# Color Fidelity Across Open Distributed Systems

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## Abstract

Color fidelity is defined here as the successful interoperability of color data, from image creation to output across multiple targets, such that color reproduction quality consistent with the user's intent can be achieved. An open system is one in which the data transmitted from element N is understood by element N+1, and any proprietary aspects carried through the workflow are transparent to the non-proprietary elements. This presentation explores the issues of color fidelity, partitioning the problem domain into seven color control factors. Challenges and barriers to color fidelity will be discussed, including technical challenges, such as the evolution in color appearance models, and business challenges, such as differing customer expectations across markets.

## Introduction

The desire for automation in the delivery of color reproduction quality has never been higher. From consumers adopting digital photography, and business leaders developing enterprise communications, to ad agencies commissioning commercial print work, these users may have different color aims, but they are unanimous in their desire for improved color fidelity. Color management technologies attempt to enable the reliable flow of color information from image creation to final output - achieving a baseline of the necessary color interoperability. Yet color reproduction from one device to another is still subject to severe inconsistencies across the intervening sequence of proprietary implementations.

In the office, the same image file sent to several printers yields different results, leading to inconsistencies in presentation impact. In the commercial print world, a marketing brochure, carefully designed for a particular target output, may be subject to arbitrary changes in image appearance when re-targeted to a different output. Critical color reproduction is still in the hands of those skilled in the art.

## Is Color Fidelity Desirable?

How many of us would pay for a phone system that consistently substituted a 't' sound for every 'a' sound issued by the user? How many of us are satisfied when our cell phone connections are overwhelmed by static? How quickly did the audio industry abandon mono recordings when stereo became available? The broadcasting and telecommunications industries rely implicitly and explicitly on fundamental fidelity requirements - connectivity is their stock in trade. We note that fidelity in these communications systems is based heavily on machine to machine interoperability. However, for both audio and color visual systems, the final judgment of achieved fidelity is determined by human perception.

Is automated color fidelity desirable? Color fidelity is a key value for the electronically distributed, locally printed color documents endemic within enterprise companies. As the cost of color moves closer to the B&W baseline, distributed color printing will become the norm across office and B to B environments. In the graphic arts industries, trends such as faster job turnaround, digital data exchange, JIT short runs, and document re-targeting are building pressure to improve automation support for color fidelity.

"You want to proof your job? *Use our low-cost ink-jet printer.*"

"Approve your job through our web interface. *The results will be consistent with our press*".

"One device needs service? *Just shift your job to another device*".

"Giving a presentation? *The electronic original, slides, and printed handouts will all be consistent*".

Through all of this, one must comprehend the variety of applications, user expertise, and workflow practices that exist across the color value chain.

## Is Color Fidelity Attainable?

The first and necessary step in achieving color fidelity is examination of the interdependencies between the system elements that contribute to color reproduction quality, i.e., the fundamental issues of color interoperability. Analysis leads us to conclude that interoperability among color components, leading to consistent color reproduction quality, is both color workflow and market segment dependent.

The system elements that contribute to color reproduction quality across any capture/creation-to-output color reproduction workflow can be grouped into the following seven color control factors (CCFs):

- color source specification for each content element,
- calibration accuracy and stability in each device,
- color gamut characterization accuracy for each device,

- user color aim expectations as a function of market and geographical location,
- color aim implementation in each device,
- color translation algorithms between devices and viewing conditions,
- color control communication mechanisms between devices.

## Color Source Specification for Each Content Element

Color source specification for each content element involves the color encoding used, the color encoding identification mechanism, and any embedded or linked color transformations such as ICC (International Color Consortium) source profiles or PostScript tables (CSAs, DEFGs). Color source specification is dependent on the tags available within document and image file formats, which may be defined through standards, or which may be proprietary.

**How does color source specification impact color fidelity?**

Two key issues with color source specification are insufficiently specified source document colors and overly constrained source color gamut. Figure 1 shows two color gamuts superimposed. The wire frame represents a monitor RGB, and the solid represents a toner-based printer. Figure 2 shows two other color gamuts superimposed. In Figure 2 the wire frame represents a wide-gamut RGB, and the solid again represents the toner-based printer.

