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The Consideration of Camera Testing for Accurate Color Reproduction Within Museums and Institutions

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The Consideration of Camera Testing for Accurate Color Reproduction Within Museums and Institutions

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Abstract

The need for color accurate digital images for fine art reproduction is a reality faced by art museums and institutions around the world. It is the goal of most institutions to replace old, sometimes used and abused, transparency archives with digital image archives; many institutions have already begun this work. A number of different imaging systems with varied workflows, some idiosyncratic, are being used for this work. There is, therefore, an urgent need for the development and sharing of working methods that will ensure efficient, consistent, and color accurate results. These workflows must use camera systems to their fullest capability. It seems clear, then, that a complete understanding of the quality metrics used to assess currently available camera systems is the necessary first step in the development of newly suggested workflows.

The goal of this research project was to consider all of the steps necessary for photographers to create color accurate images of fine art for both archiving and reproduction purposes, and to introduce camera testing as the new starting point for digital imaging workflows. Introducing camera testing as part of imaging workflows will assist photographers with their imaging endeavors by enabling them to understand what quality metrics should be considered when working with digital imaging systems.

This research was restricted to the currently available colorimetric imaging equipment because most professionals within the industry use these types of imaging

devices. One of the main concerns with most digital cameras is that their "spectral sensitivities are not linear transformations of an average human visual system's spectral sensitivities. This is the underlying reason why color inaccuracies exist in digital images" (Smoyer, Taplin, Berns, 2005, p. 4). This research has been focused on the most affective and efficient ways for museum photographers to accommodate for this inaccuracy.

This research began by considering a group of camera tests previously introduced to museums and institutions during a research project entitled *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs*. The goal of this research was to consider all of the tests that were introduced, and to narrow the testing criteria down to four or five tests. This was completed and the key finding suggest that traditional photographic quality metrics remain the most important parameters to test for, in order to ensure high quality photographic reproductions. Thus, the key findings of this research recommend that tone reproduction, spatial frequency response, image noise, and color reproduction accuracy be tested for as the first step in a fine art reproduction imaging workflow.

Also considered within this research were the influential variables that play a part in digital imaging workflows within museums and institutions. These have been outlined and taken into consideration during the selection of the recommended camera tests. It is the feeling of the researcher that introducing camera testing to photographers will help them to understand the equipment, technology, and workflow parameters with which they work, and that this type of quality characterization is needed and very valuable.

Chapter 1

Introduction and Statement of the Problem

Statement of the Problem

Digital imaging technologies have taken a stronghold within museums and institutions, replacing some or all traditional photographic procedures. This shift in technologies has created a need for photographers to adjust to and to re-educate themselves in order to implement these new technologies. Although digital imaging technologies offer a wide range of benefits, often the necessary workflows are not fully understood; therefore, the benefits are not fully realized. A recent survey conducted by Rochester Institute of Technology (RIT) scholars points out that "more than half of the respondents report a perceived lack of knowledge about digital, however a majority feels comfortable with their institutions embracing digital photography" (Berns, Frey, Rosen, Smoyer, and Taplin, 2005, p. 1).

The results from this survey also point out that the top three reasons for digital imaging within museums and institutions are "to make collections accessible over the Internet, to include digital images in a collection management system, and to produce reproductions" (Berns, Frey, Rosen, Smoyer, & Taplin, 2005, p. 1). This is a major concern because, if imaging departments within museums and institutions are creating digital images of their collections mainly for purposes that do not require archival quality,

then time, money, and man-hours are being lost. When an artifact is imaged, it should be done in order to achieve the best possible representation of the piece. This can allow for image repurposing for future needs, such as the Internet, databases, and reproduction. But if the goal when imaging is the Internet, databases, or reproduction, then it is likely that the quality of the archival image will be compromised in order to fulfill an immediate goal (Berns, Frey, Rosen, Smoyer, & Taplin, 2005).

Background and Significance

RIT scholars recently conducted a research project funded by the Mellon Foundation, entitled *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs.* This research project was carried out in an effort to document, to evaluate, and to understand the current practices of imaging departments within museums all over the United States.

One of the main components of this project was a survey which was available online for a year. Participants from more than 50 museums filled out the 78-question survey; the results established a clear understanding of the current issues faced by museum photographers.

The researchers conducting this project also completed an in-depth investigation into four museums that had adopted a digital workflow early on, allowing them significant time to establish their workflow. The same two paintings were imaged at each venue, using their respective workflows.

The results of the four varying workflows and the information gained from the survey project were presented at a conference at RIT in September of 2004. All who participated were invited to attend the conference to discuss digital imaging workflows and the available equipment, as well as to define future needs (Berns, Frey, Rosen, Smoyer, & Taplin, 2005).

The information gained from both the survey and the varying results of the in-depth look at four different imaging workflows provides a clear picture of the idiosyncrasies which have a large effect on the imaging practices at various museums and institutions. One of the key findings of the research suggests that "it is possible to develop a single experiential procedure to evaluate color and spatial quality" (Berns, Frey, Rosen, Smoyer, & Taplin, 2005, p. 2). This implies that if the cameras being used within museums could be assessed for quality purposes, it would then be possible to construct a workflow based on a concise knowledge of the cameras' performance. Specifically, if a camera is tested for color reproduction capability by analyzing the spectral sensitivity of the camera's imaging device, this will create a starting point for anticipated deviation from the standard observer. This is the first discrepancy in the color reproduction process; when the deviation is known, a workflow can be constructed, or adjusted to account for the deviation.

Another key finding of the research is "there is not a common workflow among the tested institutions" (Berns, Frey, Rosen, Smoyer, & Taplin, 2005, p. 2). It would be beneficial if a suggested workflow was in place to assist photographers with "how to" information about making the best quality digital images, one that was not so complicated

as requiring numerous and often complex equipment testing. If simple testing could access the condition of the imaging equipment, a workflow could be constructed and implemented to provide and to enable greater quality and consistency in the images created. This would allow for consistent images for archival purposes, for easy sharing of digital files, and for repurposing of images as needed.

Reasons for Interest

Personal interest in the topic of fine art reproduction stems from the researcher's first-hand experience as a photographer working in a museum. Employed at the Wadsworth Atheneum Museum of Art, Hartford, CT, the researcher experienced the trials and tribulations of assisting in the creation and initiation of a digital imaging department. The department was originally funded with the intention of producing fine art reproductions and catalogues. However, once research had been conducted and the equipment had been purchased, it was apparent to the photographers that reproduction was not the sole purpose of the imaging department. The researcher worked with photographer Allen Phillips; together they began digitally imaging paintings with archival goals. (A description of the entire workflow can be found in Appendix A.) Each image created could be repurposed for different applications, such as catalogues, brochures, advertisements, the Internet, and so on.

The experiences at the Wadsworth Atheneum Museum of Art lead the researcher to investigate the topic of digital imaging within museums. Having received a BFA in photography at RIT in 2000, and having knowledge of the type of research that takes

place at RIT, the researcher came across the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* research project on the RIT website. This project brought together a community of photographers from museums around the country to address issues concerning digital imaging practices within museums. The reports from this project provide a significant amount of information about the current state of digital imaging within museums, enabling the researcher to continue the investigation with support from the digital imaging community at RIT.

The researcher would also like to highlight the driving factors of imaging projects within museums and institutions. Imaging departments often suffer from small budgets, and have to make do with the imaging equipment they have. "Many systems use components re-purposed for this specific application. As a consequence, there is a wide range of quality of these various image archives" (Berns, Frey, Rosen, Smoyer, & Taplin, 2005, p. 1). Not only may imaging departments be restricted by a small budget, but they may also be required to work quickly, imaging certain items at specific times in specific locations. In addition, they must often cater to the specific needs of curators or marketing personnel. All of these factors and many more can influence the quality of the produced digital images. Thus, the researcher has a desire to assist imaging departments within museums to make the most out of the equipment they have, to help them assess what equipment they may actually need, and to illustrate the procedure of creating archival images which can be repurposed for multiple applications.

Chapter 2

Literature Review

Digital Imaging within the Museum Environment

Photography is used within museums for the purpose of reproducing artwork. Until recently this type of photography was primarily traditional in process, using a view camera, 4 x 5 color positive film, and traditional processing. The most common images created were 4 x 5 color transparencies, which could be used for reproduction, as well as to provide a reference for reproduction matching. Over time, museum photographers and printers became very accustomed to this traditional workflow. However, with the advent of digital photography and the implementation of this technology within the photography industry as a whole, it is now imperative that museum photography follows suit.

The migration from traditional photography to digital photography within museums should begin with a well thought-out, long-term plan which focuses on the creation and maintenance of a digital image archive. A transition to digital imaging requires new equipment, technically skilled photographers, collections management personnel, and a database for storing digital images, metadata, and object information. Funding allocated for the upkeep and maintenance of an archive of digital images is also essential. Although these requirements seem clear, they are often not the most prevalent factors considered when deciding on the implementation of a digital imaging innovative

(Kenney, Rieger, 2000). Abby Smith, Director of Programs of the Council on Library and Information Resources, states "most digital projects are driven at least in part by strategic institutional considerations that often conflict with the well-ordered and narrowly confined parameters of an ideal digital conversion project" (Kenney, Rieger, 2000, p. 2).

The digital age and the Internet have changed the way people acquire all types of information. This change is seen as a driving force behind digitizing collections in order to provide a secure Internet presence for museums or institutions. "Cultural institutions are investing in digitization for two reasons: First, they remain convinced of the continuing value of such resources for learning, teaching, research, scholarship, documentation, and public accountability. Second, they recognize that changing user behavior may jeopardize these resources and their stewardship" (Kenney, Rieger, 2000, p. 1). The trend in digital imaging is being driven by the demand for digitally accessible information via the Internet. This is beneficial to a museum or institution, as well as to the user, because by making collections available over the Internet, images of art and artifacts can be viewed from anywhere in the world. This increased access is one of the most valuable aspects of digital imaging projects. Digital access decreases physical access, which can be favorable to an artifact, as well as favorable for the researcher who will save time and money by not having to travel to the location of the artifact (Kenney, Rieger, 2000).

Digital image archives are now being viewed as institutional assets, and this trend has a significant impact on the value of the digitizing initiative. It is apparent that images created can be repurposed for multiple uses only if high image quality is a priority at the

time of conception. The development and maintenance of an efficient digital imaging system relies on the decisions made at each stage of the imaging process. These decisions affect the usage of the images now and in the future. In their book, *Moving Theory into Practice,* Kenny and Rieger (2000) present a management wheel for digital imaging programs. (See Figure 1.)

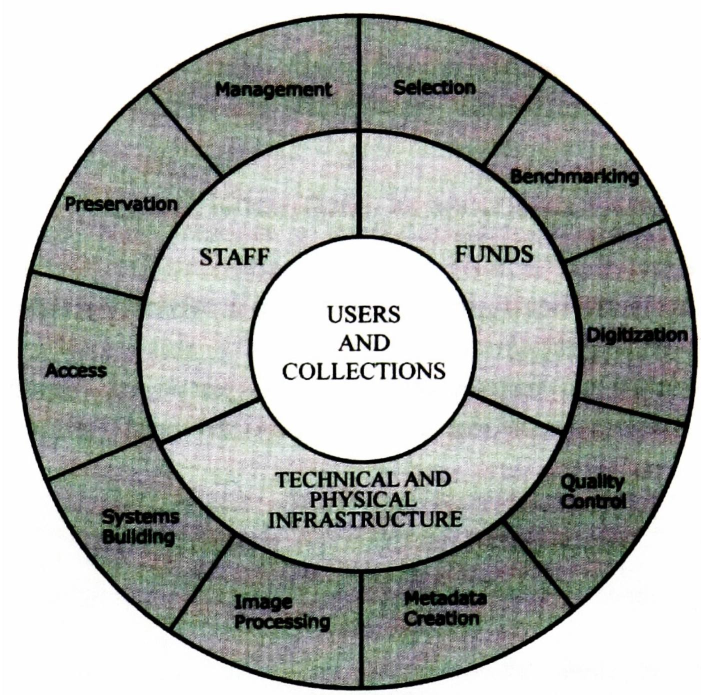

Figure 1. Management wheel for digital imaging projects.
[Source: Kenney, Rieger, 2000, p. 6]

This wheel illustrates all of the elements of a digital imaging project. At the center of the wheel are users and collections. The middle ring represents the institutional resources made up of the staff, funding and the infrastructure, both technical and physical. The outermost ring of the management wheel is made up of all the aspects of a

digital imaging program, including preservation, access, systems building, image processing, metadata creation, quality control, digitization, benchmarking, selection, and management. It is suggested that the institutional resource elements within the middle ring of the management wheel "will enhance or constrain digitization programs" (Kenney, Rieger, 2000, p. 6). However, it is imperative that all aspects of the management wheel are considered at the time of initiation and are maintained for the future in order to provide an efficient digital archival system capable of serving users for years to come (Kenney, Rieger, 2000).

RIT Benchmarking Conference Key Findings

The RIT-based research project, *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s, establishes the current status of digital imaging projects within American museums. Principle investigators Roy Berns and Franziska Frey, along with researchers Mitchell Rosen, Erin Smoyer, and Lawrence Taplin, completed (July 2005) two years of work investigating the topic. The key findings of the project are listed in Table 1 (Berns & Frey, 2005, p.1).

Table 1. The Benchmarking American Museum Project key findings.

Key Findings
Imaging will be mainly digital in the near future.
Museum imaging was output driven (e.g., printed publications and the Internet).
Library and archive imaging was focused on creating semantic-based image archives.
Selection criteria for camera systems were determined primarily by subjective criteria, word of mouth, and technical support rather than objective measures.
It was possible to develop a single experimental procedure to evaluate the objective quality of a camera system.
The ideal photographer has 10-15 years experience photographing cultural heritage and in-depth knowledge in information technology and art history.
Workflows varied widely.
Procedures and workflows are not well documented.
Color management was not used to its fullest capabilities.
Differences in lighting were one of the main factors leading to aesthetic differences in archives.
Aesthetics were often deemed more important than scientific rigor and reproducibility when imaging.
Most institutions included visual editing in their workflows, adding significantly to the total time required from setup to archiving a digital master.
There was not a well-defined digital master that would enable cross-media publishing and that could also be used in scientific imaging.
Digital preservation is still in its infancy.

