A System Design for Color Conversions

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Jobs to be printed may have colors that are specified in many different color spaces. A printing system must convert those colors to the device CMYK of the printer. In complex printing environments, color conversions occur at many places throughout the system. In an Advanced Function Presentation (AFP) printing environment, data is processed on application development tools, in the print server, and in the printer itself. Further, there are different types of data formats, such as PostScript format and AFP Mixed Object Document Content Architecture (MO:DCA-P) format, which require color conversions by different processes. It is particularly important to produce consistent colors across all data paths for both device-dependent and device-independent colors. The system designers must decide which input color spaces to support. For instance, support may be needed for some device-dependent color spaces such as CMYK SWOP, CMYK Euroscale, and SMPTE-C RGB that have become industry "standards". There may be requirements to support a toner-saving mode. This article will describe some of the work that was done during the development of a high-end, full-color printing system. It will discuss methods used to make the color conversions more consistent and multiple methods that may be used to control color conversions.

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Overview

Advanced Function Presentation (AFP) environments are complex. There are many sources of data, many different color spaces used in the data, and many places where the color can be converted.

This article discusses our experiences in developing color management for IBM's Infoprint Color 130 Plus printer. Figure 1 shows the data paths through an AFP system. Input jobs pass through a print server such as IBM's Print Services Facility (PSF) or, as discussed here, Infoprint Manager (IPM). PSF and IPM repackage AFP Mixed Object Document Content Architecture (MO:DCA-P) format[1] into the Intelligent Printer Data Stream (IPDS) format.[2] The IPDS format is used to send data to the printer. Colors in the data may be converted to printer CMYK in one of several places:

- In the application: The job may be created using application development software. Some of these tools, such as Quark and Adobe Photoshop, support the use of an ICC Profile which enables creating data with colors specified in the device CMYK of the printer. The International Color Consortium (ICC) has defined a format for specifying color conversion information. The Infoprint Color 130 Plus provides an ICC profile which specifies how to convert from a Profile Connection Space (PCS) of CIELab to the device CMYK color space of its printer. It can be used by the application development tools.
- In the print server: Jobs are processed by the IPM or PSF print server. The IPM server includes an Image Transform which converts TIFF, GIF and JPEG images to AFP image format. It also includes a PostScript RIP which can convert PostScript or Portable Document Format (PDF) to AFP image format with the help of an image-formatting back end. Both of these processes perform color conversions and the output image is expressed in the printer's CMYK color space.
- In the printer: Jobs are sent to the printer using the IPDS format. In the printer, data may be processed by either the IPDS rasterizer or by the PostScript RIP that is part of the IPDS rasterizer. Both of these RIP's perform color conversions.

Performance is critical for the Infoprint Color 130 Plus that prints 4 bits per spot per color at 130 pages per minute. The AFP system handles several different types of data and the type of data determines the best place to do the color conversion. If processing and color conversions take too long, the printer won't run at rated speed. When processing and color conversions are done in the server, page data may be stored in a format that is easy to print until a complete job is ready. Then the job can be downloaded to the printer and it will print at rated speed. TIFF/GIF/JPEG images that are to be included in an AFP workflow require millions of color-conversion operations. Therefore, they are converted to AFP CMYK color image by the Image Transform in the server. Similarly, processing of PostScript and PDF print files can be slow, so they are converted to AFP CMYK color image offline in the IPM print server. This is shown in Fig. 2.

Encapsulated PostScript (EPS) may be included as an object on an AFP page. If the object is not too complex, it is possible to rasterize it in the printer using the PostScript RIP without impacting throughput. This is shown in Fig. 3. In this case, the server will wrap the EPS in an IPDS object container and send it to the

