DIGITAL COLOR PRINTING

Digital color printing exploits modern computational capabilities to give greater control and repeatability than does analog printing. Soon high-quality color reproduction may be brought to the desktop.

Gary K. Starkweather

Color printing is a modern technological wonder that appeals to an impressive sensory ability: human vision. Colorful images influence what we buy, how we dress and the decisions we make on a host of other life-style issues. Digital color printing provides ease of control and the potential for repeatable, WYSIWYG—"what you see is what you get"—printing. Analog color printing does not permit a comparable level of editing and control, and only in the hands of craftspeople does it provide repeatable results. Digital color printing transfers image control from the chemical tank to the computer. (See figure 1.) Furthermore, personal computers have increased so much in speed, memory and computing power that processing requirements deemed virtually impossible to satisfy only ten years ago are now met routinely. The emergence of digital (or electronic) photography will bring new and exciting capabilities to users and allow us to optimize the preparation of information.

This article presents the basics of digital color printing technology. It looks at how digital color printing works and what governs the quality of the resultant images. While this subject is too vast to cover in totality here, the discussion should at least acquaint the newcomer with the issues surrounding digital color printing. Hopefully, it will stimulate the reader to learn more about this exciting new area.[1]

The precursor of modern color printing was invented almost 100 years ago. In 1902 the Lumière brothers in France invented the autochrome process. Four decades later, in 1940, Kodak workers invented color negative film. Until the advent of digital color, chemical and other analog processes, such as optical filters, as well as other expert techniques were (and in many cases still are) used to get quality color images.

When a color image is digitized, the resulting pixels, or picture elements, lend themselves to processing by computer. The pixels are often digitized to 256 levels of intensity, each represented by an 8-bit binary number, or byte. Separating a color image into red, green and blue images at 8 bits per color yields an image having 24 bits of data per pixel. Such images may occupy large amounts of storage space. An 8×10-inch color image printed at 300 pixels per inch in the horizontal and vertical directions and 24 bits per pixel yields 21.6 million bytes of image data. This is no small amount of data to process, even for very capable computers.

The quality of a printed image is directly proportional to the quality of the scanned image. Color scanners typically produce numbers that vary either linearly or logarithmically with the intensity of reflected or transmitted light. Reflectance and transmittance are radiometric quantities. Reflectance is the ratio of the amount of light leaving a material to the amount of incident light. Transmittance is similar except that transmitted light is used. Scanners typically record reflectance and transmittance linearly. Thus, for example, the digitized image signal at 50% reflectance or transmittance would be half the peak value. Logarithmic scanners digitize in log space, or optical density, which is the base-10 logarithm of the reciprocal transmittance or reflectance. Because vision is more logarithmic than linear, log scanners produce much better shadow detail in images. Due to the complexity of the necessary optical and mechanical systems, however, log scanners are costly to build, and so most desktop scanners use the linear intensity model for digitizing images.

Subtractive color principles

There are basically two types of color systems: additive and subtractive. Additive color is generated using primary colorants whose spectral components combine additively to produce a resultant color. The most prevalent example of additive color is color television, which uses red, green and blue primaries. Additive systems are emissive in nature and therefore generate light. Additive color systems are the easiest to work with, but because they are not the model for color printing, I will not consider them further.

Color printing uses the subtractive system, which differs from the additive in that varying amounts of primary colors are subtracted from white to get the

Gary Starkweather is an Apple Fellow at Apple Computer Inc, in Cupertino, California.

Matching the color on the printed page with that on the color computer monitor is difficult because the printer cannot reproduce some of the colors that the display is capable of generating. The top picture was printed on a Canon CLC500 color laser printer–copier without the benefit of color-matching software. The bottom picture was color-matched using a color-correction matrix technique that compensates for dye impurities. (The pictures may appear slightly blurry due to the resolution used in printing.) **Figure 1**

desired color. In additive systems, black is produced by turning off all emitters, whereas in subtractive color, black is produced when all the primaries are present. Subtractive color systems require at least three primaries. As figure 2 shows, the typical primaries are cyan, which absorbs red; magenta, the green absorber; and yellow, the blue absorber. Paper illuminated by a conventional light source provides the reference white. The primary dyes are placed on the paper in the correct proportions to subtract the amounts of red, green and blue necessary to yield the desired printed color.

