut.

11.5 Requirements and problems for ICC profiling

There are many wants and requirements for ICC profiles or rather the profiling software.

1. Color precision. Certainly the major task is to offer perfect color matching. Color management must be able to deliver exactly the same output color for a desired input color. While this is the objective for all colors when

colorimetric rendering intent is used, it is also the objective for certain colors when perceptual rendering intent is used. In the latter case, especially neutral gray colors or human skin colors have to be matched very precisely because the human eye is very sensitive to color shifts in these shades.

2. Output profiles should take advantage of the whole gamut of the output device.
3. Color gradients must be reproduced without any steps, especially for the perceptual rendering intent.
4. The profiling software must offer opportunities to limit the amount of ink that is used in an output profile: for example, since one is highly unlikely to find a medium that is capable of taking up to 400% ink (100% cyan + 100% magenta + 100% yellow + 100% black) the ink usage must be reduced. Usually a paper can handle up to 300%, more or less.
5. Different ways to control the black should be offered (black generation models): sometimes it might be preferable to print light shades of gray using cyan, magenta and yellow instead of pure black, because single black dots can disturb more than dots of cyan or magenta do, but the contrary may be preferable in other cases, such as when a light black ink is present or the black dots are too small to disturb. This would save ink, reduce color shift in neutral gray tones and reduce metamerism effects: it is called GCR (gray component replacement).
6. Output profiles should contain not only tables to do color conversion in the direction of the output color space but also tables in the opposite direction and preview tables. This provides the possibility to do a backward translation of the output data or a simulation of the output device. In addition the profile should contain a gamut table that describes the gamut of the output device – which colors can be reproduced and which cannot.
7. Profiling software, especially when used for digital textile printing, must be able to handle more than just CMYK. It must be able to deal with additional red, green, blue, navy, orange, golden yellow or any other special color to generate profiles with bigger gamut.
8. Ink should not be wasted: if a color can be reproduced by two different color recipes, the recipe that uses less ink should be used.
9. Since color reproduction using subtractive color mixing (e.g. ink jet technology or other CMYK devices) is a very non-linear process compared to additive color mixing (e.g. RGB monitors), prediction of the colors is very difficult. The only way to do this is to print out big calibration charts with many different color recipes and measure the result with a spectrophotometer. The more intelligence is spent on the profiling software, the better the color prediction can be made and the number of calibration recipes reduced. This has serious impact on productivity, and one profiling software can get the same output quality with just 300 measurements where a competitive product needs more than 2000 measurements! Also the

method of interpolation between single measurements highly influences the precision of the color calculations. Therefore, smart profiling software does not use just simple linear interpolation.

10. In output profiles color recipes must be defined not just for colors inside the gamut, but also for any color outside the gamut. To do this, the color outside the gamut must be mapped to a color inside the gamut. Usually this will be a color with the same hue, the same brightness but lower saturation. Good profiling softwares provide more sophisticated 'gamut mapping', and allow some configuration of the mapping algorithm. Actually, it is not a simple task to enforce a (subjectively) constant hue, because the value for hue in the Lab or Lch color space is only an approximation of the perceived hue. If the gamut mapping algorithm is looking just at the Lab/Lch hue, blue colors may become somewhat purple and red colors may become orange.
11. Since profiling is not a simple task, many users are not willing or able to understand all the details, so that profiling software should offer different automatic modes to make it easy enough to use.

11.6 Current technologies

Many companies provide software for creating ICC profiles. The most famous in the market are Logo, that unified later with GretagMacbeth (Gretag Profile Maker), Heidelberg (PrintOpen), Color Solutions (BasICColor), Monaco (now Xrite) (Profile Creator), PraxiSoft (WiziWyg), and ErgoSoft (ColorProf and ColorGPS). Only ErgoSoft provides not just a single profiling software but also a complete software RIP (TexPrint). TexPrint is a powerful software that allows efficient printing on large-format ink jet printers, with many extensions specialized for digital textile printing. It offers a very user-friendly interface to intuitively create print jobs, direct control of many large-format ink jet printers, an integrated halftoning engine, sophisticated linearization, complete color management, PostScript interpreter and much more. The integrated profiling software (ColorGPS) is cutting edge and delivers superior profile quality at minimal effort for calibration. It is the unique software that is capable of generating profiles for up to 12 different output colors that are in demand, particularly for textile printing. The combination of RIP and profiling software allows extensive data exchange between the two parts of the software and therefore provides serious efficiency benefits for the user. We focus on this solution for digital textile printing as a reference and limit our further discussion to this software package.