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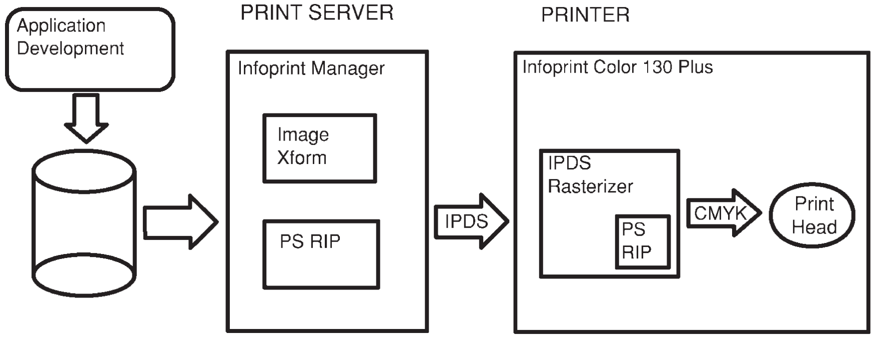

Figure 1. Data flow through an AFP system showing where color conversions may occur.

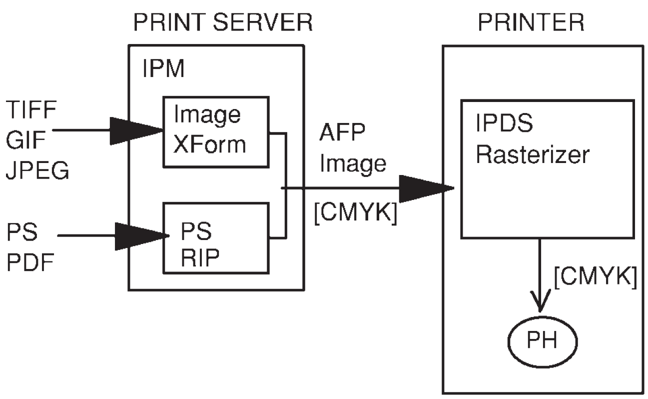

Figure 2. Path followed by a TIFF, GIF or JPEG image and by a PS or PDF job. Color conversions occur in the Image Transform or in the PostScript RIP.

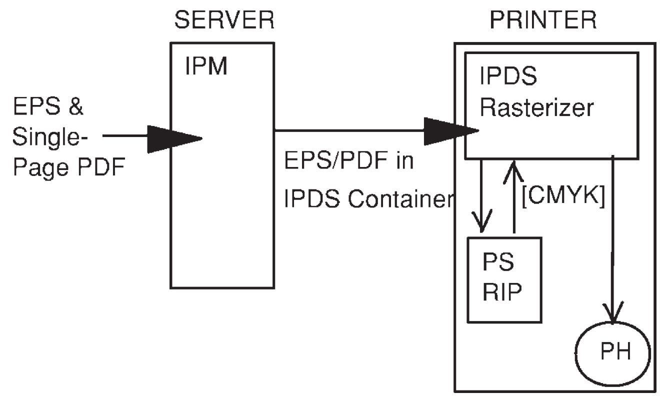

Figure 3. Path followed by EPS or single-page PDF when lengthy processing will not degrade the performance of the printer. Color conversions are done by the PostScript RIP in the printer.

printer within the IPDS data. Similarly, if a large EPS or PDF object is used many times, it can be specified as a reusable resource, in which case the printer will RIP it once and then reuse the RIPped version. When data is RIPped and color-converted by the PostScript RIP in the printer, the IPDS rasterizer merges the resulting bitmaps into the sheet data which it is creating.

Figure 4 shows traditional AFP data such as text, graphics, and bilevel image being color-converted in the printer. There is typically one color conversion required for lots of data processing, so performance is not impacted.

The goals of the Infoprint Color 130 Plus color management system are:

- To render device-independent colors accurately (within the limits of the printer's gamut).
- To render colors consistently regardless of where the color conversion occurs.
- To perform color conversions without adversely affecting performance.

Color Spaces in the Input Data

In IPDS data, the following input color spaces are supported:

- Device CMYK
- SMPTE-C RGB
- CIELab
- IPDS named colors (about 20, not discussed here)

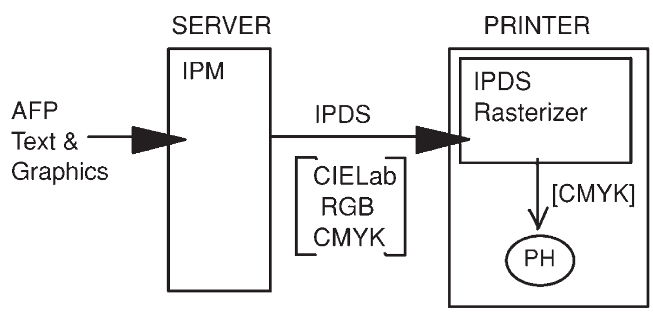

Figure 4. Path followed by AFP text and graphics. Color conversions are done in the IPDS rasterizer in the printer.

