Color Strategies for Image Databases

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ABSTRACT

In this paper, color encoding strategies for different image database applications are discussed. The color image workflow is examined in detail, and master and derivative file encoding strategies are outlined in relation to capture, maintenance, and deployment of image files. For the most common image database purposes, recommendations are given as to which type of color encoding is most suitable. Advantages and disadvantages of sensor, input-referred, output-referred, and output device specific color encodings are discussed in relation with image usage. The role of ICC color management in an image database environment is also considered.

Keywords: Image Databases, Master and Derivative Image Files, Color Image Workflow, Color Encoding, ICC

1. INTRODUCTION

Image database is a very general term for describing a repository of digital images, deployable for various purposes. An image database may contain any number of images, from a few hundred to millions of image objects. These image files can either *represent* digital reproductions of original artwork, such as photographs or paintings, or can *be* the original digital artwork, such as if an original scene was captured with a digital camera. The purpose of image databases vary: they can either contain digital image files that represent scenes or replace original artwork; they can contain digital image files that only represent a reproduction of the scene or original artwork, optimized for a given use and workflow; or they can contain a combination of both. It is usually implied that images should be accessible and usable over a long time frame, and should keep their value to the user indefinitely. The database should also be easy to manage, i.e. digital images should be deployed, processed, converted, and transmitted automatically. All this implies that certain strategies of initial image capture and processing techniques and a certain standardization of the workflow should be well defined before an image database project begins.

The *usage* of the digital image files ultimately dictates image quality and the necessary processing steps to be taken before archiving and delivering images. The higher the quality, the more expertise, time, and cost are associated to the generation, processing and storage of image files. While this paper focuses primarily on color issues relating to the capture, maintenance, and deployment of digital images in a database, the same applies, of course, to other image database issues, such as capture and maintenance of text and administrative metadata, storage issues like file format and media, and other image processing steps like noise filtering and sharpening. Following are three cases of most common digital image usage that define quality criteria [1]:

The digital image is only used as visual reference: the required digital image quality is low, both in terms of spatial and color resolution content. The display is limited to a screen or a low-resolution print device. Exact color reproduction is not critical; the image has only to “resemble” the original artwork or scene. Images are usually compressed to save storage space, but primarily delivery time. For cases where original artwork is digitized, it suffices to use existing photographic duplicates of the originals and low-resolution scanners. Analog, low-cost digital cameras can be employed when capturing scenes.

The digital image is used for print reproduction: the requirements for the digitizing system depend on the desired reproduction quality. Limiting output to certain spatial dimensions and a certain color encoding will define the digitizing devices and initial processing. Commercial digital image archives, such as Corbis Corporation [2,3] and Getty Images, Inc. [4], and many cultural institutions digitize their analog image collections with this purpose in mind. Similarly, professional photographers who use digital cameras will build a collection of such images, and therefore an image database, over time. Commercially available scanners, digital cameras, and imaging software can produce image files for such applications.

The digital image represents a "replacement" of the original in terms of spatial and color information content: this goal is the most challenging to achieve. The information content in terms of pixel equivalency varies from original to original. In terms of scanning original photographs, for example, it is not only defined by film format, but also by emulsion type, shooting conditions and processing techniques. Color information can only be captured adequately if the digitizing device supports the originals' color gamut in terms of encoding bit-depth and lack of metamerism. Such image library applications can be found in museums and other collections, where colorimetrically accurate capture is important, and/or the physical artwork is too fragile to be handled daily, or is already deteriorating so that the image content as seen today needs to be preserved. Producing these files usually requires specialized hardware and software.

Each of the usages outlined above will determine the quality of the *digital master* to be archived. It represents the highest quality file that has been digitized [5]. Since it represents the information that is supposed to survive long term, the encoding has to be appropriate for all current and future–as yet unknown–usage. The choices made in the initial digitization and processing of images are final and can usually not be reversed, and therefore great care should be given in designing the technical specifications of the initial capturing process. For daily use, *derivatives* of digital master files can be created, which are encoded according to their purpose. In many image databases, various image derivatives are found, each appropriate for a different application [6]. See Table 1 for a comparison of different image database usage and recommended encoding specifications.