Each of the key findings listed illustrates the need for guidance and supports the concerns associated with digital imaging projects within the museum environment. For example, the key finding that output, either on the Internet or in publication format, is the driving force behind digital imaging initiatives is a great concern, because if resources are allocated and utilized for the creation of a digital image, then it is most beneficial if the image be of archival quality. The other finding related to this is "there was not a well-defined digital master that would enable cross-media publishing and that could also be used in scientific imaging" (Berns & Frey, 2005, p.1). Although the research indicates that the digital master file is not well-defined, the importance of creating this type of file

has been a consideration for some time now. Kenney & Rieger (2000) give this example: "there is a growing support for creating digital masters that are rich enough to be useful over time and cost effective. This position presumes that conversion standards are set higher than the immediate requirements" (p. 25). The discussion of the creation of digital master files leads to considerations about equipment evaluation, characterization, and workflow guidelines.

The findings from *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* indicate that the transition from analog to digital photography is well underway. "Over half of the survey respondents took at least 90% of their photographs digitally in 2003...[which] was all happening despite a perceived lack of knowledge about digital imaging by the practitioners" (Berns & Frey, 2005, p. 55).

There is also a wide range of imaging workflows among museum photographers, not many of which have been documented. The findings also suggest that there is little structure to the evaluation of digital imaging equipment prior to purchase (Berns & Frey, 2005). This suggests that the evaluation of a cameras imaging quality is overlooked when purchasing decisions are taking place. Although "procedures for testing the quality of digital cameras have been established in the recent past" (Smoyer, Taplin, & Berns, 2005, p. 1), they have yet to be implemented into the mainstream museum environment. This is because the tests "are not yet suitable and comprehensive enough to be used in a museum setting and have not been developed specifically for the direct digital capture of artwork" (Smoyer, Taplin, Berns, 2005, p. 1). However, now that professionals are becoming more

aware of the possibility of camera testing, perhaps individual camera image quality will now be considered when purchasing decisions are being made.

The key findings from the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* project also indicate that most of museums surveyed have not fulfilled benchmarking procedures to the fullest capacity.

What exactly does benchmarking mean? Kenney & Rieger (2000) state that "benchmarking is primarily a management tool, designed to lead to informed decision making about a range of choices and an understanding of the consequences of such decisions" (p.24). Considering the findings of *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs*, it is clear that the implementation of benchmarking procedures does not always happen at the beginning of the transition from analog to digital photography; however, it would be beneficial if it did.

Benchmarking procedures can assist a management team in defining the terms of its project. According to Anne R. Kenney in *Moving Theory into Practice*, the categories to consider when benchmarking are: requirements definition, measurement, tolerance values and verification. Requirements definition consists of assessing "source documents and identifying the variables associated with quality, cost, and/or performance" (Kenney & Rieger, 2000, p. 24). The measurements category consists of gathering and documenting data, objectively characterizing material, and determining the variable interrelationships. "Measurements include document attributes such as detail size and

tonal range, scanning requirements (resolution, bit-depth), and the corresponding imaging metrics (MTF and signal-to-noise ratio)" (Kenney& Rieger, 2000, p. 24). The tolerance values category recommends to "determine how much variance" will be tolerated throughout the workflow, as well as for different quality requirements for different image usages (Kenney & Rieger, 2000, p. 24). The verification category of benchmarking requires approval and modification to the benchmarked procedures through testing and procedure evaluation (Kenney & Rieger, 2000).

Benchmarking procedures can "reduce both experimentation and the temptation to overstate or understate requirements" (Kenney & Rieger, 2000, p. 24). The development of benchmarked procedures, such as camera testing and workflow documentation for a digital imaging project, allows for a consistent and controlled workflow that may be adjusted to ensure high image quality.

RIT Benchmarking Conference Defining Current Needs

The outcome of the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s project is an assessment of the current practices of digital imaging within museums and suggestions for the future. The suggestions for future research and development are listed in Table 2 (Berns & Frey, 2005, p.2).

Table 2. The Benchmarking American Museum Project suggested future research.

Suggested Future Research
Establish a user group devoted to imaging, archiving, and reproducing cultural heritage.
Hold periodic informal conferences for information gathering and sharing.
Develop a practical characterization test method.
Incorporate characterization data into a metadata structure.
Develop and test a system calibration protocol.
Define quality criteria based on objective and subjective metrics.
Establish a testing service.
Establish an informal imaging inter-comparison.
Research and develop new imaging systems.

The need for camera testing procedures is a recurrent theme among the findings. To "develop a practical characterization test method...and to establish a testing service" are listed as areas for suggested future research (Berns & Frey, 2005, p.2). Part of this project was an in-depth look at four different imaging workflows, along with objective characterization of the four camera systems. The tests used to characterize the cameras for each workflow were complex. The goal is to be able to "consolidate the characterization procedure by reducing the number of targets that must be imaged" (Berns & Frey, 2005, p. 59). Target consolidation is needed because some of the targets used proved redundant, and often the targets were created for cameras of lesser quality.

The targets are not specific to digital imaging within museums, and they are not optimized for this type of characterization. Therefore, it is proposed that testing procedures and targets be created specifically for digital imaging workflows within museums.

A concern also regarding the current camera testing procedures is the complexity of the data processing. It is desirable to create "an application to guide a novice user through the testing procedure…[including] instructions for capture of the test images and automatic processing of the images data…[as well as a] metric report" (Berns & Frey, 2005, p. 59). The establishment of a testing service that could provide a metrics report is also desirable because it could serve as "an important tool for industry to gauge their measurement quality compared with each other and with standard instrumentation" (Berns & Frey, 2005, p. 61). A testing service could also serve as a catalyst for improving imaging technology by allowing photographers to communicate their needs.

Also listed for future research is the development and testing of "a system calibration protocol," as well as the incorporation of "characterization data into a metadata structure," both of which are examples of benchmarking procedures (Berns & Frey, 2005, p.2). The development of a system calibration protocol will require a set of standard conditions for each component of an imaging system. These components include "lighting, camera setup (exposure time, dynamic range, depth of field, magnification, etc.), color management, file format and encoding, metadata, and workflow" (Berns & Frey, 2005, p.60).

Once a system calibration protocol has been established, the respective imaging system can be adjusted to the protocol, resulting in an image archive that conforms to the standard conditions. A system calibration protocol would allow standardization of imaging procedures, allowing for multiple image archives created under the same imaging conditions, regardless of where the imaging took place. This would reduce image appearance discrepancies and allow for easy sharing of archives.

However, whether or not an imaging system has been calibrated to a set standard, the imaging procedures within a given system are important to document. The imaging procedure is referred to as the system's characterization. The characterization of any imaging system is like the system's fingerprint. "Characterization data can be also be used to determine a system's repeatability and reproducibility" (Berns & Frey, 2005, p. 60). If characterization data is stored with an image's metadata, it is then possible to know under what conditions the image was created. "Including the characterization data in an image's metadata structure ensures that an image will not be separated from the imaging system characteristics" (Berns & Frey, 2005, p. 60), thus allowing for the repeatability and reproducibility of a specific image with the specific imaging system characteristics.

The *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s research project has established a clear assessment of the current status and the current needs of the digital imaging environment within in museums in the United States. It has provided an excellent foundation for the continuation of the investigation and has established a community of interested parties

eager to communicate the needs of photographers within this industry. This research serves as a catalyst for change, encouraging the progression of imaging technologies, imaging procedures, and community commitment.

Color Reproduction

Introduction

The discussion of digital imaging requires a review of color management theory. In order to utilize color management theory to the fullest, it is helpful to understand color reproduction, how it developed, and what it is based on. It is first helpful to realize that "color is a property of light" (Fraser, Murphy, & Bunting, 2005, p. 5). Without light, there is no visible color. The next consideration is that, in order to experience the event of seeing color, there must be an observer, a light source, and an object or scene. "The color event is a sensation evoked in the observer by the wavelengths of light produced by the light source and modified by the object; if any of these three things changes, the color event is different...we see a different color" (Fraser, Murphy, & Bunting, 2005, p. 5).

The Visual Spectrum

Light is one on the main components to the visual color experience. Without light, there is no color to be seen. "But all light isn't created equal: the characteristics of the light have a profound effect on our experience of color" (Fraser, Murphy, & Bunting, 2005, p. 6). Light energy is classified as photons. A photon is "a fundamental packet of electromagnetic energy traveling through space. In some ways, photons behave like

particles, and in other ways photons behave like waves" (Fraser, Murphy, & Bunting, 2005, p. 548). Each photon exists with a specific energy level, which does not affect the speed at which it travels (since the speed of light is constant); rather, the energy level determines how fast the photon pulsates. The higher the energy level the photon has, the shorter the wavelength at which the photon pulsates. "The spectrum refers to the full range of energy levels (wavelengths) that photons have as they travel through space and time" (Fraser, Murphy, & Bunting, 2005, p. 7). The visual spectrum refers to the part of the spectrum to which the human eye is sensitive. The visual spectrum ranges from approximately 380 to 700 nanometers (nm) (Fraser, Murphy, & Bunting, 2005). Figure 2 illustrates the visual spectrum.

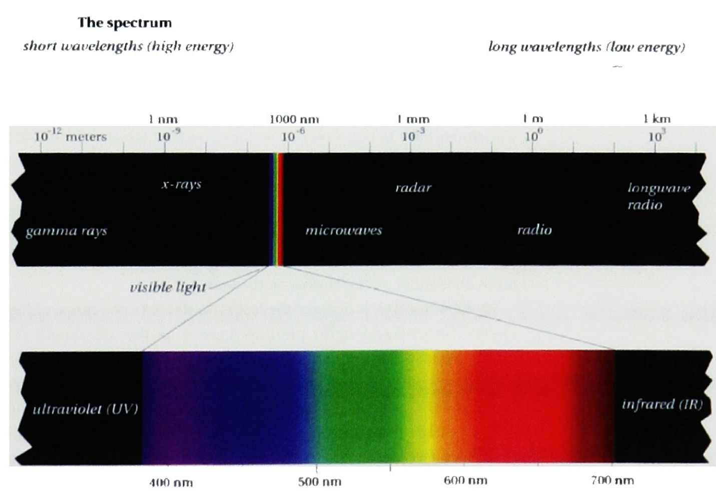

Figure 2. The visual spectrum.
[Source: Fraser, Murphy, & Bunting, 2005, p. 7]

The human eye has varying responses to the different wavelengths within the visual spectrum. For example, the long wavelengths (700 nm) evoke warm colors (such

as red and orange), and the short wavelengths (400 nm) evoke cool colors (such as blue and violet.) The visual spectrum ranges from red to orange to yellow to green to blue, and finally, to violet. There are also wavelengths just outside the visual spectrum which can indirectly affect human vision. For example, when fluorescent agents are present in objects such as paper or laundry detergent (in clothing once washed), these agents will absorb non-visible photons in the ultra violet (UV) region of the electrometric spectrum and emit visible photons, causing the phenomenon referred to as fluorescence, creating a brighter appearance. Infrared (IR) photons are also concerns for digital imaging devices. Most digital imaging devices are highly sensitive to infrared and, therefore, must contain an infrared filter to absorb non-visible IR photons prior to them entering the imaging device (Fraser, Murphy, & Bunting, 2005). Understanding the visual spectrum of light is an important aspect of understanding color management, as well as understanding the human visual system.

The Human Visual System

Color management in the digital age stems from color science and from color appearance models. An understanding of the human eye and how color is received and interpreted by the brain is essential to understanding all aspects of color reproduction. "The sensation of color is caused by electromagnetic radiation of various frequencies being received by the cones in the retina" (Rajala, 1995, p. 1). The retina, located in the back of the human eye, is made up of a thin layer of photoreceptor cells referred to as rods and cones. The rods and cones of the retina "serve to transduce the information

present in the optical image into chemical and electrical signals that can be transmitted to the later stages of the visual system" (Fairchild, 2005, p. 4). Next, the signals are "processed by a network of cells and transmitted to the brain through the optical nerve" (Fairchild, 2005, p. 4). This is how the human eye and brain work together to create the experience of seeing.

The photoreceptor cells in the retina, the rods and cones, serve different visual functions. The rods allow for vision at low luminance levels, and the cones allow for vision at high luminance levels. Rods and cones can function separately or together, depending on the luminance conditions. The visual color experience is dependent on the cones within the retina.

There are three types of cones and only one type of rod, making the rods unable to aid the color vision experience. The three types of cones within the retina allowing for color vision are known as L, M, and S cones. These names are used to describe the sensitivity function of the cones, respectively, long-wavelength, middle-wavelength, and short-wavelength (sometimes referred to as RGB, red, green and blue). It is important to note the relative distribution of the L, M, and S cones throughout the retina. "The relative population of the L:M:S cones are approximately 12:6:1 (with reasonable estimates as high as 40:20:1)" (Fairchild, 2005, p. 10). This cone distribution requires extra consideration when addressing issues of visual response. That being stated, it is these L, M, and S cones within the human retina that allow for human color vision, and they also form the basis for trichromatic color reproduction.

Trichromatic Color Reproduction

"The retina contains three types of cones which filter the incoming electromagnetic radiation forming the basis for the three color primary systems used in television, printing and photography. That is, any color can be reproduced by combining different amounts of red, green and blue primaries" (Rajala, 1995, p. 1) Although any color can be visually created by combining varying amounts of the primary colors, reproducing any color is technically not so simple.

The investigation of trichromatic color began in the 1700s. In 1722, Jakob Christoffel LeBlon is credited with printing using a three-color technique. In 1807, "Thomas Young was instrumental in gaining general acceptance for the view that it is the retina of the human eye that is responsible for this triple feature of color" (Hunt, 2004, p. 9).

