Practical approach to color management

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'To guess is cheap, to guess wrong is expensive'.

(Chinese proverb)

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Introduction

As we all know, digital imaging requires not only expensive hardware and software, but also a complex, systematic approach to achieve proper results. One of the most commonly misunderstood and difficult processes is color management. Due to a lack of user-friendly information and the high cost of hardware and software, color management still is as much an art as it is a science.

Historically, there were many attempts to ensure reliable color in the digitization process. The printing industry developed BVD/FOGRA (Bundesverband Druck – German Printers' Federation/Forschungsgesellschaft Druck e.V. – Graphic Technology Research Association), a standard that defined process colors, the color of the paper, measuring conditions and dot-gain in the printing process. Another standard was SWOP (Standard for Web Offset Printing), developed in the US. In the realm of pre-press, the PVD (Partner vor dem Druck) system has been developed to obtain correct results. Color management was also introduced in the video and motion pictures industry. Of all those systems, the ones still in use remain quite complex and expensive. They are also hardware and software dependent, and can not always be used with the vast number of devices and operating systems currently available.

To solve this problem, several companies formed a group called International Color Consortium (ICC). ICC decided to create an open color management system (CMS) that will allow users to achieve reliable color throughout the entire digitization chain. Since then, the ICC standard has been widely accepted. The standard describes color profiles that have to be created for all input, output and display devices. Other profiles (color space conversion, device linking, abstract, and named color profiles) are also specified. These additional profiles are not attached to an image. They are being applied to the image data, for example, when a graphic file has to be converted from one color space to another. To make the standard more flexible, ICC created a profile connection space (PCS) - an intermediary device-independent color space which we can think of as a common translator between various devices. The ICC has chosen two PCSs – CIELab and CIExyz, both device-independent standards for viewing color developed by the Commission Internationale de l'Éclairage (CIE).

ICC profiles are files of data describing the color characteristics of a device – device settings and numeric data describing how to transform the color values from the device color space into a common color space. Most modern Color Management Systems are based on the ICC standard and use ICC color profiles.

Processes involved in color management are very complex. In this short article, I will very briefly explain CM basics, and then concentrate on describing some practical techniques.

Basic color theory

To better understand color management principles, let's look at the basic color theory first.

The human eye perceives color when it is being stimulated by a particular wavelength of the electromagnetic spectrum. The eye has three basic color receptors with peak sensitivity at red, green and blue. If all three basic colors are equally represented we see gray or white. Physiological and psychological processes involved in color perception are very complex and still not well understood.

Digital capture devices and monitors work using the RGB (Red, Green and Blue) model. We call it the additive color system. Printers and some other devices use a different system called a subtractive model. They use Cyan, Magenta, Yellow and additionally blacK (CMYK) to deliver full color images. We will explain these different models starting with an example of a computer monitor.

Imagine what happens when the computer is switched off. Obviously, the screen is black (no color), but when we switch it on and start adding red, green and blue (monitor primary colors), we eventually end up with a pure white screen (all possible colors mixed together). Contrary to this, when we use CMYK devices (let's use the printing process as an example) we start with a white sheet of paper (all colors already there). By applying Cyan, Magenta and Yellow we subtract colors from the sheet and, eventually, we should arrive at having a black piece of paper (no color). In reality, printing dyes are not pure enough to obtain fully saturated black. This is the reason why the fourth dye (black) has been introduced into the printing process.

Both RGB and CMYK have limited color spaces (they can describe only a limited number of colors) and are hardware dependent (colors depend on the device used and it's parameters). Problems associated with being able to print exactly what we see on the screen arise from differences between the RGB and CMYK space. CMYK is a smaller color space than RGB, which means that not all colors visible on a computer monitor will necessarily print. An intelligent conversion process that transfers non-printable colors into the closest ones that can be printed has to be employed. Of course, the process is not perfect and prints always differ slightly from what we see on the screen. The number of colors displayed or printed depends also on the device used. The so-called “color gamut” describes the maximum number of colors a particular device can output.