In PostScript, EPS, and PDF data, the following input color spaces are supported:

- DeviceCMYK
- DeviceRGB
- CIEBasedABC
- CIEBasedDEF
- CIEBasedDEFG

The CIEBased spaces include a color profile that tells how to convert the input color space to CIEXYZ. A color rendering dictionary (CRD) for Infoprint Color 130 Plus is then used to convert from CIEXYZ to printer CMYK.

In non-AFP image data, most color spaces supported by the TIFF, GIF and JPEG image formats are supported by the Image Transform. The Image Transform converts these formats to AFP CMYK color image.

In application-level data, the ICC Profile for Infoprint Color 130 Plus is used to convert from CIELab with a white point of D50 to printer CMYK. By using an ICC Profile for the input data to convert from the input color space to CIELab, all input color spaces are supported.

Color Conversions in General

Color conversions attempt to take input data and make it look the same on multiple output devices. Many factors influence how the output appears. For instance, different output devices have different gamuts, i.e., the range of colors that can be produced by the devices may differ. This is due in part to the materials (phosphor, ink, toner, …) that are used. It may be impossible to print a color that is specified in the input color space. So the color must be mapped into another color which is within the gamut of the printer.

Viewing conditions also affect the appearance of the output. The output may appear different when viewed outside in bright sunlight compared to when viewed inside under phosphorescent lights. The **white point** is used to describe the lightness characteristic of a viewing condition and is included as part of the specification for a color space. For instance, SMPTE-C RGB is defined to have a white point of D65 and the CIELab color space supported in AFP data is defined to have a white point of D50. Color conversions must compensate for different white points.

A color conversion from another color space into CMYK printer space involves some or all of the following:

1. Setup calculations such as converting white points to D50 and linearizing RGB
2. Using a color lookup table (LUT) to convert from a three-component color space (CIELab, RGB) to a four-component CMYK color space. Gamut mapping is incorporated into this LUT. When the input color space has three components (e.g., L, a, b or R, G, B), the LUT is implemented as a three-dimensional array. To limit the amount of memory used for the array, a sparse array is used. To convert a color that does not fall on a node of the array, interpolation is used
3. Post-LUT calculations such as converting CMYK to C'M'Y'K' to handle toner saving or to handle a SWOP or Euroscale CMYK color. Applying transfer curves to each color component would also be done here

A critical part of the system is the generation of the color lookup tables. For CIELab, this is a complicated process involving:

1. Analyzing halftone screens for primaries and linearizing tone reproduction curves
2. White point conversion
3. Using black toner as a replacement for some of the cyan, magenta, and yellow toner in such a way that color accuracy is not affected
4. Lightness compression and gamut mapping because some CIELab colors are not producible on a CMYK printer
5. Interpolation to create the LUT
6. Installing the LUT in the color conversion code
7. Testing

This process requires printing color swatches and measuring output. Note that 'printing colors' is a significant task when developing a new printer. It may not be possible early in the development cycle. It depends on a printer that can print reliably, on halftone screens that have been finalized, and on the existence of a system for properly calibrating the printer. It requires a well-tuned, well-calibrated printer with the proper paper.