In 1861, James Clark Maxwell created the first color photograph using a trichromatic technique. It is Maxwell's work which has had a lasting effect on the trichromatic color process. Maxwell created a color photograph by capturing the same scene through a red, green, and blue filter, and from the negatives he created three positive slides. He placed each of the three positive slides into separate projectors, with respective red, green, and blue filters with which the image was projected through, and at last, a full color reproduction of the photograph was created. "The principle of his (Maxwell's) method, reproduction of all colors by mixtures, in varying amounts, of beams of red, green, and blue light, is retained almost universally; and with modern

resources the method itself (triple projection) can produce results of very high quality" Hunt 2004, p. 9).

Trichromatic Limitations

Although trichromatic color reproduction is successful at reproducing most colors, it has some limitations which prevent it from being able to colorimetrically reproduce all colors. The spectral response curves of the L, M, and S cones within the human retina must be determined first in order to address color reproduction (Hunt, 2004). Both methods of direct measurement and indirect measurement of "the light reflected back through the pupil of the eye, have given similar results" (Hunt 2004, p.11), as can be seen in Figure 3.

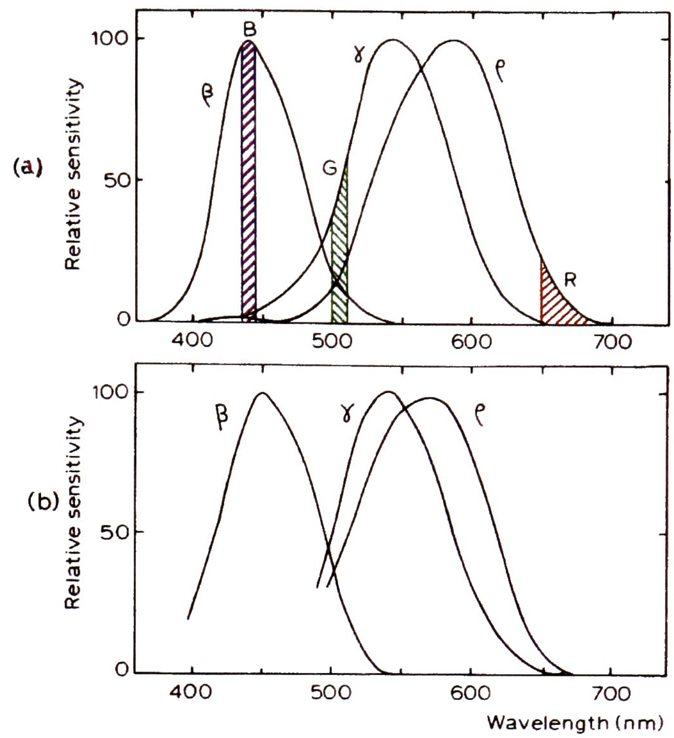

Figure 3. (a) The probable sensitivity curves for the three types of cones, with the three best R, G, and B, lights for additive color reproduction. (b) Typical spectral sensitivity curves found from bleaching experiments with the human retina. [Source: Hunt 2004, p. 12]

It is clear from figure 3 that the sensitivity curves of the three cone types within the retina overlap considerably; there is also a debate about the location of the curve peaks. Some suggest the curves L, M, and S peak at 440 nm, 530 nm, and 565 nm, respectively, while others indicate the peaks are at 440, 545, and 580 nm. The overlapping of the sensitivity curves of the three cone types within the retina causes the most concern. The usefulness of the sensitivity curves of the three cone types is the ability to transmit luminance information at the same wavelength (using suitable filters to do so) in order to create a trichromatic reproduction. However, because there is no area of

the spectrum with which the M cones are solely sensitive to, "no filter can be found to transmit light that stimulates the" M cones only Hunt 2004, p. 13). To account for this, one must select "a filter that transmits a narrow band of light in the green part of the spectrum at a wavelength of about 510 nm as shown as the G in...[Figure 3]...while the bands of light passed by the red and blue filters are those marked R and B" (Hunt, 2004, p. 13).

Hunt (2004) further states,

> ...[it] is thus clear that the inability of any beams of red, green, and blue light to stimulate the retinal cones separately introduces a basic complication into the whole of trichromatic color reproduction. If the p and b (L and S) curves did not overlap in the blue-green part of the spectrum, then green light could be found that stimulated the y-cones (M cones) on their own; but, since the p and b (L and S) curves do overlap appreciably, the y-cones (M cones) cannot be simulated on their own. For color vision, this overlapping provides the basis for good detection of changes in hue throughout the spectrum. But, for color reproduction, it means that simple trichromatic methods cannot achieve correct color reproduction for all colors. The difficulty cannot be avoided, because it stems from the basic nature of human color vision; the result is unwanted stimulations in reproduction systems (p. 13).

The CIE Standard Observer

The International Commission on Illumination (CIE) is a well-established, internationally recognized organization dedicated to the study and progression of color management systems. To continue the discussion of trichromatic color reproduction limitations, consider the CIE 2° standard observer. Due to the varying color vision between individuals, "the CIE has come up with the concept of the standard observer" (Sharma, 2004a, p. 83). "The CIE has specified three primary colors and conducted experiments to work out how much of each of the primaries are needed to match colors in

the spectrum" (Sharma, 2004a, p. 83). The results of these studies were published in 1931, and they are referred to as the Color Matching Functions (Sharma, 2004a). Figure 4 is a representation of the standard observer color matching function curves.

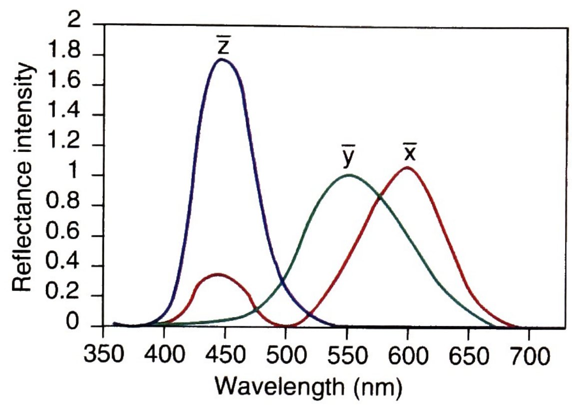

Figure 4. Color matching functions of the CIE 2° standard observer.
[Source: Sharma, 2004a, p. 84]

The CIE's 1931 2° standard observer color matching function provides the spectral reflectance curves, as well as a mathematical representation of the average human's color vision at a 2° viewing angle. The 2° angle describes the viewing angle at the eye when the viewer is looking at an object 18 inches, or at a normal viewing distance (Sharma, 2004a). "This observer receives tristimulus values CIE XYZ from a spectral stimulus φ_λ according to where x(λ), y(λ), and z(λ) denote the standard spectral matching functions and k is determined from the normalization of Y = 1 for the spectral stimulus of the illuminant" (Hill, 2002, p. 1). However, due to the phenomena known as metamerism, "different spectral stimuli φ_λ may result in the same XYZ values," causing colors to

appear the same under one illuminant and different under another (Hill, 2002, p.1). This can be both beneficial and problematic -- beneficial because it allows for color matching across a wide range of media, but problematic because "each image capturing device exhibits its own device metamerism. Color stimuli being metameric to the standard observer are no longer metameric for the image capturing device, and there are device metameric colors looking different to an observer" (Hill, 2002, p. 2). Metamerism considered, it is the goal of imaging devices to mimic the standard observer's trichromatic color vision using three channels to mimic the spectral response of the human eye. However, because the L and S cone responses overlap considerably, Hill (2002) states that cameras

> ...would run into severe problems of electronic noise when separating technical color signals like sRGB to control output devices...This is because noise components always add up even if tristimulus values are subtracted. But correct color analysis can also be realized by three technical sensors with spectral responsivities derived from any linear transform of the color matching functions. This allows optimized separation of spectral responsivities of camera channels and scanners with respect to best electronic signal-to-noise ratio. However, again a draw back comes in due to the fact that responsivities optimized in this way exhibit negative parts like all color matching functions corresponding to realizable primary colors do. Since a high signal-to-noise ratio is the more important feature in image capturing, all present cameras and scanners use an approximation to the positive parts of these curves only. As a result, there occur inevitable errors of color analysis in all our present systems (p. 2). [See Figure 5.]

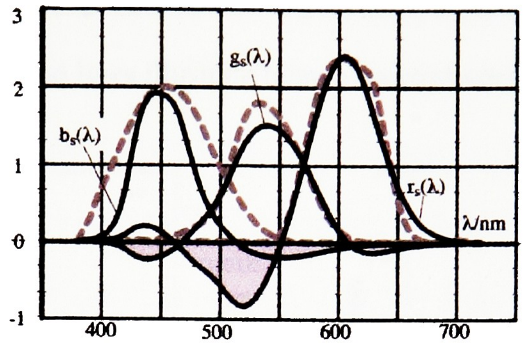

Figure 5. Example of negative color matching functions, aiding to color reproduction inaccuracies. [Source: Hill, 2002, p.5]

The Color Reproduction Inaccuracy Reality

For accurate color reproduction using a digital camera, it is ideal if the digital camera's spectral sensitivities match the spectral sensitivities of the human visual system. "Strictly, a camera's spectral sensitivities should be a linear transformation of the human visual system's spectral sensitivities. That is, through a linear transformation, the L, M, and S sensitivities are well-estimated. Thus, CIE color-matching functions, which do not resemble L, M, and S sensitivities, meet this criterion" (Berns, 2001, p. 2).

However, most digital cameras do not meet this criterion, and this is the main cause of color inaccuracies within digital images. For example, Figure 6 shows the difference between human spectral sensitivities and a typical scanback camera, the type most often used when photographing artwork. The solid lines are the camera's spectral sensitivities and the dashed lines are human spectral sensitivities. Another example can

be seen in Figure 7; here the spectral sensitivities of a CCD imaging device are illustrated in solid lines, and the dashed lines illustrate human spectral sensitivities.

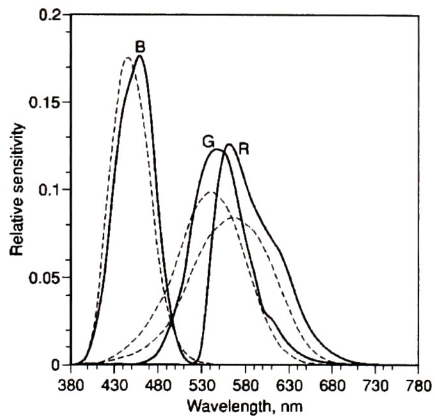

Figure *6:* Spectral sensitivities of a typical scanback camera. [Source: Berns, 2001, p. 4]

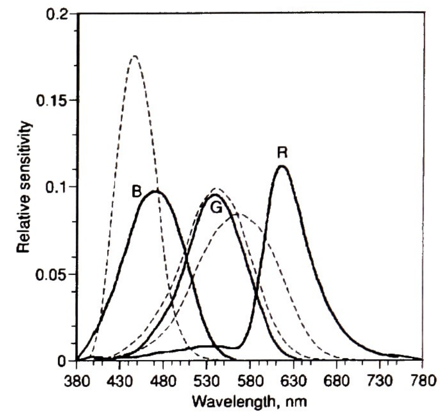

Figure *7:* Spectral sensitivities of a typical CCD camera. [Source: Berns, 2001, p. 7]

It is clear from these curves that there is a large difference in the sensitivities of humans and imaging devices, thus causing a large problem when color accuracy is the goal. It is important to realize that color accuracy is only one of the criteria considered when designing a digital camera. "Low-light sensitivity, image noise, resolution, read-out speed, manufacturing costs, and so on all must be considered. Many of these design criteria are mutually exclusive; the final design is always a compromise" (Berns, 2001, p. 3).

Color Management

Device-Dependent Color

Digital cameras, scanners, and monitors operate in the RGB (red, green, and blue) color space. Printing devices use CMYK (cyan, magenta, yellow, and black) ink to produce prints. The range of colors capable of being produced by each device is referred to as the device gamut. All devices behave differently, whether in the way they acquire color information, represent color information, or reproduce color information (Sharma, Color, 2004). For example, if the same digital image file is printed out with identical RGB values using two different printers, the prints may look different, or when the same image is scanned using two different scanners, the RGB pixel values may be different. "The conclusion to draw from this is that CMYK (and RGB) are basically instructions for a device and do not in themselves tell us what color a pixel will be" (Sharma, 2004a, p. 14). Therefore, each device is dependent on its own gamut and calibration. These differences create the need for color management.

Device-Independent Color

Color management systems are necessary to reproduce accurate color in an all-digital workflow. The questions are how to color manage and by what standards? The CIE has established an internationally recognized standard used for device-independent color identification. "CIE systems form the basis for color management. The LAB system is used in profile generation and is also used in Photoshop. The Yxy system is often used to analyze and compare the color gamut of different devices" (Sharma,

2004a, p.15). CIELAB, officially known as CIE 1976 L*, a*, b*, is the system of numeric color identification that corresponds to a color based on its position in a 3D color space. Figure 8 illustrates the LAB color space. "The coordinate L* stands for lightness, a* represents the position of the color on a red-green axis, and b* represents the position of the color on a yellow-blue axis" (Sharma, 2004a, p. 15). The Yxy color system uses a 2-dimensional graph called the chromaticity diagram to plot the x and y coordinates of a color. CIE color specification systems are reliable measurement systems that incorporate the use of measuring instruments to colorimetrically evaluate color. The CIELAB colorspace is used to create ICC profiles and is also used to calculate Delta E, which is a quantitative way of measuring the difference between colors of a printed reproduction (Sharma, 2003).