To be able to work outside the limitations imposed by RGB and CMYK systems, CIE (Comission Internationale de l’Eclairage) developed a color space standard that is based on how the human eye perceives color. Two of these models, called CIExyz and CIE L*a*b* are the color models of choice for the ICC. Both models are device independent and describe the entire range of colors the human eye can see. Plate 1 shows relation between RGB, CMYK and CIE spaces.

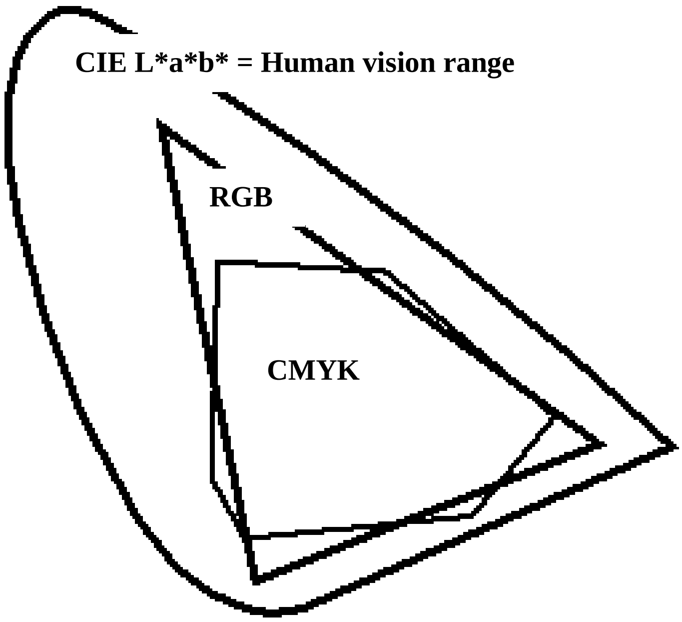

Plate 1

Digitizing system
An average digitizing system consists of three broad categories of devices:

Input	- digital cameras, scanners, etc.
Display	- CRT monitor, LCD display, etc.
Output	- printers, film recorders, etc.

Short characteristics of input devices
Input devices are RGB-based as they employ Red, Green and Blue filters to acquire full color images from a color-blind CCD (Charge-Coupled Device). Most professional scanners and digital cameras are linear devices. Software for such devices allows the user to calibrate them accurately. Unfortunately, this is not the case with less expensive equipment.
Color acquired during digital capture is device dependent. To be able to re-create true colors of the captured original from a graphic file, it is necessary to acquire information about transfer properties of the capturing device. One of the most accurate and simple methods to obtain this data is by creating ICC color profiles for each device. As scanners often employ different light sources and /or different lenses for transparent and reflective scans, it is necessary to create separate profiles for each case. Similarly, digital cameras require separate profiles for each lens (differences between some lenses may be negligible) and different light sources you may employ.

Short characteristics of output devices
Output devices often work in CMYK color space and the transfer characteristics of many of them, especially printers, are not linear (more about linearity later). Color is being determined by many elements of an output system. For printers they are: printing inks (dyes), receiving material (paper, plastic, etc.) and the property of a printer called “dot-gain”. The amount of dot-gain differs depending on the printing surface.

Short characteristics of display devices – CRT monitors

Monitors are RGB devices. Most computer monitors are Cathode Ray Tubes (CRT). Due to its non-linearity, the monitor is the main culprit in problems associated with correct color.

Plate 2 presents the input-output graph of an ideal monitor - input intensity equals output intensity, or in other words, this monitors characteristic is linear. Doubling the pixel value of the image (input) should produce twice as much brightness on the monitor (output). Unfortunately, the monitors in real life are different. Plate 3 shows the true characteristics of an average monitor. 50% of input translates into only about 18 % of output. This non-linearity of the CRT is called gamma and can be derived from a following equation:

$$\textbf{output intensity} = \textbf{input intensity}^{\textbf{gamma}}$$

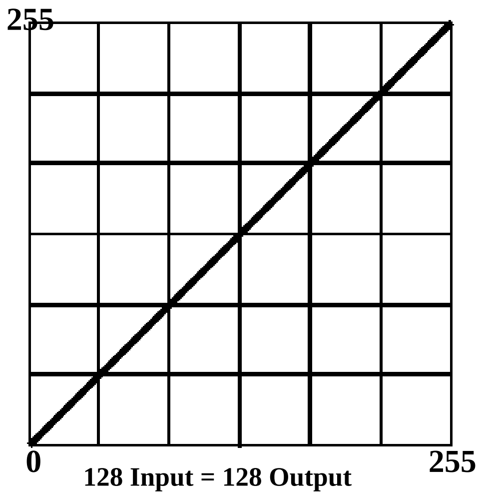

Plate 2

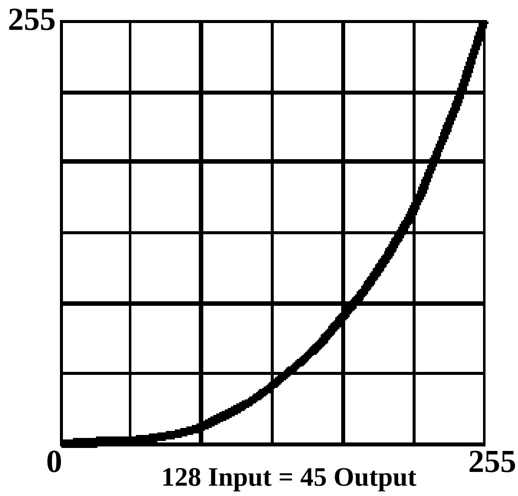

Plate 3

The gamma of an average computer monitor is between 2.4 to 2.6 (average gamma=2.5). To compensate for gamma and display images correctly, more sophisticated computer systems (they have hardware look-up tables – usually in graphic interface cards) apply an inverted gamma of 2.5 to the data (gamma $^{1}/_{2.5}$). Monitors compensated in this manner are said to be in gamma space 2.5. This is true for PCs - Macintosh systems apply a partial gamma correction (gamma=$^{1}/_{1.45}$) that results in the gamma value 1.72 on a Mac (Macintosh systems are said to be in 1.72 gamma space, often rounded up to 1.8 in popular usage). Please, make no mistake - monitors (and systems) are not calibrated when this happens, they are gamma compensated only!

Gamma is a complex and sometimes difficult concept to comprehend. In the table below I will try to explain various gamma-related terms.

TERM	EXPLANATION
Gamma function	Gamma is the exponent of the following equation: **Output=input ^{gamma}**
Gamma compensation	When a gamma function of gamma=$^1/_{2.5}$ is applied to an image, then the image is gamma compensated for gamma space=2.5 viewing.
Gamma correction	When a system is linearly calibrated (gamma=1.0), the system is called gamma corrected.
Monitor gamma	The electrical property of a CRT monitor applies a gamma function with gamma=2.5 over an image data. To show images properly, a gamma function with an inverted gamma=$^1/_{2.5}$ is applied to the image. We say that monitors are in gamma space 2.5.

Linearity and Gamma

As explained in the previous paragraph, some devices used in the digitization chain are not linear, i.e. input values do not equal output values. Systems can be set in many ways and the most common is to calibrate them to gamma=2.2 on a PC and 1.8 (1.72 to be exact) on a Mac. These gamma spaces are, unfortunately, not the ideal environment to work in. Most times we need to manipulate images after capture by applying some adjustments (like curves or levels) and filters (like "Unsharp mask"). Gamma spaces that are not linear (gamma not equal to 1.0) create errors due to gamma compensation changes during manipulation and the linearity of tri-stimuli color spaces (RGB or CMY(k)). These errors accumulate with each operation. Some examples of the most common image-gamma induced errors include deteriorated edges, increased noise and hue shifts.

Ideally, computer systems should be calibrated to gamma space=1.0, and all image manipulation should be performed in this space. For a number of reasons, this is usually not the case. First of all, linear gamma space is perceptually incorrect – tones from deep shadows (D_{max}) to highlights (D_{min}) appear to the human eye unevenly distributed. Second, often we want our systems to be compatible with other, non-calibrated computers (World Wide Web, for example), in which case gamma space 2.2 is a reasonable compromise. Of course, it is possible to work in gamma=1.0 and then apply appropriate gamma correction over the images to make them compatible with the output, but that procedure requires extra time and effort.