Several guidelines were followed to ensure that the lookup tables are essentially the same everywhere:

- The same input range for L, a, and b is assumed
- The same table size is used (e.g., 33×33×33)
- The tables use the same increments between nodes
- The tables are generated using the same algorithm for a given rendering intent
- The tables are generated for the same 'standard' media white point (D50)

Much of our testing was designed to compare color conversions across multiple paths. The data tested included color swatches (e.g., the MacBeth Chart and a regular sparse grid of the full color space) as well as photographic images. Some of the techniques we used included:

- Print rectangles; measure output
- Display output using Adobe Photoshop and the ICC Profile; read CMYK values
- Modify conversion code to print out CMYK values
- Psychophysics tests: print photographic images; many observers visually compare pairs of output with original image

Device-Independent Color: CIELab

CIELab is the basic device independent color space supported by Infoprint Color 130 Plus. CIELab was selected because it is more uniformly linear than CIEXYZ. In AFP data it is assumed to have a white point of D50. The user is responsible for converting the input CIELab colors to this white point. The basic LUT, which is used everywhere in the system, converts from CIELab into printer CMYK.

Input CIELab colors in the IPDS data stream go directly into this LUT. If a different white point is specified in a TIFF file or PS data stream, the input data would need to be converted to have this white point before the LUT is used.

The CIELab LUT is used in essentially identical form for many conversions.

- In the IPDS rasterizer and the Image Transform, it is used directly
- In the PostScript RIP's, the CIELab LUT is part of the color rendering dictionary. Any device-independent input space (CIEBasedABC, CIEBasedDEF, CIEBasedDEFG) is converted as follows:
  1. The CIEBased color with input white point is converted to CIEXYZ with the same white point using the input color profile supplied by the user with the CIEBased color space
  2. CIEXYZ with input white point is converted to CIEXYZ with 'standard' media white point, D50
  3. CIEXYZ with D50 white point is converted to CIELab with D50 white point using the CRD
  4. CIELab with D50 white point is converted to CMYK using the CIELab LUT which is part of the CRD

- When using an ICC Profile, CIELab with a D50 white point is the Profile Connection Space. The input color profile converts the input color to CIELab with D50 white point. Then the CIELab LUT, which is part of the ICC Profile, is used to convert to printer CMYK

The Infoprint Color 130 Plus system supports two rendering intents:

- Relative Colorimetric: In-gamut colors are reproduced exactly; out-of-gamut colors are mapped to the border of the reproducible gamut. Typical usage is for text, vector graphics and bilevel images such as logos and icons
- Perceptual: Colors are rendered to give a pleasing appearance. Both in-gamut and out-of-gamut colors may be modified to preserve color relationships. Typical usage is for continuous-tone images, e.g., photographs

Rendering intents define the approach used to map out-of-gamut colors into the available printer gamut. In the Infoprint Color 130 Plus color conversions, gamut mapping is incorporated into the lookup table. Therefore, there are two versions of the CIELab-to-CMYK LUT, one for each rendering intent.

The rendering intent may be specified in several ways that depend on the data path used (refer to Fig. 1):

- PS/PDF data path: Rendering intent is specified in the PostScript data stream using a rendering intent operator.
- TIFF/GIF/JPEG image path: Rendering intent is externalized to the end user by the Image Transform.
- ICC Profile: GUIs for application development tools like Quark or Adobe Photoshop allow the user to select a rendering intent which is then used to select which table in the ICC Profile is invoked
- AFP data path: There is no need to specify rendering intent for IPDS text, graphics and bilevel image; a default value of Relative Colorimetric, the obvious choice, is used

Device-Dependent Color: RGB

RGB colors are used primarily in display environments. Achieving consistency in rendering RGB colors on a CMYK printer across different data paths is one of the biggest color management challenges. There are many different RGB “pseudo-standards” that calibrate RGB colors, such as sRGB and SMPTE-C RGB. There is also non-calibrated device RGB. The problem is, when RGB colors are received, it is difficult to tell which RGB standard (if any) was followed. For example, all RGB in AFP text, graphics, and image is assumed to be SMPTE-C RGB and is rendered accordingly. If the assumption is correct, the rendering will be reasonably accurate. If the assumption is not correct and if, for example, the RGB was really sRGB, then the rendering may not be very accurate. PostScript supports DeviceRGB that is non-calibrated so there can be no expectations about how it will look.

Because the interpretation of RGB is different in AFP and PostScript data streams, color consistency across data paths was not achieved.