11.6.1 Print environments

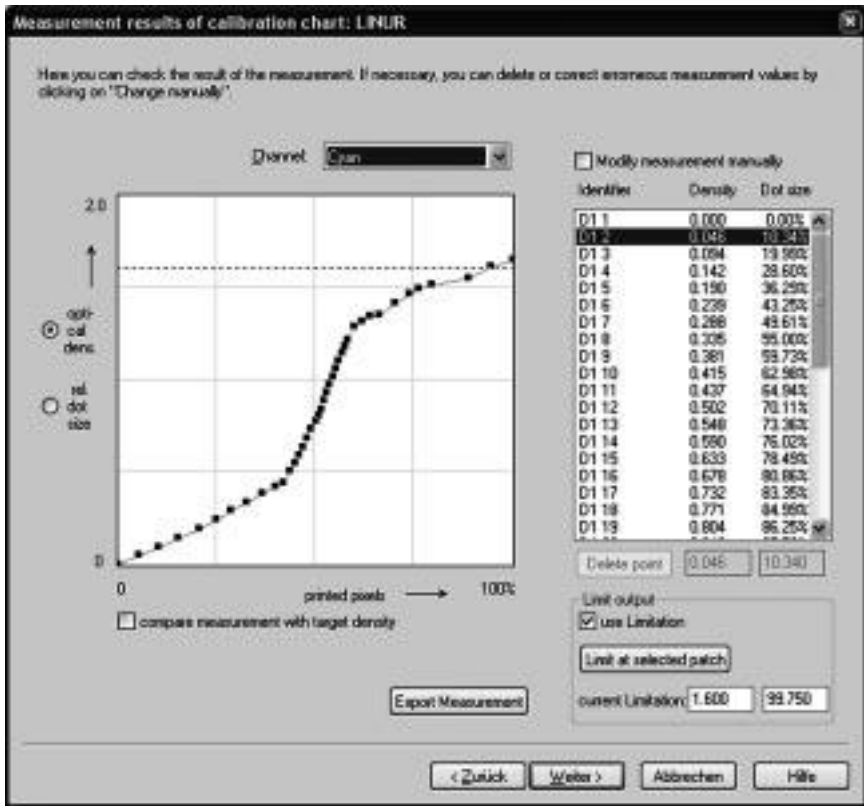
Inkjet printing is a very sensitive process that depends on many factors, for example printer type and model as well as the actual device, type of paper or

other media, ink setting, current resolution, halftoning method, printing speed, output quality, pre- and post-treatment of the media, output method and many more. If one of these factors is changed the result will or can be different. To control all these factors, print environments are used. A print environment gives detailed information about the whole configuration of your printing system. If different configurations are used, different print environments must be created, for example if you are using two kinds of paper whose only difference is their weight (grammage). To get the best results, each of these print environments must be calibrated. Sometimes this might be too time-consuming and you may share the same calibration among several print environments. To do so may be adequate if the only difference would be a small discrepancy of the grammage of the material but it would be a sin if you change from a plain paper to a glossy paper.

Digital printing on textiles compared to digital printing on paper usually takes much more time. Printing on paper is quite simple but printing on textiles frequently needs special treatments before or following the printing process, such as sublimation transfer or steaming and washing the fabric. While simplicity of the calibration process for paper printing is nice to have, in the case of textile printing it's a must: the most efficient way would be to combine all the calibrations in one single calibration task. Unfortunately this is not feasible, because the quality of the whole calibration would be too poor. A two-step process will be a good compromise between calibration quality on the one hand and usability on the other. In a first step the printing process is linearized and in the following step the profile is created. TexPrint, which offers powerful support for many different print environments, uses this two-step calibration process.

11.6.2 Linearization (calibration of single colors)

Usually, halftoning techniques for ink jet printers will give quite non-linear results. This gets more difficult in the case of the common frequency-modulated halftoning methods such as error diffusion or stochastic screening. The new ink jet print heads supporting of variable dot sizes as well as light ink usage will further increase non-linear behavior. Therefore serious linearization is essential. TexPrint offers an extensive calibration tool in the form of a wizard. The user is asked about the quality he requires, that is, the effort he is willing to put in, then a calibration chart is printed. Afterwards, this chart has to be measured with an integrated measurement tool, which supports all common color measurement devices. The results are displayed both graphically and in a text list (see Fig. 11.2) where they can be controlled and, if need be, changed. In addition, the ink usage can be limited to a certain level. This should be done if further ink usage would not result in a further notable increase in optical density, i.e. the density measurement curve runs against a saturation level. It should be used only to prevent wasting of ink for a single channel. If problems with the sum of ink of



11.2 Measurement results in linearization wizard.

all channels are present, these problems should be dealt with while creating the ICC profiles, when the mixtures of the different inks are calculated.