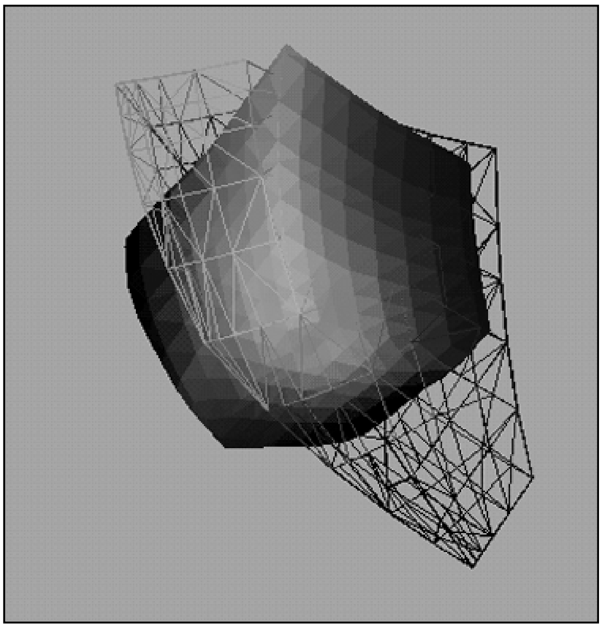

*Figure 1. A monitor RGB gamut and a printer gamut*

Today commonly used file formats and existing document files identify color in broad categories such as 'RGB' or 'CMYK'. It is clear from Figures 1 and 2 that a different gamut mapping would be required to transform images from these two different RGBs into the printer gamut shown. Thus, use of the RGB data requires additional information. A similar situation exists with color content encoded for various CMYK devices.

In addition to the CMYK color gamut, other device specific factors are often merged into CMYK document content. For example, the dot gain of a particular printing system may have been taken into account when adjusting the tone of a CMYK encoded image. Likewise, black channel behavior may be designed with particular colorant interactions in mind. Without additional specification, beyond a 'CMYK' label, color content encoded in such a CMYK cannot be translated with color fidelity to any device other than the original target device.

An overly constrained source gamut can also degrade color fidelity. Imagine, for example, that a color document printed through the printer gamut represented in Figures 1 and 2 is scanned into a widely used RGB encoding such as sRGB. When the document is reprinted, even to the same printer, the second generation document colors will not correspond to the first generation document colors, having been translated through the differently shaped and constrained RGB gamut.

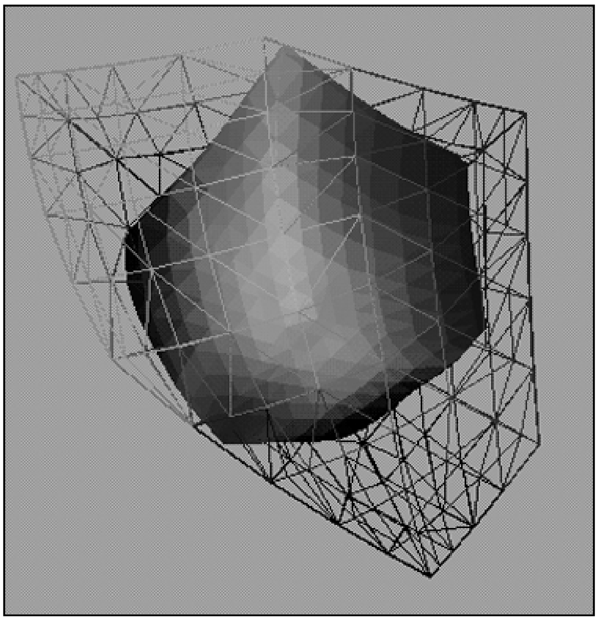

*Figure 2. A wide RGB gamut and a printer gamut*

A similar situation occurs whenever original colors are mapped to a constrained intermediate color gamut. Undesirable intermediate color gamut constraint occurs due to the relationships between the color encodings in an image path, and the relationships between their inherent color gamuts. It can be mitigated through the use of source and intermediate color encodings with color gamuts that are large enough to provide color fidelity across a wide range of output devices.