Table 1: Comparison of different image database purposes and recommended encoding specifications.

Master file	**Visual Representation**	**Print Reproduction**	**Replacement of the Original**
Purpose of the image database	• Consumer (digital camera files, print scanning) • On-line visual representation (electronic catalogues, image kiosks, insurance databases) • Low-end print representation (prints up to 4 x 6 inch)	• Commercial image libraries (picture agencies, publishing houses, news agencies) • Professional photographers • Museums, cultural, and government institutions • Consumer printing (8 x 10 inch)	• Museums, cultural, and government institutions with high quality demand and/or fragile original artwork.
Derivatives	• Screen resolutions • Thumbnails	• Lower print resolutions • Screen resolutions • Thumbnails	• Print resolutions • Screen resolutions • Thumbnails
Spatial Resolution[1] (for one dimension)	• Thumbnails: ≤ 250 pixels • Screen resolution: ≤ 1600 pixels	• Dependent on the reproduction intent, the size and quality of the original artwork, and/or limited by the maximum spatial resolution of the digitizing device. • ~ 2000 to 7000 pixels	• Dependent on the size and quality of the original artwork, and/or limited by the maximum spatial resolution of the digitizing device.
Image encoding of master file	Output-referred	Output-referred	Sensor Input-referred
Compression of the master file	None, lossless, or lossy (JPEG, JPEG2000)	None or lossless	None or lossless
File Format of the master file	Exif, TIFF, JFIF, JP2	EXIF, TIFF, JPX	TIFF, JPX

[1] Note that pixel dimension is only one parameter describing the spatial resolution of a digital image file. Other factors, such as the size, resolution and sharpness of the original, the spatial frequency response of the digitizing system, the quality of pixel reconstruction and interpolation algorithms, and the resolution of the output device all influence the resolution and apparent sharpness of the image reproduction [7,8].

2. DIGITAL IMAGE COLOR WORKFLOW

The color workflow of a digital image can be generalized as follows (see Figure 1). An image is captured and encoded into a sensor or source device space, which is device and image specific. It may then be transformed into an input-referred image representation, i.e. a color encoding describing the scene's or original's colorimetry. In most workflows, however, the image is directly encoded from source device space into an output-referred image representation, which describes the image appearance on some real or virtual output. If the output-referred color space describes a virtual output, then additional transforms are necessary to encode the image into output coordinates, which are dependent on the specific device [9,10].

According to the CIE, a *color space* is a geometric representation of colors in space, usually of three dimensions [11]. The basis functions are color-matching functions, usually CIE color matching functions. Spectral spaces are spanned by a set of spectral basis functions. The set of color spaces is therefore a subset of the set of spectral spaces. However, in practice, the difference is often neglected, and all representations of color in space are called a "color space." *Color encoding*, on the other hand, refers to a quantized numerical representation of an image in a color space including any associated data required to interpret the color appearance of the image [12]. A color space can have more than one color encoding associated with it. For example, CIE XYZ is a color space, but the encoding of images within the color space, and the image appearance associated with it, is determined by the color encoding specifications such as viewing conditions, transformation from device encoding and quantization. These color encodings are also often called "color spaces," which leads to some confusion in the imaging literature and industry. Note also that color reproduction quality is not necessarily defined by the color space an image is encoded in, but by the quality of the transformation applied to the image data to encode the image into a given color space.