To describe the result of a density measurement, two different measuring units are common:

1. Area coverage: the ratio of an area that is partially filled with 100% of color; e.g. an area coverage of 50% means the same density that you would get by printing a pattern where exactly 50% of the area is covered with full color.
2. Optical density: the negative decade logarithm of the re-emission ratio.

The two measuring units are linked by the formula of Murray Davies (Yule, 1967):

$$a = \frac{1 - 10^{-D}}{1 - 10^{-D_{full}}}$$

where a is area coverage, D is optical density, and D_{full} is optical density of full color. Although optical density is the unit that is normally provided by the

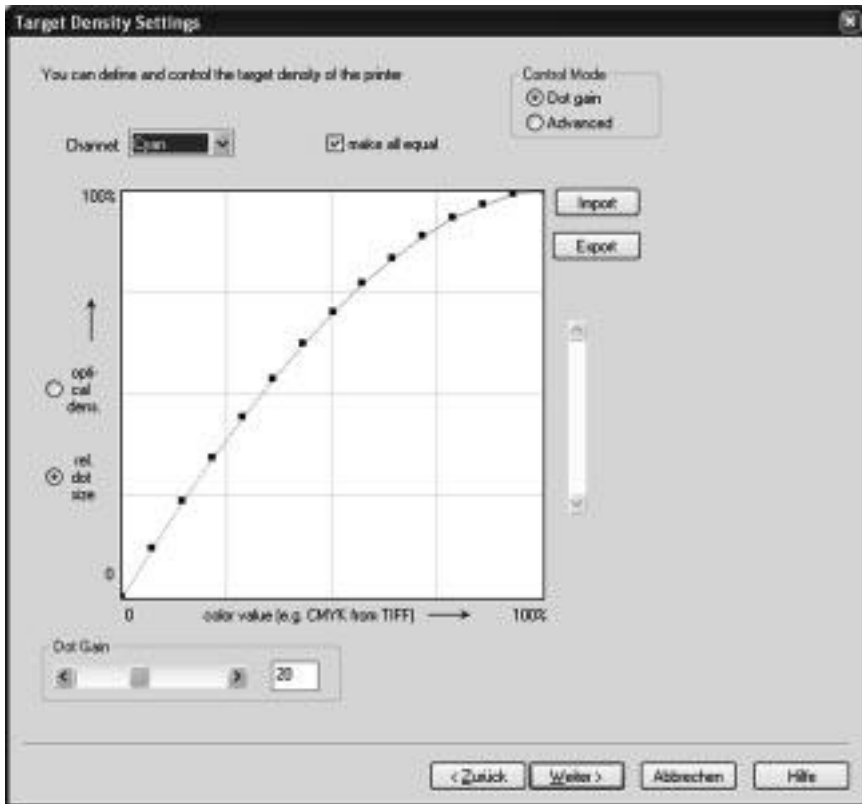
measurement devices, area coverage is widespread among experts. This has its origin in the (offset) printing industry.

Usually when we talk about linearization of the printing device, our goal is not to get perfect linear behavior, i.e. a color value of 50% should not result in an area coverage of 50%! In former times, especially in the case of newspaper or offset printing, even a well-calibrated printing machine was not able to offer perfect linear behavior, but it was able to provide well-defined dot gain behavior. The effect of dot gain is a curve above the perfect linear curve with a smooth shape. The value of dot gain is the difference between this curve and the linear curve: for example, a dot gain of 20% would mean that an input of 50% would lead to an output of $50\% + 20\% = 70\%$ area coverage. Since the kind of paper used for printing greatly affects the dot gain of the printing process, there is no common standard value for the dot gain parameter. A value of 20% can be recommended as somewhere between newspaper printing and glossy printing. It also results in a constant visual contrast over the whole range: a step from 10% to 20% in color value would lead to similar contrast as a step from 80% to 90%. Nevertheless the calibration wizard of TexPrint allows extensive definition of the linearization target (see Fig. 11.3). This is only useful and necessary if you work without ICC profiles, and the color space of your design application would be the color space of your ink jet device. We do not recommend this and therefore it will not be discussed in detail. But there is another feature provided by the linearization target definition in TexPrint that is very useful: you can export and import linearization targets. Using this feature you align a whole set of printers just by exporting the target of the weakest printer and importing this to any other. By doing so, all printers will behave exactly the same.