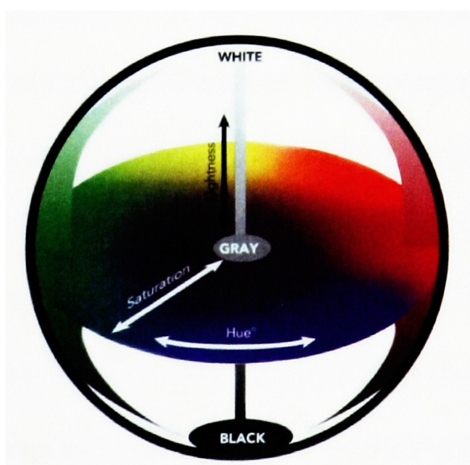

Figure 8. The LAB color space represents lightness, hue, and saturation.
[Source: Sharma, 2004a, p.79]

Color Profiles

Digital devices such as cameras, scanners, monitors, and printers produce color that is device-dependent. This means that the same color may look different, depending on which device reproduces it. The fact that different devices reproduce the same color differently creates a big problem when performing color management. This is the primary reason why color profiles are necessary. Profiles are used to transform device-dependent hardware into device independent color spaces. "Colorspace definitions" (King, n.d., p. 2) are profiles used to transform device-dependent hardware into device-independent color spaces.

The International Color Consortium (ICC) "was established in 1993 for the purpose of creating and promoting the standardization of an open, vendor-neutral, cross-platform system for managing color" (Romano & Riordan, 2003, p. 221). The ICC is an independent organization which was founded by these companies: "Adobe, Agfa, Kodak, Taligent, Microsoft, Sun, and Silicon Graphics...[today] the ICC is open to all companies who work in fields related to color management" (Sharma, 2004a, p. 22). The ICC standardized "colorspace definitions" naming them "profiles" (King, n.d., p 2). ICC color profiles are created using the device-independent CIELAB color space (Sharma, 2003).

Profiles are communication tools allowing for the correct interpretation of color image data, regardless of the type of hardware or software being used. Profiles are created using a combination of software and hardware, such as spectrophotometers and colorimeters, which are used to measure the colors of monitors, or printed targets. The measurements are related back to a known color target, and the measured differences are

accounted for. An ICC profile is created to adjust for the difference between the known target and the device capabilities. Products such as GretagMacbeth's Eye-One profile solution system and X-Rite's Color Master Software can be used to create ICC profiles (Bury, 2004).

Profile Connection Space

ICC color management provides a standard reference space, known as the profile connection space, which is used to transmit profile information (King, n.d.). An all-digital workflow can spread over a wide variety of monitors and printing technologies in different locations. These devices require a reference point so that they can all represent accurate color without having to be connected to one another, as in a closed loop system. The difference between a closed loop and an open loop color management system is the ability for an open loop system to communicate accurate color information to any device operating through the profile connection space. In an open loop workflow, each device is independent, and consistent color using ICC profiles requires communication with the profile connection space. Sharma (2004a) further states that

> ...[every] device must have a profile. Thus, we need a scanner profile for a scanner, a monitor profile for a monitor, and a printer profile for a printer. A golden rule of color management is 'image + profile'...In a typical workflow, images from a scanner may be 'brought into' the profile connection space using the scanner profile. To print the image it would be 'sent out' from the connection space to a printer using a printer profile. Thus, color management operations require a source and a destination profile-we need to know where the image is coming from and where it is going. Another golden rule in color management is 'profile-PCS-profile' (p. 12).

Proofing systems have benefited from color-management systems based on ICC profiling capabilities. For example, "these technologies have allowed inkjet simulations of final press results" (Felici, 2004, p. 7). Figure 9 illustrates how an open loop workflow uses the profile connection space.

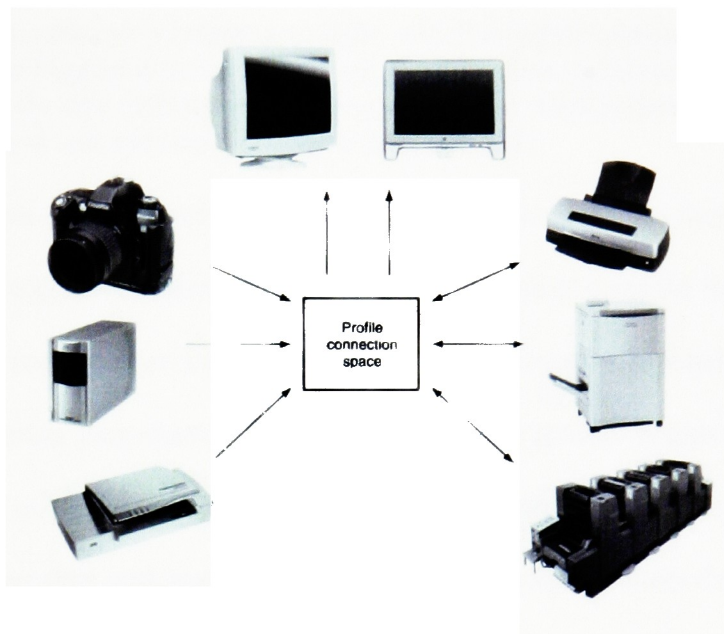

Figure 9. Profile Connection Space as part of an open loop workflow.
[Source: Sharma, 2004a, p. 157]

Photographic Considerations

Film vs. Digital

Imaging technologies have undergone a transformation in recent decades. The biggest change has been the introduction and widespread use of digital imaging

equipment, leading to color management issues, as well as to the need to understand the new challenges presented by this new technology.

Digital image capture varies greatly from film capture. Fraser and Raw (2004) state offer this explanation:

> Film mimics the eye's response to light, which is highly non-linear... Perhaps the biggest difference between shooting film and shooting digital is the way the two different media respond to light. Film responds to light the same way our eyes do, but silicon does not (p.1).

For example, film can suffer reciprocity failure, which "means that the response (density) of a photographic material cannot be predicted solely from the total exposure a film has received (except over a small range of exposure times)" (Stroebel, 1990, p. 121). In other words, during long shutter times, the build-up of exposure begins to block the light illuminating on the film as time passes; this slows down the response time of the film. Thus, a longer than anticipated exposure is required to completely expose the image.

Film not only has a nonlinear response to light, it also comes with an embedded, predetermined tonal curve response. Each different film type has a unique curve, applicable for a desired result. Different films have different qualities for varying reproduction objectives. These differences cause the film to respond differently to the illuminant in terms of both tonal and color response. Film is made to give a pleasing result in response to an average scene. Different types of film may be used when photographing different scenes in order to enhance a specific reproduction objective. There is opportunity to bend and to manipulate film's response (curve) by using filters

during image capture and also through exposure and developing variations (Kodak, 2005).

Digital imaging technology differs from film technology mostly in the digital imaging sensors response to an illuminate. The term "raw" in reference to file type is used in conjunction with digital imaging technologies. A raw digital file is a direct record of the luminance data collected by the digital imaging sensors. Raw files are made of unprocessed linear data that are captured by the imaging sensors, which count the photons reaching the sensor.

Where film has a predetermined embedded tonal curve, raw camera data does not. Typical digital imaging sensors that acquire data in this form are referred to as "mosaic sensors" or "color filter array" cameras. Color filter array cameras have a two-dimensional array that is made up of rows and columns of photosensitive detectors. These detectors are usually made up of CCD (charge-coupled device) or CMOS (complementary metal oxide semiconductor) technology. These are the sensors that count the photons and thus "produce a charge that's directly proportional to the amount of light that strikes them" (Fraser, 2004b, p.1).

The initial data captured by the sensors is in grayscale. Hence, the color filter array is also responsible for creating color images using the grayscale data. This is possible because each element in the color filter array is filtered so that it is only responsive to red, green, or blue light. The color receptive elements are patterned, commonly in a Bayer pattern, so that each sensory captures the respective light for a given photo sensor which corresponds to an image pixel. Through the use of a "decoder

ring," which is stored in the metadata of the file, the grayscale information for each pixel is converted to color information when the file enters the raw converter. Because the photo sensors are spaced in a pattern, the raw converter also relies on the metadata to interpolate the "missing" color information for the respective color by looking to a pixel's nearest neighbor. This process is referred to as demosaicing (Fraser, 2004b).

The Raw Digital Image

When a raw digital file enters into a raw converter and goes through the demosaicing process, it is then ready to be "developed." Developing a raw image file allows for the following image aspects to be selected: white balance, colorimetric interpretation, gamma correction, and noise reduction.

White balance can be set on camera; however, this is simply acquired as information which is added to the file's metadata. When a raw file enters into the raw converter, the converter will either use the white balancing information from the metadata or the converter will determine the white balance itself by analyzing the image. However, white balance can also be selected or adjusted by the operator.

Colorimetric interpretation of a raw file requires the raw converter to assign "specific color meanings to the red, green, and blue pixels, usually in a colorimetrically defined color space such as CIE XYZ" (Fraser, 2004b, p.3).

Gamma correction is the most important aspect of the raw converter, because we rely on this step to be able to "see" a normal looking image. Because digital imaging sensors capture linear data, or linear gamma which is equal to gamma 1.0, a tonal curve

must be applied to it in order to account for the difference in tonal response between raw data and both film and the human eye. "The raw converter applies gamma correction to redistribute the tonal information so that it corresponds more closely to the way our eyes see light and shade" (Fraser, 2004b, p.3). The gamma / tone curve determines the light-to-dark relationship within the visible image, and it can also be adjusted by the operator in an effort to enhance the desired results created through the raw conversion response.

The noise reduction, antialiasing, and sharpening steps help to ensure the image detail that may be compromised through the demosaicing process. Digital raw converters are relatively new to the imaging industry; prior to their introduction, raw conversion most often took place within the camera, before the digital file was downloaded to a computer. The important aspect of off-camera digital raw converters is that they allow for operator input. This is a significant difference between on- and off-camera raw converters. When shooting digital images in either JPEG or TIFF format, conversion from raw linear data to an adjusted visible image takes place within the camera, thus restricting operator input (Fraser, 2004b). However, some digital camera systems (such as the BetterLight) allow for operator control over the raw data in order to attain the desired results prior to the final image scan. Thus, once an image is acquired through the BetterLight camera and software system, it has already been subjected to operator input and has been "developed" (BetterLight, 2001).

Operator Control

In order for photographers to accurately replicate a scene (as closely as possible), it is beneficial for them to have access to the linear data; in this way, they can control the adjustments made to the image during the raw conversion process. It is possible to make adjustments to a digital image, using image-editing programs such as Photoshop, and this is a common practice. However, it should be clear that post-production image adjustments are not required in order to attain a specific result, if the photographer has access to pre-processed linear data.

The adjustment of tone curves has the greatest effect on an appearance of an image. These curves are either embedded within film, embedded within a camera's raw converter, or are more accessible through a digital raw converters that an operator has access to. "Tonal adjustments affect the digital translation tables which convert the CCD's 'raw' luminance data (expressed as EV) into 'finished' brightness data (expressed as RBG units)" (BetterLight, 2001, p. 49). Most often, tonal adjustments are used to change the overall contrast of an image, or to adjust the mid-tone, highlight, or shadow values independently of one another. It is important to be aware of the changes that happen to the appearance of color when changes to the tone curve are made, for example:

> ...when contrast is reduced with a tone curve change, the difference (in data values) between the bright areas and dark areas of an image is reduced, as expected, but this also reduces the difference (in data values) between the dominant colors and secondary colors in every colored (non-neutral) object in the image. Color saturation, which is the difference in brightness between the dominant colors and secondary colors, is therefore also reduced, since the dominant colors are 'bright,' and the secondary colors are 'dark,' and this difference is reduced along with the overall image contrast (BetterLight, 2001, p. 49-50).

Since tonal curve adjustments can have such a significant impact on the color fidelity of a scene, it is only reasonable to expect that scene reproduction methods allow for operator control over the curves applied to the image. Film offers operator manipulation, but not control; however, digital imaging offers both control and manipulation. Therefore, it is expected that an operator would benefit from the digital raw converters available for use today.

The Digital Scanback Camera

The Scanback Camera

The scanback camera is, in principle, similar to flatbed scanners; except that cameras have an optical, on-camera lens system. Digital scanbacks can be used with traditional 4 x 5 cameras; instead of a film holder, the digital back can be placed into the camera, and the photograph is captured with relatively the same procedure as is used in traditional photography. Scanback cameras are well-liked because they can be used to create high quality, high-resolution images. Scanback cameras are referred to as line-by-line scanning devices because the light sensitive CCD array moves along the imaging plane, imaging one line at a time.

> "In the linear *three-line sensor* (trilinear sensor), the three color channels are alongside one another so that the color information for each sensor position is captured simultaneously. Due to the *sequential image scanning*, line scanning cameras require constant lighting conditions" (Kipphan, 2001, p. 521).

Line scanning cameras also tend to be used for still life imaging. Since the CCD array is constantly moving, it would be close to impossible to capture a moving subject. Figure 10 is an illustration of a typical scanback camera color-imaging sensor.

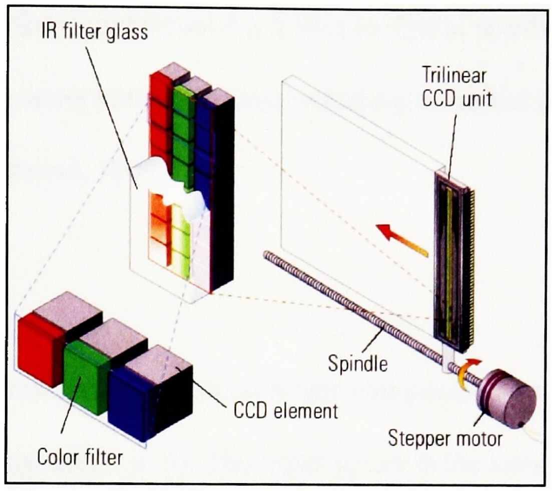

Figure 10. Trilinear color imaging sensor.
[Source: Kipphan, 2001, p. 522]

Scanback Cameras: A Brief History

Scanback cameras have been widely used in the photography industry since the late 1990's. The primary function of these cameras is based on studio photography, and these cameras are now widely used for fine art reproduction, archival imaging projects, and product advertisement. In October of 1999, Shutterbug magazine published an article describing the BetterLight 6000 scanback camera. Author, Jay Abend, describes his first encounter with this camera and endorses the scanback camera for studio photography. Abend discusses the price drop of the scanback cameras, which created greater accessibility for a wider range of photographers. The cost has an impact on the transition

from analog to digital photography. Once the cost of traditional photographic materials for a year outweighed the cost of the scanback, there was no turning back. Abend makes mention to both the BetterLight and Phase One scanback cameras, both of which had dropped significantly in price since they first appeared on the market. The late 1990's was a time of transition from traditional 4 x 5 film to digital scanback cameras. Scanback cameras were becoming more accessible and switching to digital photography was becoming beneficial. (Abend, 1999).