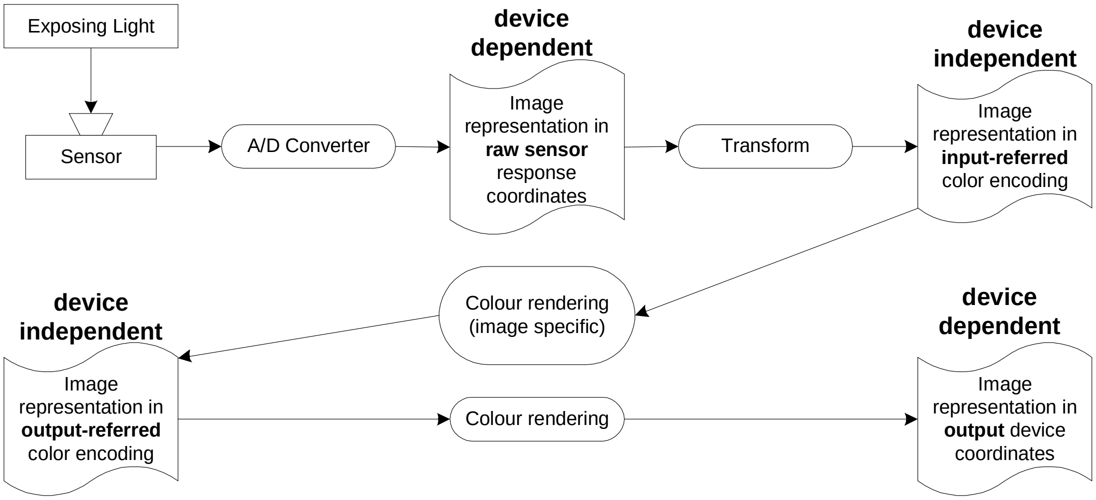

Figure 1: Color image workflow from capture to display.

2.1 Sensor Encoding

When a scene or original is captured, either by a scanner or by a digital camera, its first color encoding is device and scene specific, defined by illumination, sensor, exposure, and filters. In the case of scanners, the illuminant should be nominally constant for each image. With natural scenes captured by digital cameras, the illumination can vary from scene to scene, and even within a scene, and usually has to be estimated. The spectral sensitivities of the filters for a digitization device should be chosen, if possible, according to the original. When scanning color negatives, for example, the filters used should be optimized to the film dye spectral sensitivities. Filters for scanning color positives, as well as digital camera filters, are usually broader and overlap. Out of image system considerations such as noise and speed, it is rare to find filters in commercially available capturing devices that match the color matching functions of the human eye. As a result, device metamerism can occur, i.e. two different colors that can be distinguished by the human eye can be encoded to the same digital values and vice versa. Depending on the application and originals, that effect is more or less negligible. If very precise color reproduction is required, the use of a multi-spectral capturing system is appropriate. Such systems are usually employed in a museum environment where original paintings are scanned. Depending on the system, they consist of six to eight filters with varying bandwidth and peak spectral sensitivities [13,14,15]. XYZ tristimulus values can then be calculated from the different channels for a colorimetric representation of the original.

When images are archived in sensor space, camera or scanner characterization data, such as device spectral sensitivities and illumination data have to be maintained so that further color and image processing is possible. Additionally, it has to be clearly noted which processing has already been applied to the image. The image should be saved in a standard file format, such as TIFF, whose encoding specifications are widely published [16], and libraries are available. The International Organization for Standardization (ISO) has developed a specific TIFF format called TIFF/EP [17], which has defined tags for the necessary information that has to be stored to further color process images from digital cameras, such as spectral sensitivities, sensing method, illuminant, opto-electronic conversion function (OECF), color-filter array pattern, and more. TIFF/EP can also store tags about the camera shooting condition that are used to determine noise filtering, sharpening, and preferred reproduction algorithms. Similar tags can easily be developed for scanning applications. It is also advantageous to store as much information as possible about the original artwork, such as original size, reflection characteristics, and film emulsion type in case of photographs. In general, it is always advisable to archive more, rather than less, information about the original scene or artwork, the digitizing system, and the lighting conditions.

If the capturing conditions are always the same, it might be advantageous to store the color metadata not in the file, but in a separate database, which allows the creation and definition of the tags necessary for an individual application. However, in real situations it can occur that the image data and metadata are de-synchronized, usually due to human error. Storing image metadata in a database and in the master file can prevent that this has a negative effect on future automated processing.

Images encoded in raw-data, or sensor space, are not viewable without further processing. However, they represent the true archive files necessary for many high-end image database applications. Any further processing can degrade the image, as algorithms are based on today's know-how and might be improved in the future. Additionally, these transforms are not always reversible, even when stored with the image files. In most cases, the hardware and software necessary to create and archive such master files is not commercially available and has to be developed in-house or with academic or industrial partners [18,19].