**How is Color Source Specification Market Dependent?**

If a document's color content is fully specified then it can be correctly interpreted, whether it originated from a home office, or a corporate office. When color is not fully specified in a document file, imaging components receiving the document must make certain assumptions. Those assumptions should be in line with the probable source and history of a document. For example, an RGB file might be either sRGB if created recently by a Microsoft application, linear RGB as recorded from an RGB scanner, or Adobe RGB (1998) if created on a Macintosh by a graphic artist. A file described as CMYK may have been prepared for a specific printer, may have been prepared as a standard CMYK, or may simply have been created in PhotoShop using the default color settings. A color fidelity strategy should attempt to give the most probable interpretation of the color encoding, given the marketplace and the sourcing workflow.

## Calibration Accuracy and Stability in Each Device

Calibration accuracy and stability in each device involve the control capability supplied with each device such that the device can be maintained consistently within its optimal operating range. Devices must be able to reproduce the same color in different places on a piece of paper, across multiple sheets of paper, and from one day to the next. A fleet of identical model devices should produce the same color given the same input signal. Control of neutral behavior is fundamental to device calibration. Each device manufacturer is responsible for providing this capability.

**How Does Device Calibration Impact Color Fidelity?**

A large share of color complaints are related to issues that could be solved by equipment calibration.

First, the challenge is that although calibration for each device is a local proprietary function, any device in a workflow that is not controlled (e.g., widespread uncalibrated office computer displays) can adversely impact color results on the other devices in the workflow. This means that, for example, the colors in a print output from a well-calibrated office printer are not likely to correspond with the source colors displayed on an uncalibrated office PC.

Second, there is an interdependency between source device calibration and document color source specification, and between source device calibration and source device characterization. Unless a source device, such as a monitor used in graphical design or a scanner used to digitize hardcopy art originals, is accurately calibrated and characterized, a correct source color definition cannot be associated with the document content produced through that device.

We should also note that in many cases the device calibration can only be as good as the measurement process employed in the calibration. For this reason, improved open system color fidelity requires improved consistency between color measurement tools.

**How is Device Calibration Market Dependent?**

Engineering for device stability, on-board color controls, and re-calibration procedures can result in controllable devices. However, imaging systems are built with tolerances, based on specifications for how good is ‘good enough.’ These tolerances differ across markets, and between imaging component vendors. Color fidelity challenges arise when imaging components originally intended for one market end up in another, e.g., desktop inkjet printers used in a networked enterprise environment. In such cases the available color calibration controls may not be appropriate to the users, and the device color control accuracy and stability may not be consistent with users’ expectations of the workflow. Color fidelity is diminished due to cross-market differences in device calibration tools and tolerances.

## Color Gamut Characterization Accuracy for Each Device

Characterization accuracy for each device involves the capability of measurement and modeling software, tools, and procedures, to represent the full range of color device behavior. Characterization methods may be proprietary, but characterization results must be recorded for unambiguous exchange and interpretation in standard data formats such as ICC profiles or PostScript tables (CSA, DEFG table, or CRD).

An ICC profile is a data file that maps the set of colors of one device (i.e., capture or print condition) to a standard set of colors that a color management module (i.e., a color processing software module) can interpret. A color management module (CMM) uses a sequence of ICC profiles to map the colors of one device into the colors of any other device. This mapping enables each device to display colors appropriately, so that color fidelity is maintained as a color element moves between devices in a workflow. The process used to build an ICC profile is called characterization.

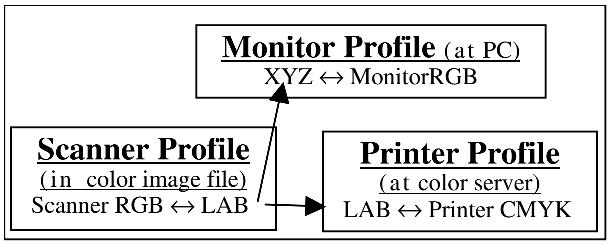


*Figure 3. ICC Color Profile Usage*

Figure 3 shows a schematic of how ICC profiles may be used. In the diagram, Monitor RGB, Scanner RGB, and Printer CMYK are device-dependent color spaces. CIELAB is a standard, device-independent color space that is used as an intermediary between various device-dependent color spaces (such an intermediate color space is known as a Profile Connection Space, i.e., PCS). CIEXYZ is another such PCS color space. An ICC profile maps a set of device-dependent colors to/from corresponding colors in the PCS (LAB or XYZ) color space.