11.6.3 ICC profile generation (calibration of mixed colors)

In the previous paragraph the calibration of each single ink channel was described. Now we'll describe how mixtures of inks can be calibrated. This is done by ColorGPS, the ICC profiling software of the TexPrint suite of ErgoSoft. Although ColorGPS is very powerful software with lots of adjustments, it is simple to use and will find by itself highly useful presets for virtually all the parameters. Only the quality the user wants to get, or rather the effort for calibration he is willing to spend on the one side, and the amount of ink that the printing media can handle on the other side, has to be defined manually. With this information a calibration chart is calculated.

The calibration chart is optimized to reduce the number of calibration patches to a minimum. Without this optimization the number of patches needed for the calibration will increase enormously with the number of inks: to get a good color calibration it's not sufficient to measure only recipes where the different inks are printed with either 0% or 100%. Mixing colors of an ink jet device is a very non-linear process and therefore levels between 0% and 100% have to be tested as



11.3 Target definition in linearization wizard.

well, for example 0%, 25%, 50%, 75%, 100%, i.e. five levels. In the case of three different inks this would result in 125 (5^3) patches, or for CMYK 625 patches. This can be handled, but how about 400,000 patches in the case of eight colors? Either the accuracy is reduced (check out just 0%, 33%, 66%, 100%, or only 0%, 50%, 100%), or one has to find other rules, as ColorGPS is doing. The idea behind those rules of ColorGPS is that not every combination of ink will be tested, depending on the current ink set. To explain this, consider a setup of CMYK plus two additional inks. Sometimes it is useless to combine both additional inks in a recipe: if orange and green were the additional inks, a combination of them would result in a gray color that can be printed using just CMYK. But also the opposite can happen: if red and orange were used as additional inks, a mixture of orange and red could result in a color unattainable by any other ink combination, and thus a combination of these two inks is reasonable. ColorGPS is able to decide, without any user interaction, which ink combination should be used. It extracts the color information needed for each ink from the linearization measurement that has been done previously. The

reduction of calibration effort is enormous: for example, for an eight-color profile ColorGPS gets an even better result with just 300 patches where other profilers need more than 2000 patches. The calculation of the optimal calibration chart is done very quickly, usually within one or two seconds. Afterwards the calibration chart can be printed and finally measured with the integrated measurement tool that supports all common measurement devices.

Having done the color calibration, the ICC profile can be calculated. Depending on the precision, namely the size of the profile, this may take a while (up to some minutes). You can save the profile, test it and use it to check whether it's acceptable or not. It may happen that for some colors too much ink is used. If so, the ink limit of ColorGPS can be reduced, and without redoing the calibration, a new profile can be calculated. Only if the change of the ink limit is serious (e.g. from 300 down to 180) should you do a new calibration, because otherwise the accuracy would become too poor. It is also possible to increase the ink limit after a color calibration has been executed, but the increase should be moderate (not exceeding 50%). ColorGPS is able to accept even extreme values for the ink limit: for example, it can manage a limit of 80% as well as a limit of 600%, so that there is no need to limit a single ink channel within the linearization as there would be when other profilers are used, where sometimes ink limits under 200% are not supported.

ColorGPS provides another amazing advantage: the calculation of the final ink recipes that are used in the ICC profile is done completely automatically. The user does not have to specify rules as to how (additional) inks should be used. ColorGPS finds out whether, for example, an additional blue ink might be used for colors that are darker, or brighter, or more saturated than cyan plus magenta, or whether the additional blue ink is covered by the gamut of the other inks and therefore can be omitted. The way the different inks are utilized is defined by an algorithm that results in smooth gradients of the different inks. Changing from one ink to another for neighboring target colors is inhibited as far as possible, because this would always result in color steps whenever the profile is applied.