2.2 Input-Referred Image Encoding

The transformation from raw data to input-referred, device-independent color encoding is image and/or device specific and includes the following steps: linearization, flare correction and pixel reconstruction (if necessary), white point selection, followed by a transformation to the input-referred color space.

The purpose of input-referred image encoding is for the image to represent an estimate of the scene's or the original's colorimetry. An input-referred encoding maintains the relative dynamic range and gamut of the scene or original. A scene-referred encoding describes the input-referred encoding of an original scene, where as an original-referred encoding describes the input of original artwork. Scene-referred encodings usually need to support a higher dynamic range.

The quality of the colorimetric estimate depends on the ability to choose the correct scene illuminant, and the correct transformations from device RGB to standard input-referred color encodings. The transformation is usually based on minimizing an error criteria, such as minimizing CIE XYZ, CIE ΔE_{Lab}, CIE ΔE_{Lab94}, or CIE ΔE_{Luv} [20]. The choice of which error criterion to use, and therefore the method of calculating the transform, is input system and application dependent [21]. If the illuminant spectral power distributions, the reflection spectra of the original artwork, the spectral sensitivities of the filters and CCD, and the OECF of the digitizing system are known, the transform can theoretically be calculated. However, because digitization devices have spectral responsivities that are usually not equivalent to a set of color-matching functions, this transform cannot be perfect for all possible original stimuli. In practice, it is therefore advisable to image a test chart that has similar or identical reflection or transmission spectra as the original's to be digitized. For many applications, the commercially available MacBeth ColorChecker™ [22] is used as target. For photographic slide and print scanning, an IT-8 [23] target on the same film or print material can be imaged. When paintings are digitized, a target with representative color samples should be used so that the transform is based on realistic reflection spectra.

Examples of color encodings that are used to encode an estimate of the scene's or original's colorimetry are CIE XYZ, CIE Lab, CIE Luv, Photo YCC [24], and RIMM RGB [25]. Input-referred image encodings can be used for archiving master image files when it is important that the original colorimetry is preserved so that a facsimile can be created at a later date, and the transformation from sensor encoding to input-referred encoding is unambiguous. Another advantage of input-referred encodings, especially if the images are encoded in higher bit-depth, is that they can always be tone and color processed for all kinds of different rendering intents and output devices at a later date, without having to maintain all the device characterization data necessary to process a raw sensor data encoded image.

2.3 Output-Referred Image Encoding

Output-referred image encodings refer to image representations in color spaces that are based on the colorimetry of real or virtual output characteristics. Images can be transformed into output-referred encodings from either source or input-referred image encodings. The complexity of these transforms varies: they can range from a simple gamma-function, such as is employed by video encoding [26] to complicated image dependent algorithms. The transforms are usually non-reversible, as some information of the original scene encoding is discarded or compressed to fit the dynamic range and gamut of the output. The transforms are image specific, especially if pictorial reproduction modeling is applied.

Most commercially available scanners and digital cameras, except for the high-end models, automatically apply some preferred pictorial reproduction model and deliver files in an output-referred encoding. With scanners and high-end digital cameras, the user can additionally “manipulate” the model by changing color, saturation, contrast, etc. As the transform algorithms – and the resulting image reproduction quality – are the differentiating factors between manufacturers and their devices, it is hard to obtain much information about them. Additionally, these transforms can never be standardized, as most images are subjectively evaluated, and preference varies between observers. It is also difficult to commercially obtain software that automatically applies preferred reproduction models to sensor or input-referred encoded images, especially if the images are encoded with higher than 8-bits/channel. The closest to such applications are high-end scanner and digital camera drivers that allow importing high bit-depths data files. However, they are usually only capable to interpret the image files coming from their own devices, as the device metadata is stored in the driver and not in the image file. This is the main reason that commercial image archives, as well as many cultural institutions, archive their master files in an output-referred encoding. It is to be expected that the imaging industry will soon address this missing piece in the image production pipeline.

Output-referred color encodings, based on real or virtual output devices, are e-sRGB [27], sRGB [28], ICC PCS [29], ROMM RGB [30], Adobe 98 RGB [10], and SWOP CMYK [31]. Output-referred image representations can also be encoded in other color spaces, such as CIE Lab, CIE Luv, Photo YCC [24], YUV [32], and YCrCb [32].