Scanback Technology

All "digital cameras consist of three major components: input optics, sensor, and signal processing" (Berns, 2001, p. 3). The input optics is the same for both digital and traditional cameras. Scanback cameras can be thought of as digital film holders, instead of film a light or photosensitive material is used to record an image. Digital cameras often use a charged-couple device (CCD) sensor to capture and then convert the recorded light energy into an electrical signal. This electrical signal is then converted to a digital signal through signal process (Berns, 2001). The digital signal can then be computed and as a result turned into a digital image file that can be viewed on a computer monitor.

Scanback cameras use CCD imaging sensor technology. These sensors are one-dimensional and are made up of a single row of sensors. "In one-dimensional systems, the row of sensors is scanned across the image plane. For color, the one-dimensional detector array is trebled, each having either a red, green, or blue (RGB) filter in front of the detector, often referred to as tri-linear arrays" (Berns, 2001, p. 3). Another option for

color reproduction in scanback cameras using linear array technology is achieved by the use of a color filter wheel that is placed in-between the camera optics and the CCD. The linear array used in these systems is monochrome, and it only captures luminance information in grayscale. The linear array will scan across the image area (as many times as there are filters on the color filter wheel) and then compile this information and transposes it to color information through signal processing (Berns, 2001).

How the Image is Created

In order to further understand the image capture components of digital scanback cameras, it is important to understand how the image is built. *Ultra-High Resolution 14,400 Pixel Trilinear Color Imaging Sensor,* an Eastman Kodak Company white paper (available at the time of this writing at Kodak's website) offers an inside look at how trilinear CCD sensors capture and distribute image information. Kodak refers to their imaging sensor technology as Kodak Digital Science™. Each trilinear image sensor is made up of three identical sensor arrays containing photodiode pixels. Each of the three arrays is covered with a filter -- one red, one blue, and one green. When the trilinear sensor is used to create an image, it scans the image area and "for each color channel, the charge generated in individual pixels is stored in an adjacent accumulation region" (Carducci, Ciccarelli, & Kecskemety, n.d., p. 1).

Also stored in this accumulation region is "a lateral overflow drain to provide over-exposure / blooming protection, and an independent exposure control gate, allowing for on-chip color balancing" (Carducci, Ciccarelli, & Kecskemety, n.d., p. 1). The

accumulation region is separated from the CCD shift register region by way of a transfer gate. “Readout of the image signal for each channel is accomplished through dual CCD shift registers utilizing double-level polysilicon, buried-channel, and true two-phase (two electrodes per CCD stage) technologies, which are charge domain multiplexed into a single output buffer per channel” (Carducci, Ciccarelli, & Kecskemety, n.d., p. 1).

Each channel of the Kodak Digital Science™ trilinear imaging sensor has a specified number of primary photodiodes and a smaller number of test and reference photodiodes. The photodiodes capture luminance information and then transfer it into pixel information. The information is processed in two halves: one half of the information is processed in the CCD shift register above the sensor (the odd register) and the other half is processed in the CCD shift resister below the sensor (the even register). This more technical description of the image creation process is included:

> During the integration period, an image is obtained by gathering electrons generated by photons incident upon the photodiodes. The charge collected in the array is a linear function of the local exposure. Within a given channel, the charge is stored adjacent to the photodiode in the accumulation region PhiA, which is isolated from the CCD shift registers during the integration period via the transfer gate TG, which is held at a barrier potential. At the end of a given integration period, the CCD register clocking is stopped with the Phi1 and Phi2 gates being held in a 'high' and 'low' state respectively. Next, the TG gate is turned 'on' causing the charge to drain from the PhiA region, through the TG region and into the Phi1 region. The dual shift registers receive signal from alternate photodetectors in an odd/even fashion. As the TG gate is turned to an 'off' state, residual charge is transferred into the Phi1 storage region, and the shift registers are isolated from the detector region once again. Complementary clocking of the Phi1 and Phi2 phases is then resumed for readout of the current line of data while the next line of data is integrated. The parallel connection of the shift register clocks requires that Phi1/Phi2 clocking of all three channels be momentarily suspended during the parallel transfer from channel photosites (Carducci, Ciccarelli, & Kecskemety, n.d., p. 3).

Figures 11 and 12 illustrate Kodak's Digital Science ™ trilinear imaging sensor technology (Carducci, Ciccarelli, & Kecskemety, n.d.).

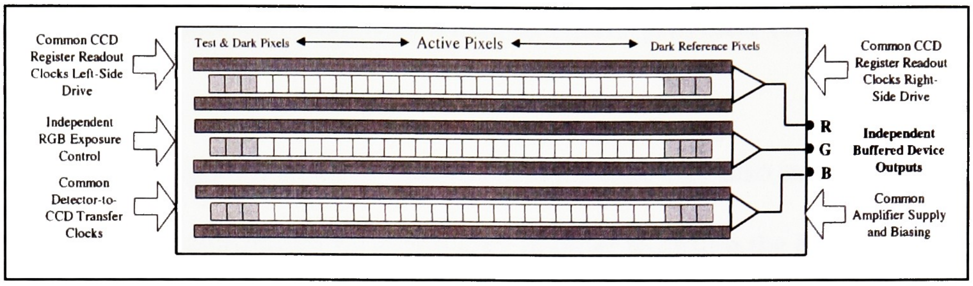

Figure 11. Functional block diagram of the Kodak trilinear array sensor. [Source: Carducci, Ciccarelli, & Kecskemety, n.d., p. 2]

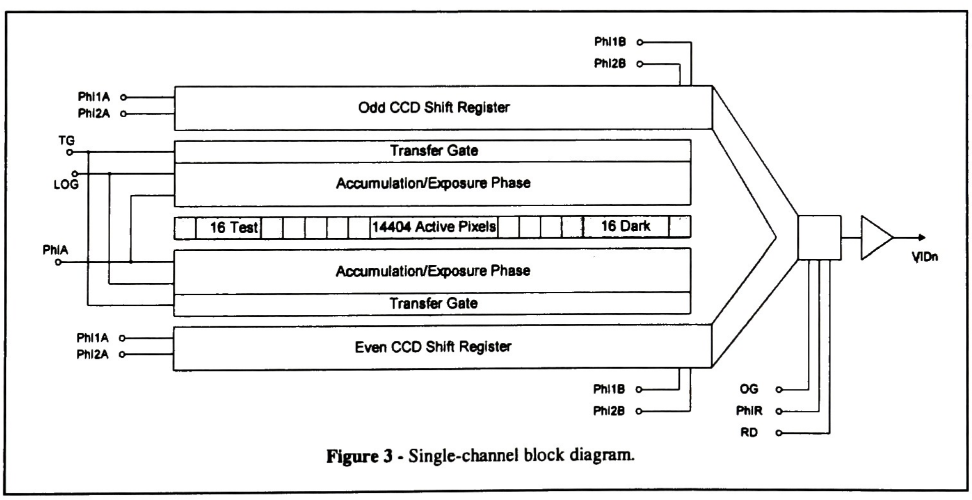

Figure 12. Single-channel block diagram of the Kodak trilinear array sensor. [Source: Carducci, Ciccarelli, & Kecskemety, n.d., p. 2]

Readout or output of the image signals is achieved by a "two-phase, complementary clocking of the Phi1 and Phi2 gates" (Carducci, Ciccarelli, &

Kecskemety, n.d., p.4). Once all of the data is registered, it is simultaneously sent toward the output elements, and the odd and even signals are transferred to one common output structure. Then a charge-to-voltage conversion is achieved thought the used of resettable floating diffusions, while buffering is provided by source providers (Carducci, Ciccarelli, & Kecskemety, n.d.).

The Kodak Digital Science ™ trilinear array technology also incorporates exposure control and anti-blooming technology in order to ensure the best possible image. Exposure control sets limitations on the amount of photocurrent that will be processed at a given time. Anti-blooming technology prevents overflow of photo-generated charges that can wind up affecting the adjacent CCD cells or photosite (Kodak, 1994).

Software Technology

It is important to consider that, for each camera on the market, there is a proprietary capture software that accompanies it. Also, there are different manufacturers of calibration software and profile software. Although the choice of what manufacturer to use is ultimately up to the user, it is important to consider the pros and cons that a system offers. For example, the BetterLight capture software allows for operator control of exposure, ISO, and tonal range, but some other capture software packages do not offer as much control (BetterLight, 2001). It is best to assess the requirements of the digital imaging project and to assess camera options prior to purchasing equipment. The same

assessment applies to calibration and profiling software, as well. This assessment step is considered part of project benchmarking (Kenney & Rieger, 2000).

Standards and Camera Testing

An Introduction to ISO Camera Testing Standards

Digital photography has come a long way in recent years. There are many different cameras to chose from, all of whose manufacturers' claims suggest excellent results based on what Don Williams of Eastman Kodak company calls "specsmanship." This concept of "specsmanship" is used to describe the claims made by manufacturers about a camera's performance. In *Debunking of Specsmanship: Progress on ISO/TC42 Standards for Digital Capture Imaging Performance*, Williams describes the imaging performance standardization criteria established by ISO/TC42, the International Standards Organization body which focuses on the standardization of still image capture (Williams, 2003). This information is included because it can help to facilitate the understanding of where to begin when considering digital imaging equipment and the procedure used to evaluate the quality that a device may or may not produce.

The ISO/TC42 standards covered by Williams are:

- terminology – ISO 12231
- opto-electronic conversion function – ISO 14524
- resolution for still picture cameras – ISO 12233
- resolution for reflection scanners – ISO 16067-1
- resolution for film scanners – ISO 16067-2

- noise for still picture cameras – ISO 15739
- dynamic range for film scanners – ISO 21550
- speed for still picture cameras – ISO 12232

The importance of covering these standards is to provide photographers, both amateur and professional, with the ability to understand and to compare the different image quality parameters that different manufacturers claim to provide. These standards are also important because they enable the evaluation of camera systems in order to determine a camera's realistic performance capabilities.

A Detailed Introduction to ISO Camera Testing Standards

Terminology is an important aspect of digital imaging procedures. The standard, terminology – ISO 12231, provides the foundation for digital imaging terms. It is an important first step for the understanding and clarification of digital imaging terminology (Williams, 2003).

The opto-electronic conversion function (OECF) – ISO 14524 provides the foundation for most of the ISO/TC42 camera performance standards. The OECF is similar to the characteristic or tone curves of film which "characterizes the transfer of exposure into optical film density, the OECF defines the relationship between exposure, or reflectance, and digital count value of a capture device" (Williams, 2003, p. 2). The OECF allows for evaluation of the effective gamma which is applied to an image, it can identify unusual tonal manipulations of an image, and it can also detect device non-linearities. "Its real power though lies as the rosetta stone for remapping count values

back to common and physical image evaluation space. Without it, meaningful cross-device and cross-parameter performance evaluation would be very difficult" (Williams, 2003, p. 2).

Resolution is an important imaging parameter to consider because manufacturers' claims may indicate one resolution, and device evaluation may indicate another. The following standards are, therefore, used to help resolve the issue of manufacturers' resolution claims:

- resolution for still picture cameras – ISO 12233
- resolution for reflection scanners – ISO 16067-1
- resolution for film scanners – ISO 16067-2

Interpolation techniques are to blame for the misleading information about device resolution and final image file size. "Through interpolation, an infinite amount of 'empty' resolution can be synthetically created that has no physical bearing on spatial detail detection (i.e. real resolution)" (Williams, 2003, p. 2). The determination of a device's spatial detail detection requires the consideration of a device's factors, such as optics, motion, electronics, and image processing. "For this, the measurement of Spatial Frequency Response (SFR) or Modulation Transfer Function (MTF) of a device is required" (Williams, 2003, p. 2). Each of the resolution standards mentioned here used a "slanted edge-gradient MTF analysis technique especially suited for digital capture devices" (Williams, 2003, p. 2).

Williams (2003) further states:

> The suitability of MTF as an objective tool to characterize spatial imaging performance is well documented and has been used as an

> imaging tool for more than fifty years. By characterizing contrast loss with respect to spatial frequency, one of its many uses can be to objectively establish the limiting resolution of a device. This is done by determining the spatial frequency associated with a given MTF value, typically 0.1. This frequency is then translated into limiting resolution for a given set of scan conditions and compared to the manufacturers claim to determine compliance (p. 3).

Noise and dynamic range will be discussed together because, in both of the standards considered here, calculations for one depends on evaluation of the other. The camera standard, noise for still picture cameras – ISO 15739, serves to measure noise; however, it includes recommendations for dynamic range. The film camera standard, dynamic range for film scanners – ISO 21550, serves to measure dynamic range; however, this does require noise characterization. The techniques for both noise characterization and dynamic range characterization are the same as each of the standards discussed here. Williams defines dynamic range as "the extent of energy over which a digital capture device can reliably detect signals: reported as either a normalized ratio (xxx:1) or in equivalent optical density units" (Williams 2003, p. 3). The key to this definition is the term, "reliably detect;" the characterization method must be reliable in order to confidently evaluate a digital imaging device. Detection is a function of signal strength; the stronger the better. The reliability, or probability, of that detection is a function of the noise associated with that signal, the lower the better.

This logic suggests that "maximizing the signal-to-noise ratio (SNR) is appropriate for increasing the dynamic range of a device" (Williams, 2003, p. 3). The standards described here both use an incremental SNR method to measure dynamic

range. The incremental method is based on a derivative of the OECF method. This allows for precise evaluation and comparison of digital capture devices.