Note that PostScript also can support calibrated RGB, which may be specified using the CIEBasedABC or CIEBasedDEF color space. (These spaces are not available in PostScript Level I.) The definitions of these color spaces include a user-specified transform that converts the RGB (i.e., the CIEBasedABC/DEF) to CIEXYZ, which is then converted to device CMYK using the CRD. Specifying RGB in PostScript using one of these color spaces will enable consistency across data paths.

RGB that is specified in AFP data is assumed to be SMPTE-C with a white point of D65. SMPTE-C (the Society of Motion Picture and Television Engineers) is the current color standard for broadcasting in America. Conversion of RGB in AFP data involves:

1. Linearizing the R,G,B by raising each component to the power 2.2
2. Converting to CIEXYZ (D65) using a 3x3 matrix
3. Converting to CIEXYZ with a white point of D50
4. Converting CIEXYZ to CIELab (D50)
5. Using the CIELab LUT to convert to CMYK.

For performance improvement, steps 1–5 are collapsed into a single LUT. This LUT is used by both the IPDS rasterizer and the Image Transform, so RGB conversions are consistent in these two places.

PostScript conversion of RGB to CMYK[3] is entirely different and is very simple.

$$c = 1.0 - R;\ m = 1.0 - G;$$
$$y = 1.0 - B;\ k = \min(c, m, y) \tag{1}$$

$$C = c - k \tag{2}$$

$$M = m - k \tag{3}$$

$$Y = y - k \tag{4}$$

$$K = k \tag{5}$$

In these equations, the input color values are R, G, B which are in the range [0.0, 1.0]; the output color values are C, M, Y, K; and c, m, y, k are intermediate values. Note that black is being substituted for some of the cyan, magenta and yellow toner. These equations assume that the default blackgeneration (BG) and undercolorremoval (UCR) are in effect. The defaults are maximum BG and maximum UCR.

The RGB in PostScript may be qualified by PS operators:

- The setblackgeneration operator BG(k) may be specified to change the amount of black (K) that is generated. If the operator is specified, Eq. (5) changes to the following:

$$K = \min(1.0, \max(0.0, BG(k))) \tag{6}$$

- The setundercolorremoval operator UCR(k) may be specified to subtract an amount from the computed C,M,Y values. If the operator is specified, Eqs. (2) through (4) change to the following:

$$C = \min(1.0, \max(0.0, c - UCR(k))) \tag{7}$$

$$M = \min(1.0, \max(0.0, m - UCR(k))) \tag{8}$$

$$Y = \min(1.0, \max(0.0, y - UCR(k))) \tag{9}$$

Adjustments to CMYK Colors: SWOP CMYK & Euroscale CMYK

In the absence of any other qualifying attribute, CMYK colors are treated as **device** colors. That is, CMYK colors do not go through any additional color transformations. A given CMYK color will print the same on the Infoprint Color 130 Plus printer when specified in any data path.

SWOP (Specifications for Web Offset Publications) and Euroscale are two CMYK color spaces that have become *de facto* industry “standards”. Colors expressed in SWOP or Euroscale should look the same regardless of the printer used. Therefore, these colors must be converted to the device CMYK color space of the printer. Because many enterprises have jobs created using these color spaces, Infoprint Color 130 Plus supports SWOP and Euroscale in addition to device CMYK.

When a CMYK color is used, there must be some way of identifying whether it should be interpreted as SWOP or Euroscale. The SWOP/Euroscale designation must be supported on an **object** basis, not just on a job basis. This is necessitated by the fact that a job may include some objects with Device CMYK colors, other objects with SWOP CMYK colors, and still other objects with Euroscale CMYK colors.

Different data paths require different ways of specifying SWOP/Euroscale for CMYK objects. (Refer to Fig. 1.)