Archiving images in output-referred encoding is appropriate for image libraries that archive primarily master files whose purpose is to be a reproduction of the original, and not a representation. Most current image libraries fall into this category, as commercial hardware and software are available for this task. The choice of which output-referred color encoding is appropriate for the master file and its derivatives depends on the database applications. However, whenever possible, the same encoding should be chosen for the master files, especially when large number of images are processed to derivatives at a later date. In general, all image library derivatives are encoded in output-referred representations.

2.4 Output Device Specific Encoding

Transforms from output-referred encodings to output coordinates are device and media specific. If an output-referred color space is equal or close enough to the real device characteristics, such as “monitor” RGBs, no additional transformation to device specific digital values is needed. For other output applications, such as print, there is a need for additional conversions. This can be accomplished using the current International Color Consortium (ICC) color management workflow [29]. An “input” profile maps the reproduction description in the output-referred space to the profile connection space (PCS), and the output profile maps from the PCS to the device and media specific values. However, if the gamut, dynamic range, and viewing conditions of the output-referred encoding are very different from those of the actual output, it might be more advantageous to use a reproduction model that allows image specific transforms than to use the current ICC color management systems that only contains “device-to-device” mapping. Adjusting for different viewing conditions and dynamic range often are not implemented in current applications, and out of gamut colors require image dependent mapping for optimal reproduction.

Apart from some graphic arts applications, it is rare today that images are archived in output coordinates, such as device and media specific RGB, CMY, or CMYK spaces. However, there are many legacy master files, such as CMYK separations and RGB monitor specific images that need to be color managed so that they can be viewed and printed on other devices. If the color encoding is known and sufficiently characterized, it is possible to “reverse”-transform these images to another, better suited color encoding. If the two color encodings are similar and the viewing conditions assumed to be the same, for example Apple RGB and sRGB, the reverse transform can simply be executed by applying the inverse of the first non-linear encoding transfer function, followed by chromatic adaptation transform (if necessary), followed by a linear matrix conversion to the new color space, and then again perceptual encode using the new non-linear transfer function. This simple transform will clip colors that are outside of the destination gamut. Therefore, if the gamuts of the two encodings have a different shape, gamut mapping should be applied to map from one encoding to another. This can be accomplished using an ICC profile. However, if the gamuts, white-point, and viewing conditions are very different, an image dependent reproduction model might be more appropriate. Each transformation and resulting new quantization can introduce visible artifacts. It is therefore recommended that only new derivatives are “reverse”-transformed, and a copy of the original master file is kept. If, in a few years, other “standard” output-referred encodings based on new output devices become popular, then new derivatives can be created from these master files.

3. COLOR SPACES AND COLOR ENCODINGS

The correct color space and the correct color encoding parameters depend on the particular image application. The following parameters need to be considered [12]: extent of color gamut, perceptually linear tone-scale encoding to minimize the bit-depth needed to encode an image, dynamic range, illuminant white-point, viewing conditions, quantization efficiency, and compression. Table 2 summarizes the most important attributes of input referred and output-referred color encodings.

Table 2: Attributes of input-referred and output-referred color encodings.