To characterize device noise, both standards use a technique called "noise cracking." This technique distinguishes fixed pattern rms noise caused by the device itself and from random temporal rms noise caused by an imaging target (Williams, 2003). It is calculated by "taking the ratio of the incremental signal and noise at each OECF patch [which] yields the incremental SNR function. Dynamic range is then determined from the incremental SNR by noting the density at which a prescribed SNR value is met" (Williams 2003, p. 4).

Speed is the final standard included in this introduction to ISO camera testing standards. "A camera's speed rating is the most important attribute in estimating proper exposure for given lighting conditions" (Williams, 2003, p. 4). The standard, speed for still picture cameras – ISO 12232, addresses the issue of signal amplification, which is an issue with digital cameras. Due to unconstrained processing of digital images, signals can easily be amplified, which can result in a range of output levels; however, this can have the effect of amplifying noise to the point where the image may become useless. Thus, the speed standard for digital cameras also uses the incremental SNR method of evaluation.

> Through image quality studies, SNR values of 40 and 10 were chosen to describe excellent and acceptable levels of image quality respectively. The exposure required to achieve these SNR values dictate noise-based speeds. They are referred to as $S_{noise40}$ and $S_{noise10}$ and, like film, are intended to characterize minimum exposure behavior (Williams, 2003, p. 5).

Standards Defining Camera Testing Procedures

As part of her thesis, Erin Murphy, of RIT's Center for Imaging Science, completed *A Review of Standards Defining Testing Procedures for Characterizing the Color and Spatial Quality of Digital Cameras Used to Image Cultural Heritage.* Murphy reviewed these standards pertaining to digital imaging from the following standards organizations:

- ISO – International Standards Organization
- IEC – International Electrical Commission
- ANIS – American National Standards Institute
- CIE - International Commission on Illumination
- NISO – National Informational Standards Organization.

In Appendix B, there are two tables that originated from Murphy's standards review. Table B1 (Murphy, 2005, p. 12-13) illustrates the list of standards summarized in Murphy's review. Table B2 (Murphy, 2005, p. 14-16) provides a quick reference guide for the image quality parameters covered in each of standards reviewed by Murphy. It is important to note that, for the ISO standards, the status of the standards are classified as:

- WD – working draft
- CD – committee draft
- DIS – draft International Standard
- FDIS – final draft International Standard
- ISO – International Standard (Williams 2003)

These classifications will help clarify what phase each of the standards was in when Murphy reviewed them.

Testing a Camera's Quality

Also part of Murphy's thesis (and in collaboration with the primary researcher's), was the camera test benchmarking of the four workflows examined in the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* project. In each of the four case studies, nine camera quality parameters were tested. The results of each were then compared and used to benchmark the differences between the various workflows.

A brief description of what was tested, the respective targets used, and the standards associated with the tests are described by Berns and Frey (2005), extracted from the *Benchmarking* final report:

> The first one, system spatial uniformity, which assesses the amount of uncorrected system spatial non-uniformities that can be caused by such things as uneven illumination of the scene and lens fall-off, was tested using a uniform gray-card target. The second was tone reproduction, which was tested using an International Standards Organization (ISO) standard grayscale target and analyzed in the form of an opto-electronic conversion function, or OECF. The third was color reproduction inaccuracy, which is fundamentally caused by the inherent lack of correlation between the camera's spectral sensitivities and those of the average human observer. Spectral sensitivities were determined by imaging a monochromator instrument. Also, nine different color targets were imaged and analyzed. Observer metamerism was evaluated between the camera and photographer using a tool called the Davidson & Hemmendinger (D&H) Color Rule, unfortunately no longer manufactured. The fourth and fifth parameters were noise (image and color) and dynamic range. Image noise and dynamic range were both tested using an ISO standard noise target, imaged eight times at the same exposure level. Color noise was tested using selected patches of the Macbeth

> ColorChecker. The sixth image quality parameter, spatial crosstalk, commonly known as image flare, was tested using an International Electrotechnical Commission (IEC) standard target. The seventh, spatial frequency response (SFR), which is used to characterize a camera's ability to reproduce detail, and the eighth, colorchannel registration, were both tested using the knife-edges of an ISO resolution target. Depth of field was tested using a novel three-dimensional target that had a total depth of 6" (p. 28).

The testing procedures used in the benchmarking project are either directly obtained from the standards assigned to the respective quality parameter or were developed by the researchers, based on a review of the current literature. The tests that followed the standards include: system spatial uniformity, tone reproduction, color reproduction accuracy (spectral sensitivity and target-based), image noise, dynamic range spatial crosstalk, and spatial frequency response. The tests that were developed by the researchers include: color reproduction accuracy (metamerism), color noise, color channel registration, and depth of field.

Analysis of the subsequent images was performed using The Math Works MATLAB® programming language. The reference illuminant used was CIE D_{50} because it is an industry standard viewing condition, and photographers most frequently use it during image capture (Murphy, 2005). An in-depth description of the testing procedures, including image analysis can be found in Murphy's thesis, and a more descriptive overview can be found in the *Benchmarking Final Report.*

Monitor Calibration Standards

A review of the ISO – 12646, *Graphic Technology – Display for Colour Proofing – Characteristics and Viewing Conditions,* is important to the discussion of

color accurate reproduction within museum digital imaging workflows. Findings from *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* indicate the "most institutions included visual editing in their workflows" (Berns & Frey, 2005, p. 1). It is thus necessary to consider the impact this type of editing has on a digital imaging workflow. The standard, which has yet to be published, "specifies requirements for uniformity, size, resolution, convergence, refresh rate, luminance levels and viewing conditions for a color display used to simulate a hard copy proofing system" (Murphy, 2005, p. 30). The primary reason behind development of this standard was to assist the graphic arts community when assessing and comparing color proofs of both hard and soft copy. Although the standard was created for proofing, it also helps to ensure that an original will visually match the respective digital image file. More information about this standard can also be found in Murphy's standards review document; publication is expected soon.

Metadata

Metadata is data about data. In a digital imaging workflow, it is essential to record data about data for many reasons. There are different types of metadata, all of which are important to the longevity of a digital file. The categories of metadata include: administrative, descriptive, preservation, technical, and use (Baca, 1998). The American National Standards Institute (ANSI), in collaboration with the National Information Standards Organization (NISO), developed a metadata standard titled "Data Dictionary – Technical Metadata for Digital Still Images." It is referred to as ANSI/NISO – Z39.87-

200X or ANSI/AIIM 20-200X; the standard is in the final stages of review at the time of this writing. This standard will provide a data dictionary that defines the necessary elements of metadata for digital still images. "Standardizing this information allows users to develop, exchange, and interpret digital image files. The dictionary has been designed to facilitate interoperability between systems, services, and software as well as to support the long-term management of and continuing access to digital image collections" (NISO, 2005). It is very important that digital image files are accessible in the future, that this standard provides a container for the image metadata, and that this record will help maintain accessibility to the digital file well into the future.

Workflow Guidelines

The key findings from the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s project indicate that there is a wider range of workflows among digital imaging projects. "About every possible combination was found including cameras, light sources, viewing environments, color management, visual editing, spatial image processing, file format and encoding, and digital preservation of the image files" (Berns & Frey, 2005, p. 56). This melting pot of workflow procedures creates difficulty when addressing concerns of combining image databases, system interoperability, and the continued access to these digital images in the future. Some of these concerns can be corrected for in the future with the incorporation of the ANSI/NISO – Z39.87-200X or ANSI/AIIM 20-200X metadata standard. However, this supports the need for workflow guidelines that will enable the creation of digital

master files that can repurposed for multiple applications and may also be accessed well into the future.

Chapter 3

Research Objectives

The first research objective is to establish a simplified camera characterization method in order to assist with digital imaging workflows within the museum environment. An explanation of the significance of camera testing will enable photographers to understand the importance of camera characterization; simplified camera testing procedures would allow for an easier execution of these tests. This camera characterization shall be considered the first step in digital imaging endeavors. The importance of this first step in a digital imaging workflow is to understand the capabilities of the camera hardware in order to aid in the creation of best possible digital master images.

In order to establish a simplified camera characterization method, the following camera tests will be considered:

- System spatial uniformity
- Tone reproduction (OECF)
- Color reproduction
    - Spectral sensitivity (monochromator)
    - Target based color reproduction accuracy
    - Metamerism

- Noise
    - Image noise
    - Color noise
- Dynamic range
- Spatial crosstalk
- Spatial frequency response (SFR)
- Color Channel Registration
- Depth of field

Once each of these quality parameters has been researched or replicated, it will then be determined to what degree the tests provide useful and applicable information regarding image quality. What will also be addressed (and is of primary interest) is how easy it is to calculate a camera's performance based on the current testing procedures and evaluation methods. These determinations will assist in the support for or elimination of the tests in order to establish a criterion of useful testing methods; they may also serve as a catalyst for creating more user-friendly evaluation applications.

Metadata concerns will be addressed in relation to the metadata created by the camera characterization testing procedures.

The primary goal of this research objective is to help establish a new starting point for digital imaging workflows, one that incorporates camera quality parameters. This will help archival digital imaging initiatives to create the best possible digital files and will enable photographers to further their knowledge of digital imaging equipment.

It is important to note that the research objective proposed here is limited to the reproduction of fine art using a 4 x 5 digital camera. It is understood that a countless

number of camera and workflow options exist, but it the researcher's goal to focus on the specific criteria of museum photography.

The second research objective is to review the case study video interviews created during the on-location investigations of four museums during the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* project. These videos provide a close-up look at four different museum imaging workflows currently in use. The video will be edited, and then key elements will be compiled into a video documentary. The purpose of this documentary is to understand current practices and to realize where and how improvements to the workflow can be made.

Chapter 4

Methodology

The methodology for the first proposed research objective required camera-testing research and, in some cases, replication of some tests. The tests that were considered include system spatial uniformity, tone reproduction, color reproduction, noise, dynamic range, spatial crosstalk, spatial frequency response (SFR), colorchannel registration, and depth of field. These are the camera tests that were executed during the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* project, and are described in detail in *A Testing Procedure to Characterize Color and Spatial Quality of Digital Cameras Used to Image Cultural Heritage* (Murphy, 2005).

The goal was to determine which of these tests are most effective and provide the most useful information when characterizing a camera for color accurate reproduction. Another goal was to determine the ease of use; i.e., how easy is it to take pictures of the targets and to calculate the results. This lead to the selection of approximately four to five of the most important camera tests.

Once the tests were selected, they can now be considered the starting point for a color critical digital imaging workflow within museums or institutions. Some of this research was conducted while attending the *IS&T/SPIE 18th Annual Symposium:*

Electronic Imaging Science and Technology at a short course, *Image Quality Evaluation for Digital Cameras Based on Existing ISO Standards*, offered by instructors Dietmar Wueller of Image Engineering and Kevin Matherson of Hewlett Packard Company. Information was also gathered from another research project conducted at RIT, *Evaluating a Camera for Archiving Cultural Heritage*, by Karniyati (2005).

The methodology for the second proposed research objective required digitizing the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s interview video, transferring it from tape to an external hard drive using the application iMOVIE, viewing the entire footage, and finally selecting and editing the video, in order to explore the workflow at each of the four museums represented in the case study interviews. These videos also provided insight into the constraints placed on imaging departments within museums, and some of this footage has compiled into a brief documentary. The goal of the documentary is to witness current practices while considering the real world situations that can be either hindering or helping to imaging workflows. This documentary has also been used to support the need for digital imaging workflow guidelines for museums and institutions. It has also served to establish a customer base of interested parties who are in need of understanding the benefits of camera characterization, as well as "best practices" workflow assistance.

First-hand experience of the researcher working as a digital photographer within a museum is documented as a case study of the workflow and has been included as part of the proposed research. This has been completed in an effort to explore, in-depth, the

imaging procedures of a museum and to understand the constraints placed on a real word digital imaging initiative.

A trip to California was also scheduled, during which time the researcher visited a company that is successful at creating fine art reproductions of paintings to sell to a wide audience. The goal was to explore their procedure from digital capture to print and to understand the key elements of their success. A non-disclosure agreement was required to visit this facility, so the researcher is prohibited from documenting the workflow.

Chapter 5

Findings

Camera Testing

What Tests are Necessary and Why?

While at the IS&T/SPIE 18th Annual Symposium, *Electronic Imaging Science and Technology*, the researcher attended a short course, *Image Quality Evaluation for Digital Cameras Based on Existing ISO Standards*. Information obtained from that short course provides an imaging industry reference point for what camera tests are considered necessary in order to evaluate a camera's image capture quality. Co-instructor Dietmar Wueller is CEO of Image Engineering, located in Germany. Image Engineering specializes in camera testing and software development for camera testing evaluation. It is also a large manufacturer of camera testing targets. Wueller also works with standard organizations all over the world to help develop camera-testing standards. Wueller has specified that the following camera characterization tests are mandatory for evaluating a camera's performance:

- OECF / Tone Reproduction
- White balancing
- Dynamic range (related scene contrast)
- Used digital values

- Noise, signal-to-noise ratio
- Resolution (limiting resolution center, corner)
- Sharpness

Wueller has also recommended the following camera characterization tests for evaluating a camera's performance:

- Distortion
- Shading / vignette
- Chromatic aberration
- Color reproduction quality
- Unsharp masking
- Shutter lag
- Aliasing artifacts
- Compression rates
- Exposure and exposure time accuracy and constancy
- ISO speed

The tests that Wueller has suggested, either mandatory or recommended, are compared to the tests that were executed during the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs* project. These tests, the testing procedures, and the evaluation methods used in the Benchmarking project are described in detail in *A Testing Procedure to Characterize Color and Spatial Quality of Digital Cameras Used to Image Cultural Heritage* (Murphy, 2005). The list of tests conducted for this research is:

- System spatial uniformity
- Tone reproduction (OECF)
- Color reproduction
    - Spectral sensitivity (monochromator)
    - Target based color reproduction accuracy
    - Metamerism
- Noise
    - Image noise
    - Color noise
- Dynamic range
- Spatial crosstalk
- Spatial frequency response (SFR)
- Color Channel Registration
- Depth of field

These same tests were also repeated by Karniyati, an RIT Imaging Science student, and the results are available in *Evaluating a Camera for Archiving Cultural Heritage* (2005). Murphy and Karniyati both focused their testing procedures on the reproduction of artwork and cultural heritage.