Calibrating the computer system

An uncalibrated computer system is not the ideal environment for digital imaging. Every computer system should be calibrated before it is being used for digitisation, and on a regular basis thereafter (say, once a month). It is sometimes a tedious process and involves many steps. Ideally, the system should be calibrated using dedicated hardware and software, but it is possible to obtain very good results without them.

It is virtually impossible to describe all existing Color Management Sytems and calibration procedures. I will concentrate on just two options - one involving Adobe Photoshop only, and a second option that utilises a combination of Adobe Photoshop and some calibration hardware/software, in this case X-Rite's Color Shop and Monitor Profiler (DTP92 CIE Colorimeter), a monitor color measurement device. It seems to me that Photoshop is the most commonly used tool by imaging professionals in the library, museum and other image archiving environments. Photoshop’s color management system is a very powerful tool. If you do not employ any other color management system, it should be used all the time. Do not switch it off! An additional tool supplied with Photoshop is Adobe Gamma – a very useful (though not entirely accurate) utility for adjusting gamma and the white/black point of the monitor. Procedures described below focus on Windows based systems, but I tried to include details relating to Macintosh computers as well.

Calibrating using Photoshop only - calibrating gamma, grey balance and enabling color management:

1. Turn on the computer and make sure that the monitor warms up properly (at least 1 hour).
2. Make sure that there is no strong ambient light present that could affect the monitor’s image. Set up the normal room lighting you will use for work.
3. Make sure that your system is running in 24-bit, true-color mode.
4. Use the controls on your monitor to set it to color temperature = 6500K.

The next one is a bit tricky - we will correct for the monitor color temperature deviations (it works for monitors with fine color adjustments only).

5. Create a white (RGB=255,255,255) large square on a black background and position it in the centre of the screen. Either use a 6500K light source shining on a white sheet of paper or look at a white surface behind the window on a bright sunny day (it has to be between 11am and 1pm). Now try to match the color of the white square on the monitor to the white sheet of paper or the white surface behind the window using the monitor color temperature fine controls. Primitive as it may seem, this technique is capable of fine-tuning the color temperature of the monitor.
6. Make sure that your Photoshop version is at least 5.02 (there is a free upgrade from 5.0 to 5.02 available at Adobe web site).
7. Start Adobe Gamma by going to Control Panel and clicking Adobe Gamma icon (in Windows NT and Mac OS you’ll need to go to your “Photoshop>Goodies> Calibration” folder).
8. Chose Wizard view. Click Next.
9. Make sure that "Adobe Monitor Settings.icm" profile is selected and click Next. If this is not the case, write down the profile name, close Adobe Gamma, go to “Windows>system (system32 in Win NT) >color” and remove the profile. Start Adobe Gamma again.
10. This screen adjusts the black point of the monitor. I found it difficult to use and inaccurate. Below, I describe a much more precise procedure recommended by Timo Autiokari (http://www.aim-dtp.net/aim/).

    Go to your Windows Desktop by dragging the Adobe Gamma window out of the way and right-click on it. Chose “Properties>Appearance”. Make sure that the box “Item” shows “Desktop”. Click on “Color” properties and change it to pure black. Click “OK”.
    Adjust the contrast control on your monitor to maximum.
    Set the brightness control of the monitor to maximum. Locate the vertical height adjustment of your monitor and set it to some smaller size, so you can see a narrow black border at the top and bottom of the main image (Win desktop) area in the centre. Now, the Desktop’s canvas should not be quite black.

Turn the brightness down until the central, desktop area is just as black as the narrow strips at the top and the bottom. Leave contrast at maximum. The black point is set.