The key difference between subtractive and additive systems is that in the former the primary spectral components combine multiplicatively, not additively. The lower part of figure 2 shows the secondary colors, or combinations of primaries, in subtractive color: red, or magenta times yellow; green, or cyan times yellow; and blue, or magenta times cyan. "Process black" is produced by the combination of all three primaries. While a fair black is often achieved this way, most high-quality digital color printers use a fourth printing element to realize a good black. (I will discuss the use of the black printing element later.)

The upper portion of figure 3 illustrates the spectral characteristics of an ideal cyan, magenta and yellow dye set. The cyan should "subtract" only the red portion of the spectrum; the magenta, the green portion; and yellow, the blue portion. Ideal primaries do not exist in the additive system model because the combined primaries themselves yield "white." In a properly designed color computer display, applying a signal to the red input on the display does not activate the green or blue. Without question, this is a very useful feature. Due to the nature of subtractive systems, this is not the case for printers, which use real dyes. Real dyes are said to possess "crosstalk" in that each dye subtracts portions of spectra that ideally would be subtracted only by another dye. The lower part of figure 3 shows the spectra of a real cyan, magenta and yellow dye set. These real dyes bear only a partial resemblance to their ideal counterparts.

The discrepancies between the ideal and actual dyes, as well as the colorimetric differences between the computer display and the color printer, give rise to the need for color "matching." In color printers, nonideal dyes cause impure and dark colors to occur when no corrective measures are taken. For example, magenta is typically a poor dye relative to the ideal. The real magenta dye absorbs, in addition to the desired green light, a considerable amount of blue. So does cyan. Thus combining cyan and magenta generates a blue that has a much lower reflectance on the paper than in the ideal case; the result is said to have reduced chroma. This is true of the other secondary colors as well. As the uninitiated user finds out, merely printing a colorful screen image, without any correction, does not often result in satisfactory printed results.

One of the advantages of digital color printing is the ability to compensate computationally for printer dye defects. In one color-matching method, for example, the colors obtained from dye combinations can be represented by a linear model, which can be solved with matrices. Linear equations can be used to produce the modified signals that take into account crosstalk effects. Subtractive color is multiplicative, but operating in density space permits the required multiplications to become additions: Logarithms of multiplicands can be added and then the antilog taken to get the result.

Another color-matching scheme is based on measuring a large set of actual color patches produced by the printer. The colorimetric characteristics of the patches are then used to create a table. When an image is printed, the signal sent to the printer is passed through this "lookup" table to get the modified outputs for printing. There are many other methods of color matching, but these examples illustrate the principle.

Binary and gray-scale marking

Electronic printers fall into two fundamental classes. One type is termed "binary." Binary printers produce only two levels of reflectance at any pixel: Either they deposit a fixed amount of marking material, or they deposit nothing. To produce the effect of gray, printers of this type must use spatial patterns. Such patterning is called halftoning. Commercial printing (except for gravure) using ink-on-paper technology is a binary process.

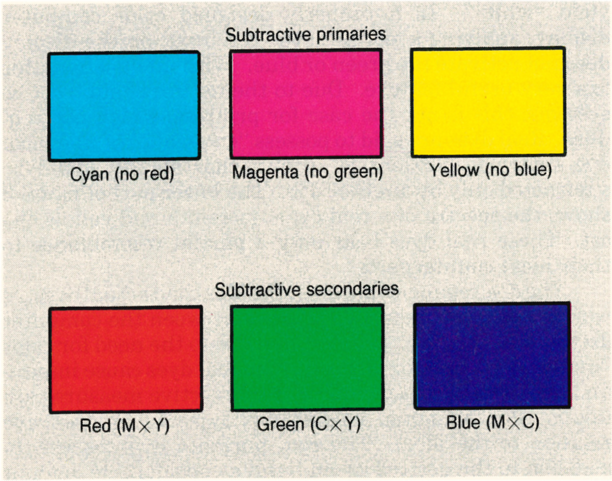
The second type of printer, termed "gray scale," is capable of placing varying amounts of material at a particular pixel location, thus generating a gray reflectance without the use of patterning. Photography is the best-known process that produces gray-level images directly. There are potential hybrid printers that would add halftoning to the gray-scale technique when the printer is not capable of generating a sufficient number of gray levels directly.