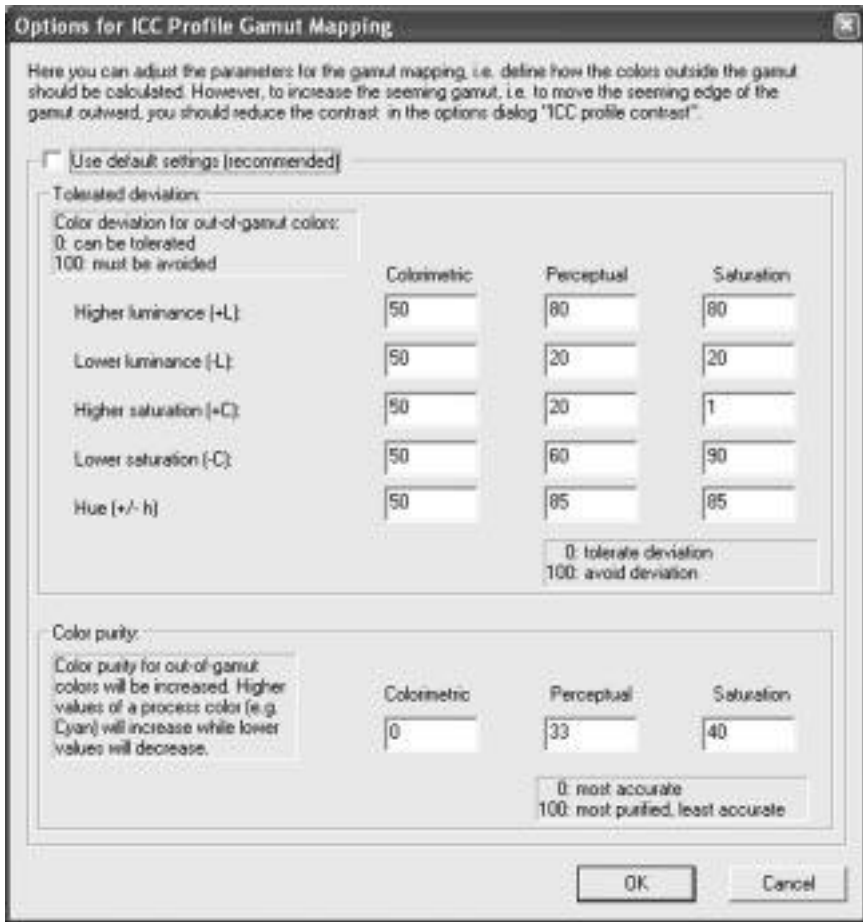
A short explanation of how the color steps arise is given here. As already mentioned in a previous section, an ICC output profile is made up of a huge three-dimensional table and two relevant colors might be located at neighboring positions in this table. Let's assume that one ink would be 'golden yellow' (g.y.) and the other would be 'orange yellow' (o.y.). Let's further assume that somewhere in the table a recipe would consist of (nearly) 100% of 'golden yellow' and the recipe at a neighboring location would consist of (nearly) 100% of 'orange yellow'. When this profile is applied, and the recipe for a color exactly in the middle of these locations is calculated, a recipe like 50% 'golden yellow' plus 50% 'orange yellow' would be the result, because this is the mean of 100% g.y. + 0% o.y., and 0% g.y. + 100% o.y. The problem about this 'intermediate' recipe is that it will look considerably different! A recipe consisting of two inks,

each at 50%, will not cover 100% of the medium. The reality would be that 25% of the medium would be covered with both inks, 25% with one and 25% with the other ink, and 25% would remain uncovered! This is a long way from the intermediate color. If you find this difficult to imagine, just think about using black as the first ink and also as the second ink. The expected intermediate color value would be black, but the reality is the mixture of 25% double black, which is black just as well, 50% (single) black, and 25% white, i.e. 75% black + 25% white, giving gray! Sometimes even seriously different recipes for neighboring colors cannot be avoided, since actually they are needed! This can happen when using inks that have almost the same color and each of them is expanding the gamut of the others, i.e. none of the inks can be omitted.

In consequence there is a trade-off between big gamut requiring many different inks, on the one side, and high accuracy with smooth color gradients, where only few colors can be used, on the other side. Using more inks neither increases the accuracy of a profile nor improves the smoothness of the colors. The only reason to increase the number of inks may be to enlarge the gamut. The following rule should be considered: use an ICC profile with fewer inks as long as it covers the gamut you need, and choose a profile with many inks only if really needed!