11. Drag Adobe Gamma window back to the centre of the screen. Click Next.
12. Set the monitor phosphors to Trinitron or P22-EBU (they are used exclusively in modern computer monitors and there is not much difference between them). If you know your monitor phosphor chromacity values, you may select “Custom” and type in the values. Click Next.
13. Set the desired gamma value to 2.2 (1.8 on the Mac). This option is not available in Windows NT or on older systems which can not control monitors. Click “View single gamma only”. Adjust the slider until the central square blends with the surrounding frame. To do it properly, move away from the monitor at least some 3 feet and squint your eyes.
14. Uncheck “View single gamma only” box. Adjust red slider if required. Adjust blue slider if required. It is possible that you will need to adjust the green slider as well. Repeat above adjustments as long as required. Click Next.
15. Set the hardware point at 6500K (daylight)*. Use the measure utility if you are not sure it is accurate. Click Next.
16. Set “Adjusted White Point” to “Same as Hardware”. Click Next.
17. Click Finish and Save to save profile as “Adobe Monitor Settings.icm”.
18. Calibration is completed.
19. Open Photoshop and go to “File>Color Settings>RGB Setup”. Check the “Display using monitor compensation” and “Preview” boxes. Set RGB to “Adobe RGB (1998)” – it is probably the best color space for practical use. However, if you need to preserve a greater range of colors you may choose CIE RGB or Wide Gamut RGB (note: since these are very large color spaces, not all colors can be displayed on a monitor resulting in errors if you do any manipulation of images). On a Mac select Apple RGB. For web based work the best option is sRGB, but images saved in this color space should not be used for archiving – sRGB is a limited color space.
    Make sure that Gamma is 2.2 (1.8 on a Mac), the white point at 6500K and primaries “Adobe RGB (1998)”.
20. Save the profile under a unique name in “Windows>system (system32 on Windows NT) >color” folder.
21. Open “File>Color Settings>Profile Setup”. Make sure that all boxes in “Embed Profiles” are checked. For “Assumed Profiles,” it is probably the best option to choose “None” for all. In “Profile Mismatch Handling” select “Ask When Opening”.

***Some researchers (Anne R. Kenney, Oya Y. Rieger: *Moving Theory into Practice* (California: Research Libraries Group, 2000)) recommend 5000K. Personally, I prefer 6500K but the choice is purely subjective.**

Calibrating using Photoshop, X-Rite’s Color Shop and Monitor Profiler (Optimizer) - creating an ICC color profile for the monitor, calibrating gamma, grey balance and enabling color management:

1. First, go through the procedure described above in “Calibrating using Photoshop only”. Remember that all preliminary conditions (monitor warm-up, correct lighting, etc.) have to be observed.

2. Install Color Shop software on your machine (it comes in Windows and Macintosh flavours).
3. Plug in (USB or serial) and power up the X-Rite profiler.
4. Start Monitor Profiler program.
5. The program asks to adjust white and black point of the monitor – do not change contrast or brightness settings if you already calibrated the monitor with Adobe Gamma as explained above.
6. After selecting the correct device (monitor optimizer) and the right computer port (USB or COM) in the opening window, position the Profiler on a piece of black cloth, check the “Calibrate device” box and press OK. After calibrating the device, the program will ask you to attach it to the screen via a suction cup. Click “Calibrate” and wait for the program to finish the procedure. It may be advisable to cover the entire monitor and the Profiler with a dark cloth.
7. Save the profile in “Windows>system (system32 on Windows NT) >color” folder using a meaningful name (eg. “27_July_00.icm”).
8. Open Adobe Gamma. Select “Step by Step Wizard”. Click Next
9. Click “Load” and select the profile that you just created and saved. Click Next.
10. Go through all the steps in Adobe Gamma. If you already went through the initial calibration, you should not need to adjust any controls.
11. Save the profile.
12. Make sure in Photoshop under “File>Color Settings>RGB Setup” that the monitor uses the new profile.

Calibrating scanners and digital cameras

High-end scanners have built-in procedures for calibrating and creating ICC profiles. Even such scanners can benefit from some additional calibration.

To calibrate a scanner, most commonly we will use Kodak Q-60 Color Input Target, also known as an IT8 target (Plate 4). It can be also used to calibrate digital cameras, however, GREGTAGMACBETH ColorChecker Color Rendition Chart (available from Kodak) is also used. Calibration has to be performed separately for each different kind of material that we intend to scan. For reflective scans or digital cameras we need to use a reflective target (Q60R1). For film we need targets that were made for a particular type and brand of film.