In a printed image, reflectance patches having linear reflectance differences are not perceived by the human eye as uniform. However, reflectance patches whose differences vary as the cube root of reflectance *are* seen as uniform. Any binary patterning system must produce a set of spatial patterns that vary in area and are small enough to give the appearance of continuous tone. In commercial printing these patterns, or halftone "dots," are quite small: There are typically 120 to 175 dots per inch. An 8×8 array would be required for 64 different levels of gray. With a digital printer, if one wants 120 dots per inch and 64 gray levels, then in the simplest case, one needs 960 pixels per inch. Resolution, therefore, is one principal requirement for binary systems capable of simultaneously producing good gray-scale appearance and fine halftone dots. Typical personal color printers today have a capability of about 300 pixels/inch. Thus a 100-dot/inch halftone would permit only about a 3×3 halftone cell, which could provide only 9 levels of gray. This is far too few levels to provide good pictorial imagery. On the same printer, a 6×6 digital halftone cell would yield 36 levels of gray but would allow only a 50-dot/inch halftone. Such dots are certainly noticeable to the unaided eye. Thus 300-pixel/inch binary printers offer few alternatives to their users.

Color images printed on binary printers may require the overlap of at least four halftone screens—one each for cyan, magenta, yellow and black. Commercial printers set the halftone screens at different angles to provide better mechanical tolerances on image and sheet registration. The halftone screen angle is the angle of the cells along their major pattern axis. Personal color printers, because of their limited resolution and sheet size, often produce better results if all the screens have the same angle, say 45°. A rule of thumb is that professional gray-scale reproduction on binary printing devices requires a printer resolution of ten times the desired halftone frequency. Commercial film imagesetters for ink-on-paper printing operate at 1200 to 3000 or more pixels per inch. This gives an excellent dot size range as well as a high halftone dot frequency. (References 2 and 3 contain more detail on halftones.)

Gray-scale printers have the advantage of not requiring halftone patterns to produce a gray scale. Furthermore, binary patterns generate a luminance or reflectance scale that is dictated by the physics of the pattern geometry. Gray-scale imagers can produce a much more arbitrary gray scale because the resulting reflectance is proportional to the amount of marking material applied by the printing mechanism. Until recently, only binary digital printing was readily available, but this is no longer true, as I shall discuss below.

Controlling the marking process is important in any electronic printing system, especially color printers. The eye is much more sensitive to differences in color than to luminance or gray-scale differences. Binary and gray-scale printers have different control requirements. Binary systems are easier to control because the marking system need only print or not print a fixed amount of material. The downside, of course, is that binary printing must have more spatial resolution to produce a given image quality. Gray-scale systems put down a variable amount of material, and hence system control is more complex. The upside, however, is that they require lower spatial resolution for equivalent image quality.