**How Does Device Characterization Impact Color Fidelity?**

Characterization is required with calibration in order to specify source document color content. Together, calibration and characterization form a bridge between device color implementations and color transforms, so that color transforms can deliver acceptable renditions of customer preferred color aims to a variety of output devices.

However, color transform algorithms today are constrained by the information available in the exchanged characterization data. For example, a 33 node printer profile can be expected to outperform a nine node printer profile. The proprietary nature of the algorithms used in creating ICC profiles can also mean that color fidelity is sacrificed when profiles from different vendors are combined (e.g., if different unidentified chromatic adaptations are used in two or more profiles that are applied in sequence, undesirable hue shifts can result).

Similarly, exchange of characterization data is limited by restrictions in document and image formats. For example, common document and image formats do not support embedding of ICC profiles.

### How is Device Characterization Market Dependent?

With devices targeted to the home office or business enterprise environment, device characterization is often provided built-in on a fleet wide basis, and device users are not expected to modify the device color characteristics. In fact, in most cases the device image processing path is fixed and the user cannot install a new characterization. This means that device characterization is only approximate with such devices.

On the other hand, when color characterization methods are applied in a quality conscious graphic arts environment, characterizations are customized for each change in printing conditions (e.g., media, colorant, screening method, target viewing environment). In addition, ICC profiles may be modified to apply preferences to particular color document elements, and tagged to documents as a means of specifying not only their source color content, but also their intended output color renditions.

## User Color Aim Expectations as a Function of Market and Geographical Location

Color aim expectations as a function of market and geographical location involve customer practices, conventions, defacto standards, and formal standards, that comprise market and geographically specific customer color print appearance preferences. A color aim can be thought of as providing a 'target' for color characterization, the ICC profiling process. In a given workflow, defined color aims (consisting of color specified digital images, reference prints, and spectral measurements of the reference prints) can be used to maintain consistent color appearance in the color production over time.

### How Do Color Aims Impact Color Fidelity?

Let us think back to the definition of color fidelity, "Color fidelity is the successful interoperability of color data, from image creation to output across multiple targets, such that color reproduction quality consistent with the user's intent can be achieved." In other words, color fidelity means that color reproduction quality is consistent with the user's color aim.

Three broad display technology classes have given rise to three categories of color aims, the sRGB aim corresponding to PC monitor color capability, press aims (such as SWOP CMYK in the U.S.) corresponding to press printing conditions, and digital printer color aims. Because of the differences in color capabilities across the various digital printers and digital printing technologies, there is a great diversity in color aims for digital printing. Color aims for digital printers often mimic either the sRGB monitor aim (in an office / enterprise environment) or the geographically proximate press aim.

### How are Color Aims Market Dependent?

Within the office and enterprise business environments, the defacto print color aim is tied to document color appearance on a typical office computer display (i.e., the sRGB aim). The following responses are extracted from the results of an international survey of enterprise color document users (conducted by the author).

Q: "When you start with electronic originals, do you expect the colors in your printed documents to match the colors you see when you view the documents on your computer display?"
A: 66 out of 73 responded "YES." In addition, two who answered "No" commented "…but it would be nice."
Q: "Do you prefer print colors matched to your computer display?"
A: 69 out of 70 responded "Yes."

This "print colors visually matching the computer display" aim is a key distinction between office/enterprise color document users and graphic arts color practitioners. Within commercial print environments, color aims are based on experience with press and/or digital printer capabilities. The typical tools and practices within a graphic arts prepress environment (e.g., hardcopy proofing) are established to examine and achieve press-based color aims.

Graphic arts print color aims also differ based on geography. For example, color press aims may be based on SWOP CMYK in the U.S., Euroscale in Europe, and Japan Standard in Japan. In practice, the color aim for each print-for-pay job is customized, taking into account the capabilities of the printing equipment and the client's cost constraints. The formal color aim standards recognized in these markets provide a common starting point for the customization.