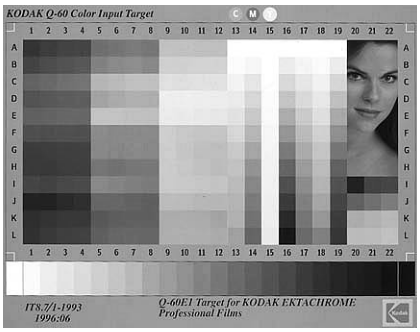

Plate 4

As always, the best results are obtained using a specialised software that reads the scan of the IT8 target, compares it to reference data created in a lab, and then creates an ICC color profile for the scanner. Examples of such software are KODAK ColorFlow ICC Input Profile Builder (www.kodak.com), WiziWYG or Compass

Profile from Praxisoft (www.praxisoft.com), and ColorBlind MatchBox from ColorBlind (www.color.com/Products/matchbox.html). By paying more you get a much more sophisticated system, but even inexpensive software like WiziWYG can do a very good job.
Calibration using specialised software is very straightforward and yields excellent results. However, it is possible to calibrate a scanner (or digital camera) very accurately using just Photoshop, an IT8 target and a digital image of a computer generated simulated Q-60 target. Such simulated targets are available from AIM (www.aim-dtp.net/aim/calibration/kodak_q60). The procedure involves scanning an IT8 target and comparing it with the simulated one in Photoshop.
Below, I describe calibrating procedure developed by Timo Autiokari from AIM.

Note: Because simulated targets are small, they have to be re-sized to the size you will be working with. As they are just patches of color you can re-size them to virtually any size you want. Just make sure that you use “Nearest Neighbor” resample method, not “bi-cubic” nor “bi-linear”. Also, make sure that you convert them from the AIM color space into your system’s color space. Another important point is to make sure that you use a simulation target that matches your real target (they all have identifying numbers).

1. Acquire a simulated target from AIM.
2. Scan Kodak IT8 target on the scanner you want to calibrate.
3. Using layers in Photoshop, position the scan on the top of the simulated target and set a “Difference” mode for the top layer. This technique allows to compare two images - if the colors are exactly the same, the result is black. In this way it is possible to visually adjust the scan.
4. Use levels (or curves) to adjust white patch (D_{min} – leftmost patch in the greyscale at the bottom) in the simulation target to RGB=255,255,255.
5. Create an adjustment layer (Curves) on top of the IT8 scan layer. Do not apply any adjustments yet.
6. Create an adjustment layer (Hue/Saturation) on the top of the Curves layer. Do not apply any adjustments yet.
7. Create an adjustment layer (Levels) on the top of the Hue/Saturation layer. Do not apply any adjustments yet.
8. Group all the adjustment layers to the IT8 Scan layer (position the mouse cursor on the line dividing the layers (in Layers dialogue box) and, while holding down <ALT> key, click the left-hand mouse button).
9. Using the white-point slider in Levels adjustment layer, make the D_{min} patch (leftmost patch in the horizontal greyscale at the bottom) as black as possible.
10. Use Curves adjustment layer to make greyscale patches as black as possible.
11. Use Hue/Saturation adjustment layer (using Master channel) to make color patches in the IT8 target as black as possible. Use Saturation and Hue sliders but NOT the Lightness slider.
12. Use individual channels in the Hue/Saturation to make patches as black as possible.
13. Procedures 9-11 may require to be repeated many times until correct results are obtained.
14. Save the Curves, Levels and Hue/Saturation settings.
15. Write an action by means of which you will be able to apply the corrections to scanned images automatically. The action should include:

16. Converting into 16-bit mode (for greater accuracy).
17. Applying saved Levels adjustments.
18. Applying saved Curves adjustments.
19. Applying saved Hue/Saturation adjustments.
20. Converting back to 8-bit mode.

An improved procedure is described in detail at
http://www.aim-dtp.net/aim/calibration/kodak_q60/calibrate2.htm
Similar procedure can be applied for calibration of digital cameras.

Calibrating printers

To calibrate printers accurately special software and hardware is needed. Best results are obtained with spectrophotometers – devices that can measure hundreds of color patches of a special target printed on the printer that is being calibrated. Results of those measurements are then automatically compared with a reference file, and an ICC color profile is created. Relatively inexpensive software and hardware can be obtained from X-Rite (www.x-rite.com).
It is possible to calibrate printers manually but usually it requires a lot of time and printing material. Also, with many printers you will need to repeat calibration procedure on a regular basis and every time you change printing inks, paper or chemicals (if the printer uses them). Some high-end printers (like Fujix Pictrography) have special calibrating devices that permit an ICC profile to be created just once and used accurately even if printing material have been changed.