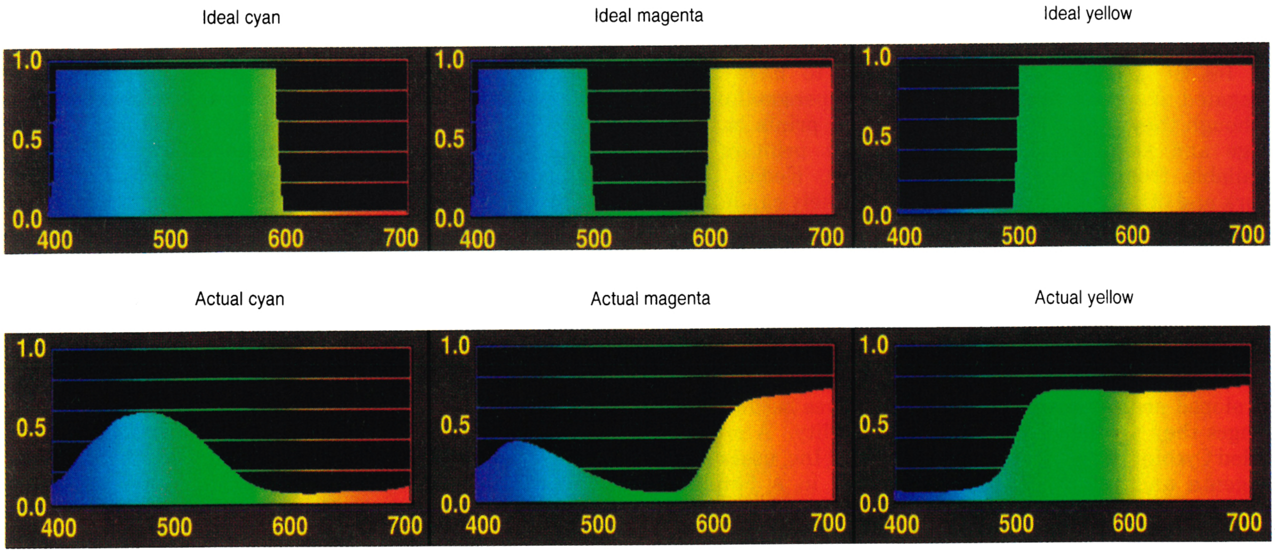
Subtractive primary and secondary colors. In subtractive color systems, which are the type used in printing, primaries are subtracted from white to produce a given color, and they combine multiplicatively. **Figure 2**

Color-marking technologies

There are four basic categories of marking technologies for digital color printing. These categories and some of the typical ways they are implemented are as follows:

▷ Electrostatic: xerography, ionography and electrography

▷ Thermal: thermal transfer, dye migration and direct thermal



Ideal and actual printer dye spectra. The abscissa shows wavelength in nanometers; the ordinate shows transmittance, where 1.0 represents 100% transmitted light and 0 represents no transmitted light. The discrepancies between the ideal and the real dyes create the need for color matching in printing. **Figure 3**

▷ Ink jet: continuous, bubble jet and hot melt
▷ Photographic: wet-processed silver, dry-processed silver and Cycolor.

Each of these four categories of printers has specific implementations that are binary, gray-scale or some combination of both. Space does not permit a detailed discussion of the physics of the processes themselves, but I shall briefly discuss the principles so that one can understand their relative capabilities for digital color imaging. (Reference 4 contains much more detail on these electronic imaging processes.)

Electrostatic printers, also known as xerographic printers, basically use a static charge pattern on a photoconductor to attract polymeric "toner" particles, which are subsequently transferred to paper and heat-fused to provide the final image. In color printing, up to four successive toner images—cyan, magenta, yellow and black—are placed on the paper in correct register, just as in commercial printing. Typically, halftoning is used to produce the required tonal scales. Newer xerographic processes, however, are capable of reasonable gray-scale reproduction.

Monochrome laser printers use various techniques to achieve a better gray scale without resorting to higher spatial resolution. Scanning-beam laser printers offer a wide variety of options for producing the latent image on the photoconductor. Ionographic printers create the required charge pattern with selective charging rather than optical patterning. Electrographic printers use selective charging and coated paper to develop the image. Xerographic devices dominate today's monochrome electronic printer market. Color xerographic printers will likely play a major role in the personal and professional color printer markets. Companies such as Xerox, Kodak, Canon and Ricoh produce xerographic color printers.