## Color Aim Implementation in each Device

The color aims that a device can achieve are determined by the physical color and resolution attributes of the device. Printer color and resolution attributes that deliver and describe device color capabilities are

- color gamut (derived from colorant spectral attributes, colorant lay-down order and interactions, and screening method),
- ink limit (limited by colorant interactions at high densities),
- printer resolution (i.e. dpi, printer addressable spots),
- screen frequencies (i.e. lpi, line screens, screen rulings),

- screen angles (e.g., offset K:45, M:75, C:105, Y:90)
- grey levels per halftone cell (traditionally: [output device resolution / line screen]^2 + 1 = grey levels),
- dot range (e.g., 5 – 95 percent dot),
- dot shapes (i.e., halftone dot design),
- dot gain (from initial rendering to final output).

**How Do Color Aim Implementations Impact Color Fidelity?**

The effective color gamut of a creation-to-display (softcopy or hardcopy) workflow impacts the range of colors that can arrive at the targeted display devices. The color gamut capabilities of each imaging device in a workflow (e.g., color scanner, softcopy display, page proof printer), and any color gamut constraints imposed by intermediate color processing (e.g., editing scanned images), contribute to the "effective workflow color gamut." When the color aim implementation in a targeted display device is compatible with the color aim and effective color gamut of a workflow, then source-to-output color fidelity can be achieved.

What is the situation with device color aims today? Color aims are built into device calibration and characterization tools. However, in many cases these aims are not explicit and are not accessible to the user. This means that the underlying targeting assumptions driving workflow component color behavior cannot be controlled. Devices from different vendors, devices based on different technologies, and 3rd party device characterization tools often have different built-in aims.

**How Are Color Aim Implementations Market Dependent?**

Color aim implementation market dependencies are driven by cost. In general, optimization of each of the device color capability attributes is limited either by development cost, or by component cost.

## Color Translation Algorithms between Devices and Viewing Conditions

Color translation algorithms translate colors between source color encodings and display-ready color encodings, making adjustment for device color capabilities and intended display viewing conditions. There are four broad categories of color translation algorithms: correction operations, appearance operations, preference operations, and gamut mapping operations.

Correction operations are image and capture method specific. "Corrections" are capture side operations that compensate for capture system limitations or anomalies, setting up an image so that it can then be processed through preference, etc., operations in the workflow.

Appearance operations are input to output environment specific. Appearance operations compensate for viewing conditions, illumination level and surround differences, and may include unsharp masking to maintain detail contrast.

Preference operations are image specific and output gamut specific, and are closely related to a user's color aim expectation. Preference operations deal with intentional alterations of appearance to increase the pleasingness of an color element. Chroma and contrast boosting are typical examples. Tone compression decisions are an important aspect of preference - and need to be image specific. However, tone compression is highly dependent on output gamut, and can also be considered as part of gamut mapping.

Gamut mapping operations are fundamentally input to output device specific, however, improved results can be obtained when gamut mapping methods are adapted for image characteristics. Gamut mapping operations fit the results of appearance and preference operations into an actual device gamut, providing a colorimetric mapping from source to destination colors, compensating for differences in the source and output color gamuts.

In an ICC workflow one or more of these color translation operations may be incorporated into the ICC profiles used by a Color Management Module (CMM) to translate document colors. In a PostScript image path, one or more of these operations can be performed by PostScript operators using color transforms formatted into PostScript tables (CSA, DEFG, and CRD transform data). In other workflows one or more of these color translation operations may be performed by the user (e.g., using Photoshop) or may be performed by proprietary color translation algorithms.

**How Do Translation Algorithms Impact Color Fidelity?**

The key interoperability constraints affecting color translation algorithms derive from their dependencies on characterization data and color document data exchange formats. For example, inconsistent persistence of metadata (e.g., ICC profiles) through diverse multi-vendor color processing paths is a key limitation. Printer drivers often constrain the types of color manipulations that can be performed, based on limited data assumptions. Current characterization data exchange formats do not support color transform algorithms that use pixel neighborhoods in determining the color translation, thereby maintaining color contrast. A key underlying workflow interdependency is that device stability and correct device characterization are required before optimized results can be delivered through any predetermined algorithm.