Manual calibration of a printer can be achieved with Photoshop. In "File>Print>Setup>Transfer" it is possible to adjust transfer curves for each individual printing color. Using an IT8 image or a simulated IT8 target (on the calibrated computer system), you can adjust the printer by comparing the original image to the printout.

Note:

It is very important to view originals and prints under correct lighting conditions. Ideally, you should invest in a professional viewing booth. However, they are quite expensive. The next best option is to buy a continuous spectrum (Color Rendering Index, (CRI) between 98 and 100 – 98 is bare minimum), 6500K (daylight) corrected light and set it up in a place where there is no interference from other light sources.

Digital imaging workflow

Providing that we calibrated our imaging system and all input and output devices, the correct digitization workflow shall include:

1. Acquiring images (scanning, capturing using a digital camera, etc.).
2. Applying color calibration to images by means of an input device ICC color profile.
3. Editing images (to avoid errors this should be done in gamma 1.0 and on a calibrated computer system. However, most PC based systems are calibrated to gamma=2.2 to compromise for displaying images on uncalibrated PCs and Macs. Usually, errors introduced by gamma=2.2 are not huge).
4. Saving images with embedded ICC color profiles.
5. Applying color calibration to images by means of an output device ICC color profile.
6. Outputting image (printing, writing to film, etc.)

Let's now have a closer look at particular steps.
Step 1. Many input devices' characteristics are not linear. To correct for this and to calibrate the white point, ICC color profiles shall be created for each capture device. Some manufacturers include color profiles with their devices. We have to be aware, however, that profiles used with digital cameras and scanning backs depend on the light used during the image capture. Ideally, every user should create color profiles for each such device for all light sources that will be used during digitization.

Step 2. If a color profile has been written into the image by the capturing device, the image can be saved for archival purposes. If not, then a profile (specifically created for the capturing device) has to be applied to the image. Applications like Adobe Photoshop allow to convert a non-profiled image, providing that we have an ICC profile for the capturing device (after opening an image, go to IMAGE > MODE > PROFILE TO PROFILE and select relevant ICC profiles conversion – FROM: input device profile that you created, TO: your system display profile).

Step 3. Ideally, editing should be done in gamma space 1.0. Only in gamma 1.0 applying filters, using curves or levels will introduce a minimum of errors. Unfortunately, most systems are calibrated to either gamma 2.2 (PCs) or 1.72 (Macs). If you choose to calibrate your system to gamma 1.0 you will find it difficult to work with some applications. It is especially annoying if you use the computer to access the Internet. The images will appear lighter than normal and flat. If your system is calibrated to a gamma other than 1.0, errors introduced during image manipulation may not be huge, but they may be visible especially in shadows. (See the paragraph on Linearity and Gamma).

Step 4. After editing images they should be saved with the embedded ICC color profiles. Photoshop does it by default. It will allow to open images correctly on systems that do not have the profile for the input device. At this step images should be written to a media for archival storage purposes.

Step 5. If we want to output images than another profile conversion is needed. This time we convert the image FROM: your system display profile TO: output device profile.

Step 6. Outputting the image.

Preservation issues
Unfortunately, it is very difficult to find anything on this topic. It seems that preservation practitioners still did not make up their minds about color profiles - same as about most other aspects of digital imaging. ICC profiles, however, are becoming de-facto standards and there is a good chance that they will be recognised and supported by future systems. In the worst case scenario they will be ignored. As they are being written into header tags (in TIFF files), they do not corrupt the image data. Colin Webb, Director of Preservation Services Branch in the National Library of Australia told me that to his knowledge, no one so far discussed those problems in detail from an archival point of view.
The following file formats support ICC color profiles:
TIFF, PhotoCD, PNG, JPEG, EPS, PCT, PDF, PSD.

Acknowledgment

I would like to thank Timo Autiokari (www.aim-dtp.net/aim) for his excellent ideas on practical digital imaging, some of which were used here.

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