- PS/PDF data path: The PS RIP in the IPM server is controlled by a job-level print attribute in the server. The data that it handles will always have the same type of CMYK for the whole job.
- TIFF/GIF/JPEG image path: The Image Transform accepts an input parameter that specifies SWOP or Euroscale. It is on an object basis.
- EPS/PDF in AFP data path: The application generating the AFP data can attach a SWOP/Euroscale attribute to the object. The print server then wraps the object in an IPDS object container, tags the container with the attribute, and sends it to the printer. The IPDS RIP in the printer recognizes the attribute and instructs the PS RIP to do the specified conversion.
- ICC Profile: SWOP and Euroscale conversions into the printer's CMYK space can be accomplished by providing an ICC profile that converts the SWOP or Euroscale into CIELab. CIELab is then converted to printer CMYK using the ICC Profile for the Infoprint Color 130 Plus. In practice, this is not typically done.
- AFP data path: There is no way to attach the SWOP/ Euroscale attribute to AFP text, graphics and image data. This is not needed since legacy AFP text, graphics, and image data was not created using SWOP or Euroscale colors.

To support SWOP/Euroscale CMYK adjustment, the Infoprint Color 130 Plus has two lookup tables which are 4D to 4D transformations. They take a CMYK color and convert it to C'M'Y'K'. The conversion involves only LUT access and interpolation. In the Image Transform, the conversion is done directly. In the PostScript RIP's in both the Infoprint Manager and the printer, if SWOP or Euroscale is indicated, after the normal PS color conversion occurs, a call is made to a function which is an extension to the PS RIP. This function uses the same LUT as the Image Transform and converts CMYK to C'M'Y'K'. This conversion is done only if the original color space was CMYK.

Toner Saver

The Infoprint Color 130 Plus supports a toner saver mode. The purpose is to use less toner and thus to decrease the cost of printing. Toner saving is accomplished by substituting black toner for some of the cyan, magenta and yellow toner.

This is a **job** level attribute and applies to ALL data that is printed. This attribute is supported in the various data paths as follows:

- Toner saver in the PS/PDF data path is controlled by a job-level print attribute in the IPM server.
- Toner saver in the TIFF/GIF/JPEG image path is controlled by an attribute in the Image Transform.
- Toner saver in the AFP data path is controlled by a job-submission attribute in the server that is translated into a printer command in the IPDS data stream.

Two levels of toner saver are supported: NONE and SOME. A limited amount of toner saving is incorporated in the normal LUT's for CIELab and RGB since as much black as possible is used while still producing accurate color. These LUT's are used when NONE is specified. The goal for SOME toner saver is to have minimal impact on color accuracy and gamut size, yet to use additional black toner and less C,M,Y toner. Thus the proportional changes in cyan, magenta, yellow and black vary throughout the color space and are not linear. The conversion is complex and requires a lookup table.

Typically, toner saver would be implemented after converting the original color into CMYK. A 4D-to-4D LUT with interpolation would be used to convert from CMYK to C'M'Y'K' (toner saved). This would adversely affect performance. This approach is used only if the input color space is CMYK. When it is used for CMYK data in the PS RIP, the implementation is the same as that for SWOP/Euroscale.

For other color spaces, SOME toner saver is incorporated directly into a new version of the LUT. So, for instance, in PostScript there are four CRD's:

- Relative Colorimetric without Toner Saver
- Relative Colorimetric with Toner Saver
- Perceptual without Toner Saver
- Perceptual with Toner Saver

The appropriate CRD is selected by control logic. Similarly, the Image Transform has four CIELab LUT's. The IPDS rasterizer has only two since it does not support the Perceptual rendering intent.

For RGB conversions, the IPDS rasterizer and the Image Transform each have two LUT's for converting SMPTE-C RGB to CMYK (with and without toner saver). The PS RIP handles toner saver for RGB by allowing control of Undercolor Removal (UCR) and Black Generation (BG).

Toner saver is not supported in the ICC profile. Nor is it supported for SWOP/Euroscale color spaces.

Conclusion

To achieve consistency between color conversions in different parts of the system, the Infoprint Color 130 Plus uses essentially the same color lookup table for each color conversion.

To aid performance during color conversion, multiple steps in the color conversion process are collapsed into one color lookup table. Performance is also controlled by doing some color conversions offline in the Infoprint Manager server.

Print controls and attributes to guide the color conversion process in the various data paths are added to the AFP (MO:DCA-P) and IPDS data streams, to the IPM and PSF print servers, and to the Image Transform. Some controls (such as toner saver control) are added at the job level while other controls (such as for SWOP/Euroscale CMYK adjustments) are added at the object level.

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