It is clear from these two different lists that a discrepancy exists between the testing of a camera's overall quality and performance for general or commercial applications, and the testing of a camera's quality for fine art reproduction and museum photography applications. The main difference lies in the consideration of color accuracy. It is apparent from Wueller's suggestions that color accuracy is not a necessary test, but

rather a recommended one. It can be argued that testing a camera's color reproduction quality is dependent on the application at hand.

Wueller has focused his mandatory testing procedures on the evaluation of commercially used cameras, and that is currently the most common application for camera testing. Manufacturers and engineers, in order to understand and to improve the performance of digital cameras, are doing most of the camera testing. It is the goal of this project to educate museum photographers about camera testing applications and quality parameters, as well as to help facilitate and to implement this type of evaluation into their workflow. The tasks presented to these photographers put them in a class of their own, one where extra consideration must be taken when creating images. These images will most likely be archived and will be called upon well into the future. Although commercial photographers should also be aware of these factors, they are less restricted by the same quality concerns that have less of an impact on their workflow.

Tables 3a and 3b show the mandatory (3a) and recommended (3b) camera tests by Wueller and the corresponding tests conducted by Murphy and Karniyati. Also shown in Tables 3a and 3b are the standard each test corresponds to, the target needed, and a checklist of camera tests that are recommended and considered useful for museums. The group of tests recommended for museums has been narrowed down from all the tests listed in these tables, and it is the belief of the researcher that these tests will provide the most useful and applicable information for museum photographers. Following Tables 3a and 3b, each of the tests conducted by Murphy will be described and assessed; in

addition, an explanation of why the given test has either been included or eliminated from the recommendation list will be given.

Table 3a. Wueller's Mandatory Testing:
A Comparison of Camera Tests.

Wueller Mandatory	**Murphy & Karniyati**	**Standard**	**Target**	**Museums**
OECF / Tone Reproduction	Tone Reproduction / OECF	ISO 14524	ISO OECF chart	√
White Balancing		(Color channel curves should fall on-top of one another, difference shall not exceed 5 digital values)	Gray Card	Pre-work
Dynamic Range (relative to scene contrast)	Dynamic Range	ISO 15739	ISO Noise Chart, target with multiple gray patches	When working with 16 bits should not be a problem
Used digital values				
Noise, signal-to-noise ratio	Noise •Image noise •Color noise	Image noise ISO 15739 Color Noise Berns	ISO Noise Chart	√ Image Noise Photoshop Plug- in
Resolution (Limiting resolution center, corner) (SFR)	Spatial Frequency Response (SFR) (Resolution)	ISO 12233	ISO Resolution target or Siemens Star	√ Plug in
Sharpness				

Table 3b. Wueller's Recommended Testing:
A Comparison of Camera Tests.

Wueller Recommended	**Murphy & Karniyati**	**Standard**	**Target**	**Museums**
Distortion	System Spatial Uniform	IEC 61966-8 IEC 61966-9	Gray Card	Pre-work
Shading / vignette	System Spatial Uniform	IEC 61966-8 IEC 61966-9	Gray Card	Pre-work
Chromatic aberration	Spatial Cross-talk	IEC 61966-8 IEC 61966-9	IEC Spatial cross-talk target	Pre-work
Color reproduction quality	Color Reproduction: •Spectral sensitivity •Target based reproduction accuracy •Metamerism	Spectral sensitivity ISO 17321-1 IEC 61966-9 Target Based ISO 17321-1 Metamerism IEC 61966-2-1	Target Based Gretag Macbeth Color checkers	√ Target Based
Unsharp masking				
Shutter lag				
Aliasing artifacts				
Compression rates				
Exposure time accuracy & constancy				
ISO speed		ISO 12232		
	•Depth of Field	Murphy	Depth of Field	Pre-work
	•Color-channel registration	Berns sfrmat2 MATLAB script	ISO Resolution target	Automatically calculated with SFR using Berns method

The Tests in Greater Detail

In order to decipher and to understand exactly what is being tested for with each camera test, it is helpful to take a deeper look. In keeping with the order of tests proposed by Murphy, an explanation of what camera characteristic is being tested and the usability of each method will now be explored.

As a general procedure, the studio is set up using evenly placed daylight balanced lights at an approximately 45° angle from the subject (i.e., the targets) on both sides; the targets were placed in the same spot against a black background. The camera is then situated parallel to the targets. This is the testing method for all of the tests proposed by Murphy, except for the color reproduction spectral sensitivity test that requires the use of a monochromator; another exception is for the depth of field test, in which the lights were adjusted to reduce the shadows caused by the target itself.

All of the analysis for Murphy's testing was performed using The Math Works MATLAB programming language. This is the fundamental reason why camera testing is difficult for photographers. It is easy enough to image the targets, following the set up criteria, but it is another thing to understand a programming language in order to evaluate the test images. If photographers are to perform these tests, it is imperative that simplified, user-friendly analysis procedures be introduced to enable this type of subjective analysis. The usability of the testing analysis is considered in the determination of the recommended tests.

System Spatial Uniformity Testing

The first test proposed by Murphy is for system spatial uniformity. This test is based on the standards IEC 61966-8 and 61966-9. System spatial uniformity looks at the non-uniformity of an image. This non-uniformity can be caused by uneven illumination, lens fall-off, and lens flare. Evaluating non-uniformity is done by imaging an even surface (such as a gray card) and analyzing the resulting image. The standard describes how to image a gray card and how to analyze the results by calculating the non-uniformity. Once the non-uniformity is calculated, the results can be incorporated into a correction factor, which can be programmed into the imaging workflow.

It makes sense that this test is considered first, because from a photography standpoint, it is very helpful to consider non-uniformity. However, practically speaking, this is a common practice among photographers; if one is unable to calculate the non-uniformity and thus create the correction factor and apply it, then this seems to be an ineffective approach. Instead of calculating this, it is recommended that photographers simply follow the practice of imaging a uniform surface and visually analyzing the results. Light can be adjusted until illumination is even, lens hoods and light blocking baffles can be introduced into the studio to minimize flare, and a polarizing filter can also be introduced to minimize surface reflectance. Therefore, this test is considered pre-work (a term introduced to describe initial evaluation of a setup by the photographer) without having to calculate the exact results. It is the belief of the researcher that system spatial uniformity or non-uniformity can be addressed and accounted for without calculating a correction factor.

Tone Reproduction Testing

The second test considered is tone reproduction using an opto-electronic conversion function, or OECF. A tone reproduction test evaluates the relationship between initial scene log luminance input levels and the corresponding digital code output values of the opto-electronic imaging device. Methods for measuring and calculating OECFs are described in the ISO 14254 standard, and a target called the ISO OECF Test Chart is required. OECF measurements can be used to evaluate dynamic and or tonal range, white balancing, gamma and tonal adjustments introduced by the devices' linear output conversion, used digital values, signal-to-noise values, and ISO camera speed. The procedure for imaging the OECF target requires focusing the camera on the target and imaging it nine times; the exposures must range so that the first four images are under-exposed, the fifth image must be properly exposed and the remaining four images must be over-exposed. The reason for this is to acquire a group of images that represent the full range of digital counts that the camera is capable of generating, thus yielding the dynamic range of the camera. The luminance value of each of the patches on the target should be measured before the target is removed from the scene. Analysis begins with examining the relationship between the red, green, and blue (RGB) output values for each patch in the dynamic range, this relates to the white point. The target is comprised of neutral gray patches so the R, G and B, values should be relatively close in order to obtain a neutral white balance.

The next step is to rescale and to normalize the digital counts of the patches in order to build three one-dimensional OCEF look-up tables (one R, one G, and one B.)

These tables have normalized digital count values as input and luminance values as output. Once the tables are created, the clipped digital count values, which are any values falling above 0.95 and below 0, are removed for the set. The remaining points are then linearly interpolated, extrapolated, and smoothed; these make up the final look-up table. These data can now be plotted in gamma curves, and the mean digital count for each patch can be derived. It is important to note that the OECF measurements and calculations are specific to the luminance ratio and the luminance distribution. Thus, when conducting this test, it would be most beneficial for museums to use the same type of lighting and studio set-up with which they would typically photograph. It is the belief of the researcher that the tonal range of an imaging device should be known and, therefore, tested for under the same imaging setup typically used during the photographer's workflow.

Color Reproduction Accuracy Testing

The third group of tests proposed by Murphy is the color reproduction accuracy tests. Murphy has proposed three tests under this category: spectral sensitivity, target based color reproduction accuracy, and metamerism.

Spectral Sensitivity. The first test, spectral sensitivity is described in both the ISO 17321-1 standard, and the IEC 61966-9 standard. Spectral sensitivity is an important consideration when it comes to digital imaging devices. This is because most digital camera spectral sensitivities do not match the CIE color-matching spectral sensitivity functions. Thus, most digital cameras lack a linear transformation of the average human

observer. This is the initial reason why color inaccuracies occur. The spectral sensitivity test allows for the determination of the spectral response of a camera, which can then be plotted in comparison to the CIE color matching functions. If the spectral sensitivity is known for a device, this information can be used to create a correction factor, which would prove useful if programmed into a workflow. However, simply knowing the camera's default spectral sensitivity can be helpful in understanding color reproduction inaccuracies.

The procedure used to determine a camera's spectral sensitivity requires a device called a monochromator. A monochromator is a device that creates a rainbow of light ranging from 380 nm to 730 nm, and this light is projected into the camera at 10 nm increments. When performing the test, all other light sources are removed from the studio, and the monochromator is placed in the viewing field as if it were a target, the lens is focused on the integrating sphere or the light output area of the device. The monochromator allows only 10nm of light to pass into the camera at one time. Once the exposure setting is determined, the monochromator is imaged 36 times at 10 nm peaks between the band pass range of 360 nm to 730 nm. The radiance of the device output is also measured for each 10 nm increment.

Both the radiance and image data are then analyzed by first averaging the RGB values for each image, and then by applying the inverse OECF curve in order to linearize the data. The OECF curve must first be calculated, as described in the tone reproduction tests. Next, the radiance wavelengths are determined, and the linearized digital count

values are divided by the radiance in order to calculate the camera's spectral sensitivity. This can then be plotted against the CIE 2° standard observer color matching functions.

Although this test seems to be of utmost importance, it is dependent on access to a monochromator, and calculating the results also requires the OECF of the camera in the same setting. It is unlikely that museum photographers will have access to a monochromator; therefore, it is the belief of the researcher that this test be eliminated from the recommended museum testing practices. If, however, the museum photographer would like to know the spectral response, then testing service may be utilized to determine the results.

Target Based Color Reproduction Accuracy. This test enables a practical way for museum photographers to evaluate their camera's capability. This type of testing is described in the ISO standard 17321-1.

Target based color reproduction accuracy testing requires the use of color targets (such as any of the Gretag Macbeth Color Checkers) or another target created with even color patches. Once the target is in hand, the spectral response of each patch can be measured with a spectrophotometer. If a spectrophotometer is not available, the spectral response characteristics of the MacBeth Color Checkers should be easy to find via the Internet.

To execute a target based color reproduction accuracy test, the target should be placed in the studio, which should be set up for typical imaging work. Next, the target should be imaged, and then opened in Photoshop. The image should be opened in Photoshop with the embedded RGB profile; this can be the camera color space or the

camera's profile. Once the image is opened in Photoshop, it should then be converted to the L*a*b* color space. Then, using the Info tool to scroll over each patch, the L*a*b* coordinates of each color patch can be recorded.

This information can be entered into an Excel document and compared to the spectral reflectance L*a*b* coordinates of each color patch from the actual target. Using Excel, the Delta E (ΔE), the difference between the color on the target and the color from the image, can be calculated. This is the best method for museum photographers to use to determine the color reproduction accuracy of their cameras, simply because it is something they can easily do and easily evaluate. Calculating ΔE is also optional; the photographer could simply view the imaged target on screen, compared to a digital reference version of the same target. Digital reference targets are available. (At the time of this writing, the MacBeth Color Checkers comparison charts could be downloaded at http://digitalkamera.imageengineering.de/index.php/Downloads.)

Metamerism. Murphy also conducted a color accuracy test to examine metamerism. Metamerism is a visual sensation that occurs when two different stimuli appear to match when viewed under one illuminant, but then do not match under a different illuminant. This is referred to as illuminant metamerism and is one type of metamerism. Observer metamerism, the other type, occurs when a pair of stimuli match to one observer, but not to another.

Metamerism testing is described in standards IEC 61966-2-1 (1999) and IEC 61966-2-1 Amendment 1 (2003). This test requires the use of the Davidson & Hemmendinger (D&H) Color Rule target. This target is only applicable for observer

metamerism, and in camera testing applications, the observer is the camera; however, the photographer and the CIE 2° standard observer can also be observers. The D&H Color Rule is made up of two rows or strips of 42 colors, one is labeled alphabetically, and one is labeled numerically.

To test for metamerism, each of the strips is placed in a holder that masks all but one color patch per strip. The observer can then slide the strips back and forth until a color match appears (one patch from each strip) to the observer under a given illuminant. When testing a camera's metamerism, each strip of the D&H Color Rule must first be spectrally measured and the data documented. Next, the strips are imaged with the camera, then opened in Photoshop with the embedded camera profile, and then converted to L*a*b*. Next, the values from each patch can be obtained, and the camera match is determined by the lowest color difference between the alphabetic patch and the numeric patch.

This seems simple enough; however, this test requires use of MATLAB to calculate because the data must be taken from CIELAB (Photoshop L*a*b*), to XYZ tristimulus values, then it must be flat-fielded and lightness corrected, then converted back to CIELAB data in order to ensure correct calculation of the ΔE.