Calculating a profile is done by ColorGPS in two steps. First, for every color within the gamut an ink recipe that will match the color is calculated. Second, any color outside the gamut is mapped to a color within. Theory about gamut mapping can be found in Morovic (1998) and Morovic and Luo (2001). The mapping is controlled by two methods: first, changing the contrast, and second, the 'real mapping'. Changing the contrast will change the 'pretended gamut'. If the contrast for the colors within the gamut is reduced, the pretended gamut increases, i.e. fewer colors remain outside. If the contrast is increased, the same input colors become more saturated or darker, the edge of the gamut will be reached earlier and therefore the pretended gamut will become smaller. The contrast calculations can be described as a kind of scaling. Scaling can be done in the direction of the L-axis (for contrast in the luminance direction) and the C-axis (for the saturation direction). Afterwards, the 'real gamut mapping' will replace any color outside the gamut by an appropriate color inside the gamut. This replacement will change depending on the character of the original color: hue, saturation or lightness will be affected. For the colorimetric rendering intent all three values are equally important and therefore the weighting factors for each deviation should be equal. In the case of perceptual or saturation rendering intent usually they will be different: for example, to preserve hue is more important than to preserve lightness or saturation. Although the standard setting leads to fine results, all the parameters that control the gamut mapping may be changed to fulfill special needs (for an example see Fig. 11.4).

Finally a tip for daily work: you should develop a system to define names for profiles or other calibration files. Include all the necessary details, like printer



11.4 Parameters to control gamut mapping of colors.

model, resolution, quality, media, etc., in the file names. You will have to invent some abbreviations, otherwise the names become too long. Without this information at a glance, efficient work with many different profiles will not be possible.

11.7 Results

Using ICC-based color management helps you to control the color output of your ink jet device. To determine the quality of the color management is not a simple task and a benchmark must contain more than just a single discipline. At least three of the following tasks should be checked:

1. Precision of color matching
2. Smoothness of color gradients

3. Largeness of the gamut
4. Suitability of gamut mapping.

For tasks 1 and 3 an objective measurement can be defined. For the other tasks this will hardly be possible and they have to be judged subjectively. A benchmark for the color matching may be the color difference between target and measurement of some test colors after printing. The difference can be scaled in units of ΔE (i.e. Euclidean distance for the two Lab values) or in some derivatives like ΔE_{94} or ΔE_{CMC} (Clarke *et al.*, 1984). The test patches should be within the gamut of the target device because treatment of out-of-gamut colors is mainly a concern of gamut mapping and should not be judged by a simple ΔE value. The average and the maximum color difference are very significant figures and are appreciated as a benchmark. The largeness of the gamut can be determined using the gamut tables of the profile. This can be done very easily, but since there is no well-defined rule how the gamut tables have to be calculated by the profiling software, they can be used just to compare profiles created by a single profiling software, otherwise it's like comparing apples and oranges.

For subjective testing, appropriate test images are needed. They must cover the regions of interest. Since color spaces are three-dimensional and an image is always restricted to two dimensions, it can cover only a subset of the whole color space. Furthermore, a very common mistake is to use RGB images for testing where sometimes sRGB is the color space. sRGB may provide a gamut with a larger volume, but an actual ink jet device can also produce colors that are not covered by the sRGB gamut anyway! Another disadvantage of common RGB color spaces is that their most saturated colors (red, green, blue, cyan, magenta or yellow) normally are quite different from the corresponding colors of the ink jet. Usually, the most saturated colors of an ink jet are darker. A good advice is to build up a generic CMYK profile where the Lab values for the different inks can be defined manually. Use values that are typical for cyan, magenta and black, or, to make sure that a larger gamut will be provided by this profile, you may use Lab values that are (slightly) more saturated. Use such a profile as the working color space within your design application to draw and generate test images with interesting and suitable test colors and color gradients.

To give you an example for an ICC profile application for digital textile printing, a comparison of six and 11 color setups is shown here. Due to limited space we will reduce the discussion to a gamut comparison of the two setups. For the experiment, DyStar Jettex R reactive inks on cotton were applied. Since the gamut of a simple four-color setup is even poorer, we used the six-color as a simple setup and the whole 11-color as an advanced setup. The six-color setup consisted of 'Yellow 5G', 'Orange RN', 'Red 4B', 'Blue 3R', 'Turquoise GM' and 'Black BN', and for the 11-color setup 'Golden Yellow GR', 'Red FB', 'Navy 4R', 'Green 2GM' and 'Brown 2R' were used in addition. In Figs 11.5