In today's color industry, ICC profiles and certain color encodings are well-specified for data exchange. On the other hand, CMM behavior is proprietary and still evolving. The computer platforms that your color managed applications (and the CMMs they use) run on can also have an impact on your display color results, if the applications invoke color functions supplied by the platform. As a result, consistency through multi-vendor color translation algorithms is a challenge to the goal of color fidelity across open distributed imaging systems.

Another challenging consideration in the quest for color fidelity is "Where in the workflow should each color translation be applied?" If source color is irreversibly translated to display color for a particular output device, then achieving color fidelity through any other output device can be problematic. On the other hand, with today's limited tools, a document designer may have no alternative other than display device encoding – if the document's appearance on the preferred display device is to be fully specified.

### How Are Translation Algorithms Market Dependent?

In office and enterprise business environments, color translation algorithms are often built into device drivers, out of the reach of the user. In graphic arts environments, color translations may be accomplished through a combination of ICC methods, PostScript methods, and manual operations carried out by an expert color practitioner. With respect to color translation algorithms, the various markets can be distinguished by the differing levels of control that the practitioners wish to exercise.

## Color Control Communication Mechanisms between Devices

Color control communication between devices involves the elements of color information that are communicated via job control protocols, or through document and image file metadata (e.g., JDF color attributes, printer driver color attributes, ICC profiles, PostScript color tables).

### How Do Color Controls Impact Color Fidelity?

Today, control of color through job attributes is dependent on interactions between multiple proprietary workflow components. For example, in a workflow involving document layout, PDF, and digital press output, various color control attributes can be set redundantly in the layout application Page Setup, in the layout application Print Driver, through the PostScript Printer Description (PPD), in Acrobat Distiller, in the Acrobat Print Driver, and in the digital printer's digital front end (DFE). The precedence model governing interactions between these color controls is not explicitly defined and is a point of inconsistency and user frustration between various proprietary systems.

### How Are Color Controls Market Dependent?

Available color controls, and color control interactions, follow from the imaging applications and devices in a given workflow. A key challenge in establishing a particular color workflow lies in understanding the color control precedence model in effect between the workflow components. User willingness to exercise control varies significantly across markets. An office color document user may prefer not to adjust any color controls; a print production equipment operator in an enterprise environment may rely on the DFE controls. Due to the complexities involved, commercial print vendors often provide specific guidelines to document originators, enabling them to set their document color control attributes as required for the printer's workflow.

With the advent and proliferation of the internet, color documents are more readily available and more easily exchanged than ever. Often, complete information about a color element is either never captured or is lost in transmission. In addition to losing information, incorrect information may be picked up throughout the lifetime of a color document. The only way to guarantee consistency is to have complete control over the print path, from application to CMM to printer. But this approach satisfies only a limited set of expert color users.

## Conclusion

While baseline elements for color fidelity, such as device calibration and limited color-enabled data exchange, are available today, distributed system color fidelity still relies on proprietary end-to-end systems. Each of the seven color control factors contributing to open systems color fidelity requires definition of and widespread cooperation with standard interfaces and standardized color element performance. Complicating the development of sufficient standardization, the diverse needs of a wide range of users call for a range of solutions from full automation on one hand, to precise step by step control on the other. A delicate balance is required, between allowance for proprietary differentiation, and standards that provide sufficient in-market and cross-market specification.

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## Biography

Ann McCarthy received her B.S. degree in Computer Engineering from the Rochester Institute of Technology in 1982, and her M.S. in Imaging Science from the Rochester Institute of Technology in 1997. From 1982 to 1999, she worked at Eastman Kodak Company in Rochester, N.Y. Since 1999, she has worked in the Xerox Architecture Center for Research and Technology at Xerox Corporation in Webster, NY. She is the Xerox representative to the ICC. Her work has focused on image path architectures, color systems engineering, color management workflows, and related image quality issues. She is a member of the IS&T and the IEEE.