	Input-referred encoding	**Output-referred encoding**
Image representation	Colorimetric estimate of a scene/original	Colorimetric estimate of a reproduction
Color gamut	Large enough to encompass most scene/original colors	Large enough to encompass most output devices
Perceptual uniformity (transfer function)	Data is optionally encoded using a transfer function for approximate perceptual uniformity (invertability desired)	Data is optionally encoded using a gamma-type power function to approximate perceptual uniformity on the output device (invertability desired)
Dynamic range	Must handle a scene luminance ratio of at least 10 000:1, or the luminance ratio of the original.	Must handle an image luminance ratio of at least 1000:1
White point	Should accommodate floating white points or chromatic adaptation to a fixed white point	Fixed white point determined by reproduction viewing conditions (D50, D65)
Viewing conditions (linkage to color appearance)	Luminance level, viewing surround, adapted white point, and viewing flare, as typical of outdoor environments for scene-referred encodings, typical of original viewing conditions for original encoding.	Luminance level, viewing surround, adapted white point, and viewing flare, as typical of indoor environments
Quantization/ Encoding	Quantization errors not visible on smooth, noiseless ramps Extended bit-depths encoding desired (10, 12, 16-bit per channel)	Quantization errors not visible on smooth, noiseless ramps, 8, 10, 12 or 16-bit encoding (8-bit for applications)
Compressibility	Not very important	Importance dependent on the imaging application (easy conversion to YCC color encoding)
Usual color encodings	CIEXYZ, CIELAB, CIELUV, RIMM RGB, Photo YCC	e-sRGB, sRGB, ROMM RGB, Adobe RGB 98, YCbCr, Photo YCC (legacy: Apple RGB)
Applications	Master files for high-end applications (replacement of the original)	Master files (for print reproduction): e-sRGB, ROMM RGB, Adobe RGB 98, Photo YCC Master files (for screen viewing): sRGB, YCbCr Derivatives for print reproduction or screen viewing

3. THE USE OF ICC COLOR MANAGEMENT IN IMAGE DATABASES

The use of ICC profiles in image database production and deployment can be manifold, and its usage needs to be discussed in the right content. It is not recommended for image libraries to archive master files with only ICC profiles to characterize the color encoding. Current ICC profiles do not contain device characterization data, they only contain the transformation from a device specific space to the PCS. For example, it is impossible to determine the sensor spectral characteristics of a scanning system from a scanner profile, as the sensor data was transformed to an output referred encoding and the specific transforms not retained. The image encoding is therefore determined by the device and non-standardized, and the only clue about its characteristics is given by the profile. Additionally, the profile and PCS specifications have evolved, and will continue to evolve. While it is reasonable to assume that applications are capable of reading older version profiles for two to three generations, accurate processing of these older profiles in combination with newer profiles is not guaranteed. In an image database environment where color transformation accuracy and longevity are important, updating all the different profiles associated with different devices and originals can be difficult to manage. It is therefore recommended that output-referred master files be archived in a well defined, if not standard color encoding. In that case, only one profile needs to be updated when profile specifications change. An ICC profile of the color encoding can be kept separately in a database, and can easily be updated when the specifications change.

The ICC profile associated with an output-referred master file encoding can be used to create derivatives files in other output-referred encodings, or it can be used to directly map to the output device coordinates. Practically, ICC profiles certainly facilitate the production workflow of images, such as for previewing and soft-proofing on a monitor and printing. Therefore, all derivative image files intended for print reproduction should be deployed with an ICC profile. Most pre-press and professional image manipulation programs can read and process them. While using ICC color management does not always guarantee perfect color reproduction, it does communicate an encoding intent. It is up to the user of the derivative files to additionally process the image if so desired.

Thumbnail and screen resolution images should be encoded so that they do not need to be color managed, i.e. their encoding should closely resemble the intended output device. It is not reasonable today to assume that a user's systems and applications are color managed. Indeed, many viewing applications assume today that if no profile is attached to an RGB image file, the file is encoded in sRGB and is displayed as such. If the applications are color management enabled, i.e. most printer drivers for desktop printers, they will transparently transform the image to device specific values.

4. SUMMARY

It is not possible today to give a general color encoding "recipe" for image databases, as the most suitable color encoding is strongly dependent on the purpose of the database, and these vary greatly. In theory, every image database can design its own color encodings optimized for the applications of master and derivative image files. The encoding would either be based on CIE XYZ, CIE Lab, CIE Luv, RGB, YCC or n-channel space. The encoding specifications need to be stored so that future processing – to new derivative files or to create new ICC profiles – can always be guaranteed. However, while an application-specific encoding might be desirable for the master archive file, it is not usually reasonable to use non-standard image encodings for derivatives files. In practice, commercial applications drive most image production workflows and display, and are therefore the recipients of image database derivative files. They only understand a limited number of color encodings, and it is advantageous considering productivity and image quality to keep derivative files in a standard output color encoding. If a (higher quality) master file is available, new derivatives with different encodings for different output-driven purposes can always be generated from these archive files.

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