Thermal printers use heat to transfer the marking material from some intermediate carrier—typically Mylar ribbon—to the paper. Thermal printers are conceptually the most simple of the various printer types. A heater head consisting of one miniature heater per pixel prints one line of data at a time. Again, three or four color separations are successively imaged onto the paper. In thermal transfer printers, the ribbon is coated with a wax material of the appropriate color: cyan, magenta, yellow or black. Thermal transfer printers tend to be binary: The heater moves a fixed amount of wax to the paper. Newer types of thermal transfer techniques are emerging that vary the amount of energy delivered to the heater to produce directly a halftone dot of the desired size. Thermal transfer printers require special paper with a very smooth surface.

The second type of thermal printer uses a ribbon with a coating of sublimable dye. The individual heaters, driven by pulse-width-modulated signals, cause migration of varying amounts of dye to a receiver sheet. The paper is a special type that often has the appearance and texture of photo paper. Thermal dye printers produce a gray scale directly. The latest thermal dye printers can produce prints and overhead projection transparencies of photographic quality, and they can address each pixel directly with 24 bits of color data and 8 bits of black. Thermal printers are available in a wide variety of sizes and capabilities from such vendors as QMS, Calcomp, Sharp, Kodak and 3M.

Ink-jet printers. Members of the third class of color electronic printers form images by depositing droplets of colored ink on the paper. Most ink-jet printers are binary in nature, and halftoning is required for the appearance of a gray scale. To produce an image, water-based ink jets use either a continuous stream of droplets that are selectively directed or a drop-on-demand process. Drop-on-demand ink jets are the most popular and can be quite inexpensive. Again, cyan, magenta, yellow and black inks are used to produce the desired colors.

The most prevalent type of water-based ink jet uses a small heater near the nozzle to produce a steam bubble that ejects a single drop of ink. Such "bubble jet" printers produce a color page in 2–4 minutes, depending on the complexity of the image. Water-based ink jets cause the dried ink to be on the surface of the paper, and the sheet needs to be protected from ultraviolet light to insure color stability.

A recent novel use of the drop-on-demand ink jet is solid, or hot-melt, technology. Whereas water-based inks can smear if water is spilled on the image and usually require special paper, solid-ink-jet printers melt a wax-like material and eject the molten drop onto the paper, where it freezes. Solid-ink-jet printers can print on just about anything.

Ink-jet printers of all types seem to have been relegated to specialty markets or low-cost personal units, although they can produce excellent color prints in both large and small formats. Color ink-jet printers are available from Canon, Hewlett–Packard, Kodak, Iris, Stork and other companies. Ink jets are likely candidates for portable printers.

Photographic printers. Photography is an old and well-known technology. Photographically based color printers are not very prevalent except for making slides. Photographic materials are expensive, and the time needed to process the film is often prohibitive in printing applications. Dry-processed color photography or heat-developed processes are limited alternatives because the images they produce are of restricted quality. A process called Cycolor, recently developed by Mead Inc, uses cyan, magenta and yellow capsules embedded in a film-like substrate. In one form of this technology, these capsules harden selectively when they are exposed to light. The exposed "film" is then put through a heated set of rollers that squeezes the capsules. Any unexposed capsules yield their colored contents to a receiver material to produce a direct color image. This process is very novel but has seen only limited commercial implementation.

Printer controllers

For a digital color printer to produce an image, it must prepare the pixels properly and feed the paper in synchrony with the printing. Controllers are usually hidden inside the printer and are therefore not sufficiently appreciated. The controller's most fundamental task is to control the printer mechanism. In a xerographic laser printer, the mechanism must be started, the paper must be fed at the appropriate time and, most critically, the data must be fed in synchrony with the position of the laser beam. Even an 8-page/minute laser printer requires a data rate of about 1-megabit/sec. In a color printer the data for each color separation must be prepared and sent to the writing mechanism at the appropriate time, and development systems or other subsystems must be synchronized. (Readers interested in more details on the controller's imaging functions should see references 5 and 6; these discuss page-description languages such as PostScript and InterPress, which allow one to work with high-level representations of how the page should look.)

At 300 binary pixels per inch, a digital color page requires approximately 4 megabytes of data. More complicated color printers that produce very-high-quality images can require much more. A Canon CLC500 or Xerox 5775 color copier used as a printer requires about 50 megabytes of data per 8×10-inch printed page. Furthermore, these data must be supplied at as much as 10 or more megabytes/sec. Few computer-based tasks are more data and computation intensive than imaging. The arduous task of the controller is not just to control the operation of the printer but also to prepare the pixel maps for printing. In the early days of electronic printing, data streams were composed by arcane bit-stream codes. Today, languages such as PostScript and Hewlett–Packard's PCL5 permit one to send compact and simple representations of page elements to the printer controller. These elements, which include text, line-and-curve graphics and images, are prepared by personal computer software such as illustrators and word processors. The high-level description of these elements, including their color, is sent to the printer controller, which "rasterizes" the image. Rasterization is the process of turning a compact representation of, say, a red rectangle into the appropriate magenta and yellow pixels in the printer controller's output buffer.

Probably the most sophisticated color printer controller available today is the Fiery, made by EFI Inc of San Bruno, California. This controller can operate the Canon CLC300 and 500 color copiers and enables them to be used as color printers operable from a network of Macintosh or IBM personal computers. The Fiery can also operate the new Xerox 5775 and Kodak 1530 color copier–printers. The newest software for this controller permits a Macintosh-to-Fiery connection via an Ethernet local area network; the digital scanned image from a Canon CLC500, for example, can be stored in the Fiery and retrieved by a Macintosh computer over the Ethernet. The image can be obtained in whole or in part and at any of several resolutions.

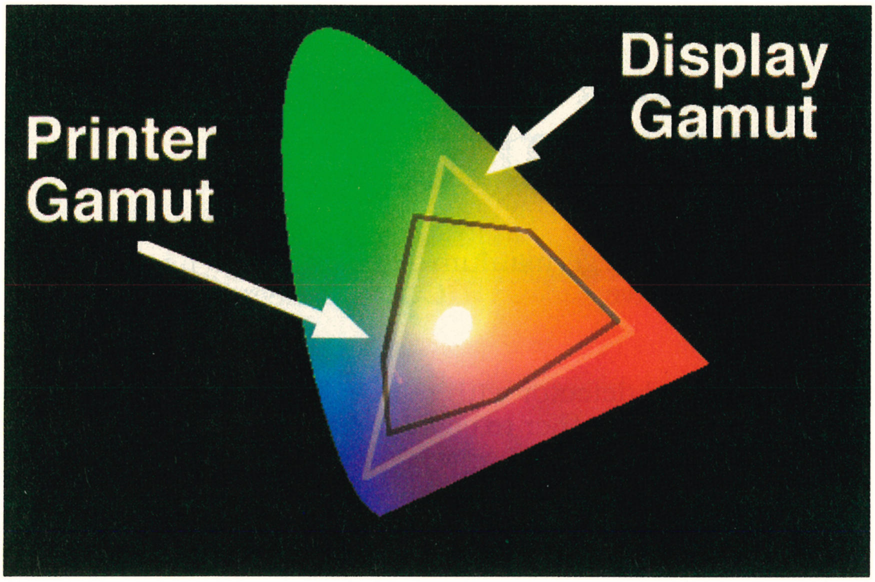
Color printing is a demanding science because each pixel can require a fair amount of computing and because the productivity of digital color printing systems is a key measure of their value. Controllers today can do the digital color imaging tasks for a simple image in a few minutes. Rasterization of complex images, especially those containing pictorial content, can take high-resolution printers hours. Emerging computing technology, however, should provide all of the controller power needed in the future to implement excellent digital color printing for both the personal and professional markets.

As other articles in this issue explain, color spaces can be created that allow the same color seen on a display to be produced on a printer if the devices are properly characterized and the color to be reproduced is in the available gamut of the printer. Controllers today do not yet broadly support device-independent color. Figure 4 compares display-system and printer-system color gamuts on an International Commission on Illumination diagram. (The CIE is discussed in Alan Robertson's article on page 24.) The triangular gamut of displays is the result of the simple addition model of their color systems. The printer's hexagonal gamut is the result of the fact that the printer dyes are not ideal.

In most cases users want what they see on the display to be output on the printed page with a minimum of interaction. From the user's perspective, having the software or controller handle the color matching is ideal. Because the gamuts of the display and the printer are usually different, some colors that the display is capable of generating are not reproducible by the printer. Various techniques can be used to compensate for this difference, such as gamut mapping or restricting the display output to the colors common to both systems. But no one technique appears to meet all user needs. Figure 1 shows an example of color matching. The top picture was printed on a Canon CLC500 color laser printer–copier without the benefit of color matching. The bottom picture was color-matched using a color-correction matrix technique that compensates for dye impurities.

Proofing systems and personal systems

In commercial printing, the separate cyan, magenta, yellow and black images on photographic film are used to make printing plates by contact exposure. The printing plates are then placed on the printing press to produce the final ink-on-paper color images. Automating the generation of the photographic films was one of the first applications of digital color printing. In commercial color printing, a proof is commonly generated before the actual printing. The proof is often made from the films that will be used to generate the printing plates. When the resulting proofs are unacceptable, reprinting of the films,



Color gamuts of a display system (triangle) and a printer system (hexagon) represented on the 1931 CIE diagram. Figure 1 shows the result produced by one technique for dealing with such differences in the range of available color. **Figure 4**

reproofing and so on become necessary. The overall process can be expensive and time-consuming, and it also runs the risk that the printing press will not yield the same results as the proofing system.

Any proofing system intended for commercial printing must use halftones, because printing presses use halftones, as discussed earlier. Press operators need some measure to use in making corrections while the presses are running. Comparison of the halftones on the proof with those on the printed sheet is a good method for control. Digital proofing systems that do not use halftones provide no direct method for assessing problems in the printed output.

Kodak and 3M have each introduced a system for direct digital color imaging of the proof. The two products, while expensive and primarily intended for professional markets, illustrate the potential for digital color printer technologies. The Kodak system, known as Approval, uses a novel form of thermal transfer to create a direct digital proof. A solid-state laser locally heats a thermal ribbon and creates the appropriate halftone dot for transfer to the proof paper or substrate. The 3M system, known as Digital Matchprint, uses a laser-exposed, liquid-development xerographic process that permits the use of very fine toner particles. It provides binary four-color imaging at up to 2400 pixels/inch; the output prints can be up to 24×30 inches.

These machines may herald a time a few years hence when users will be able to print directly in color economically and with printing-press quality but without the need for high volume. (Printing presses will still be useful for long print runs.) Needless to say, controllers for these advanced digital printers will have a great deal of computation to do in preparing the data for printing.

Personal color printing systems are just coming onto the market. (Apple Computer, for example, recently announced ColorSync and QuickDraw GX for the Macintosh personal computer.) In commercial printing, most users are experienced and well trained in the use of color. Without system-level tools and support software, color would be a frustrating and largely useless capability for the average individual.

Calibration

As other articles in this issue discuss, working in device-independent color spaces will allow one to move color data conveniently between devices without losing the color specification. However, one important requirement remains in digital color imaging: calibration. How does the user know that the color system is operating as planned?

Printers such as thermal transfer and thermal dye printers have little drift in the amount of colorant placed on the page for a given electrical signal. Xerographic systems are less stable in this regard, and ink jets experience other complex effects relating to such variables as the type of paper used. Therefore, some printers require users to provide calibration updates to tell the imaging system what the color-space parameters are at the time of printing. This is true for all components in the color system, but usually the printer has the most varied calibration requirements. Printer variables such as paper, aging of the marking system and component wear can contribute to the need for calibration. Perhaps even more critical is how the image is printed—that is, halftone, continuous tone or a combination. Halftones can be dot-on-dot or rotated dots and can also have different dot frequencies, different dot shapes and so on. Users usually have the ability to adjust most or all of these parameters. Quality color imaging is only as good as the characterization of the devices used.

In the future we can expect simple and easy-to-use digital color printing to become more commonplace. In addition to its obvious aesthetic advantages, digital color printing will permit us to be more productive in handling the increasing amount of information we face each day.

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