It is the researcher's belief that this test can be conducted in a simplified way; if initial spatial uniformity is achieved, this test can simply be conducted by imaging both strips, opening the images in Photoshop, converting them to L*a*b* color space, and then with the info tool find the closest color match between patches per strip. This test in not required for museum imaging, because it must be assumed that not all observers have the

same spectral sensitivities; therefore, color inaccuracies exist. Also, this test only allows one to determine the differences between observers under a given illuminant, conditions that are susceptible to frequent change.

Image Noise

The next test conducted by Murphy examined image noise. Murphy tested for four types of image noise, based on the guidelines presented in the ISO 15739 standard and with the uses of the ISO Noise Test Chart. The four types of image noise tested for are total noise, fixed pattern noise, temporal noise, and black temporal noise. When an image is captured from a specific camera, fixed noise will appear in each image created by that camera; other types of noise will vary, depending on the capture exposure, ISO speed, and operating temperature.

For each type of noise, the average noise was determined, and for total noise, fixed pattern noise, temporal noise, the signal-to-noise ratio (SNR) was determined. In this case, the total noise (which is considered all unwanted variations introduced by the capture system) is derived by the sum of both the variance of the fixed pattern noise and the temporal noise. Fixed pattern noise is unwanted variations that are consistent with every exposure. Temporal noise varies from image to image, and black temporal noise is used to determine a camera's dynamic range.

The testing procedure requires the ISO Noise Test Chart to be imaged eight times in the same location with the same exposure settings. The target should be in the sharpest

focus possible, and the exposure should be set so the digital values of the white patch are unclipped.

Image analysis in Murphy's case was performed using MATLAB, but an Adobe Photoshop Plug-in can be used to perform the same calculations. This Plug-in would be applicable to a museum setting. For camera evaluation, it is desirable to have low average or total noise, as well as desirable to have a high signal-to-noise ratio.

Color Noise

Murphy also tested for color noise. The importance in testing for color noise is to determine if noise is being introduced by a specific color channel and to what extent, if any, this has on the over-all image.

To test for this, a Macbeth Color Checker was used, and the percent standard deviation and the mean color differences from the initial means were calculated. Color scientist Roy Berns of RIT's Munsell Color Science Laboratory created this testing procedure, and thus no testing standard exists. However, testing guidelines are available. The results of this test were also calculated using MATLAB.

It is possible for museum photographers to evaluate color noise by photographing color patches and viewing the color channels of the image in Photoshop. Although a calculated metric cannot be derived this way, a visual assessment can be made. Therefore, it is the researcher's belief that testing for color noise can be done independently of Murphy's proposed method.

Dynamic Range

Murphy also tested dynamic range, often referred to as tonal range. This test is independent of the tone reproduction test described earlier using the ISO 14254 standard. This dynamic range test is based on the testing procedure presented in the ISO 15739 standard. This test explores the camera's ability to capture extreme density variations that may be present in a scene. It is desirable for a digital camera system to have a broad dynamic range because this will facilitate smooth light-to-dark transitions and will allow for the capture and reproduction of a wide range of tones. ISO standard 15739 defines dynamic range as "the ratio of the maximum unclipped luminance level to the minimum unclipped luminance level that can be reproduced with a temporal SNR of at least one" (ISO 15739, 2003).

This test uses the same ISO 15739 target as the noise test, the Noise Test Chart. Two of the darkest patches of this chart, along with the RGB data from the eight noise images, are used to calculate the dynamic range. This indicates that the noise tests must be completed, and the data must be applied to the dynamic range evaluation. The first calculation is the determination of the reflectance values of the two darkest patches. These are used to calculate the incremental gain (IG) of the range in terms of the luminance ratio. This luminance ratio is then converted to density units by applying $\log_{10}$ functions; thus, the dynamic range of the camera is determined. This value can then be compared to the manufacturer's theoretical dynamic range, which incorporates the number of bits per channel.

It is interesting to test for and calculate the dynamic range of a camera, but practically speaking, it is a complicated task. It is the belief of the researcher that this test

be eliminated from the recommended tests for museum photographers because it is complicated. It also seems to be a non-crucial evaluation for museum photography applications because, within the museum environment, typically the cameras are of extremely high quality, and images should be captured, adjusted, and saved as 16 bits per channel, which will produce less clipping than can compressed 8 bits per channel image data.

Spatial Cross-Talk

Spatial cross-talk is a way of describing a type of image flare that can be caused by subject surround conditions. If, for example, an object in a scene is surrounded by an area brighter than itself, spatial cross-talk would occur if this surround influenced the reproduction of the object, causing the output digital count value to be higher than if the object was surrounded by a more normal or darker background.

This test is described in the IEC 61966-8 standard. The target used incorporates the IEC Large Area Spatial Cross-Talk Chart. This target should be in sharp focus when imaged, and the exposure should be set so that the digital count values of the white areas of the target remain unclipped. The target should be imaged once, then rotated 180° and imaged again. There are 15 little gray squares on this target, half of these squares are surrounded by white and half are surrounded by black. The target must be rotated so that the difference between how the camera's imager records the gray squares surrounded by either black or white can be evaluated.

To begin, the evaluation the RGB values from each of the gray squares are averaged for both of the images. These RGB data are then linearized by applying the inverse OECF look-up table to each color channel. Using these data, two metrics are calculated: the percent relative maximum difference, and the percent relative standard deviation. It is desirable to have none, if any, relative maximum difference, meaning the closer to zero, the less spatial cross-talk.

This is an interesting test to conduct because it seems as if the camera can be affected by surround, as can the human eye. Although the camera reacts inversely to how the human eye reacts, it is important to take this into consideration when designing a studio, and perhaps when composing a picture. It is suggested that this test can be done in a simplified manner. If a target were made using a gray card that is placed onto a surround that is half black and half white, and then imaged twice with even lighting (the second image rotated 180°), the resulting images could be evaluated in Photoshop to see the difference between the recorded digital values for each image. This would create a simplified version of this test, one that would not require calculating metrics. If this were done, it would provide enough information on the amount of spatial cross-talk that could be expected and perhaps avoided.

However, it is also important to consider that as objects and scenes change, so will the amount and significance of the affects of spatial cross-talk. It is, therefore, the researcher's belief that this test not be required for the evaluation of cameras within museums.

Spatial Frequency Response (SFR)

Spatial frequency response (SFR) is a term used to describe a measurement method for testing a digital camera's resolution. Resolution of a digital camera is considered its ability to capture picture detail. The SFR measurement method described in the standard ISO 12233 is just one way resolution can tested. This method is only applicable to the "purist" type of image file, one that does not have any sharpening or processing algorithms applied to it. This test is most suitable for museum imaging procedures because, in this environment, there should never be any automatic sharpening applied to images. There are many elements of a digital imaging system that can affect the SFR, such as lens aperture, optics, field position, sampling, and imaging processing. Therefore, it is most important to stabilize these elements as much as possible in order to determine the camera's repeatability.

The ISO Resolution Chart is the target used to conduct this test. The elements on this target used for this test are the slanted black bars and squares. These bars and squares are slanted 5° and are referred to as knife-edges. The target should be imaged so that neither the black nor the white signals are clipped; the focus should be on the zone plate in the center of the target and should exhibit as must aliasing as possible. The target can then be imaged, and evaluation can begin.

Evaluation examines the relationship between the black and white edges; it determines the point where the edges can no longer be distinguished. For this test, in Murphy's case, evaluation was done using the srfmat2 MATLAB script created by Burns, but this can also be done automatically with the help of image processing software. The

SFR can be used to compare the difference between the horizontal and vertical resolution of a camera. SFR measurements are normalized with the intention that at a spatial frequency of 0, there is a SFR value of 1. If the SFR is higher than 1, automatic sharpening must have taken place somewhere during the imaging process. The SFR can then be determined for each color channel, and these can be compared, as well.

SFR or resolution is an important characteristic of a digital camera, and it is also important to ensure that no automatic sharpening is taking place behind the scenes. Thus, it is the belief of the researcher that this test be considered for museum photographers. It is also possible for museum photographers to visually determine the resolution of their camera. Wueller recommends software developed by Mr. Hideaki Yoshida of Olympus, which was available for download at the time of this writing at http://www.cipa.jp/dcs/hyres_1_e.html, for the visual test (Wueller, 2006).

Wueller also supports a resolution testing method that allows for tests on files that have been automatically sharpened during image processing. This method of evaluation is called the modulation transfer function (MTF), and it is more applicable to commercial camera testing. Image Engineering has software called Resolution Measurement to help with the calculations. Wueller uses this testing method with a test target called the Siemens Star. This method of testing can be used to analyze optical errors, to verify processing frequencies, and to determine the limiting resolution of a camera (Wueller, 2006).

Color Channel Registration

Testing for color channel registration requires the detection of color channel misregistration. Misregistration can be evident in any digital camera, whether the imaging component is an array CCD or a tri-linear scanning device. Color channel misregistration is a common occurrence, but it is found more often in scanning devices. In scanning cameras, misregistration is most noticeable in the scanning direction and occurs because the final image is often misaligned when the channels are compiled. Color channel misregistration can also be caused by chromatic aberration of the lens, regardless of the imaging device mechanism. Chromatic aberration occurs "when different wavelengths of light are bent at different angels and focused at different points behind the lens due to the index of refraction of a lens" (Murphy, 2005, p. 138). The most obvious place color channel misregistration is visible is around the edges of objects in the scene where the loss of sharpness can be seen.

To test color channel registration, the ISO Registration Chart is used as the testing target. The same knife-edges analyzed for the resolution test are used, and the same evaluation method, Burns' sfrmat2 MATLAB program, is used. The R and B channel are compared to the G channel to determine the degree of misregistration. It is desirable to have a misregistration error of less than 0.5 pixels. The edges analyzed are the center horizontal, center vertical, corner horizontal, and corner vertical; then the maximum and mean errors are calculated.

Although this is an interesting component of color reproduction, it is the belief of the researcher that this test not be included in the recommended testing procedure. This is because the only evaluation method is sfrmat2 MATLAB program, and this type of

evaluation is complicated. If, however, the sfrmat2 MATLAB program is used to determine resolution, then color channel registration should be tested for; but if an alternative method for determining resolution were used, then it would be difficult to evaluate color channel registration.

Depth of Field

Depth of field is the range of focus achievable for a specific exposure setting. Depth of field is increased as lens aperture is decreased; it is also increased when the distance the camera is from the subject increases.

Depth of field can be a challenge for museum photographers because lens aperture is dependent on luminance levels. Often in museum settings, a constant daylight balanced illuminant is used. These lights are not as powerful as strobes, and thus, compromises between depth of field and lens aperture are made. Also in a studio setting, space can be a restriction, so simply backing up the camera is often not an option. Murphy created a depth of field test and a test target. The target is made up of 13 columns, ranging in height from 0" to 6" with 0.5" increments. A knife-edged image is placed on top of each column. The target should be placed in the imaging area and the lights should be adjusted to reduce shadows. The camera should be focused on the center 3" knife-edge.

This test is also evaluated using the sfrmat2 MATLAB program; however, only one direction is analyzed: the one that had the highest SFR value. The results of the depth of field test are plotted against the area under the SFR curve from the selected direction.

This test is useful because it can show exactly where the sharpest focus is achieved and whether or not it is in the same location as the camera was focused. It is the researcher's belief that this test is not necessary for museum photographers. Although this is a useful test to determine the sharpness and acceptability of the cameras focusing mechanisms, depth of field is something photographers have been addressing all along. To test and to calculate exact depth of field performance of an imaging device is complex. The relationship between luminance and aperture will always need to be considered, and focus or the lack of focus is something photographers can see and correct.

Metadata

It is important that any camera quality metric tested for and calculated be stored with the digital files created by the device. The American National Standards Institute (ANSI), in collaboration with the National Information Standards Organization (NISO), has developed a metadata standard, *Data Dictionary – Technical Metadata for Digital Still Images,* referred to as ANSI/NISO – Z39.87-200X or ANSI/AIIM 20-200X. This standard (soon to be published as of the time of this writing) provides guidelines for the storage of all types of metadata, including camera-testing metrics. This type of metadata is referred to as *Image Assessment Metadata.* The purpose of this standard is described as:

> ...the operative principle in this section is to maintain the attributes of the image inherent to its quality. The title image assessment has both a present and future context: these elements serve as metrics to assess the accuracy

of output (today's use) and of preservation techniques, particularly migration (future use) (NISO, p. 47, 2005).

The sections of this standard that fall under the category *Image Assessment Metadata*, entitled *Spatial Metrics* and *Color Image Encoding,* are considered "high-level quantitative measures of imaging performance" (NISO, p. 47, 2005). The section entitled *TargetData* is used together with the other sections of the standard entitled *Basic Image Information* and *Image Capture Metadata. TargetData* is considered low-level benchmarking of the performance of the digital imaging system. It is recommended that the *TargetData* section correspond to available imaging performance standards. It would thus be helpful for each of the camera testing standards to make reference to and to include metadata storage recommendations.

Usability

Karniyati's research project, *Evaluating a Camera for Archiving Cultural Heritage,* is an interesting project to consider when discussing the usability or ease of execution of the camera testing procedures (2005). Karniyati's main objectives were to repeat Murphy's testing procedures, which were primarily based on the existing camera testing standards, and to determine the usability of the methods proposed and described by Murphy in her thesis. "This paper is primarily a usability study of her methods, and seeks to answer the question 'How easy are her methods to perform the necessary imaging and then analyze the results?' " (Karniyati, p. 3, 2005).

The findings from Karniyati's research indicated that this was no simple task. To begin with, there is some discrepancy between Murphy's testing set-up and Karniyati's. In Murphy's set-up, an area is masked off, each target is imaged in the same location, and the camera remains stationary regardless of the size of the target. In Karniyati's testing set-up, the camera is moved in accordance with the size of the target. This is the first indication that discrepancy exists between testing procedures.

Karniyati also found difficulty centering the targets because they all vary in size, thus if all of the targets were the same size, this could be avoided. Karniyati also found it difficult to keep the targets flat against the imaging area; however, a black easel could be used in order to avoid "leaning" the target, or magnetic targets could be created.

Dust in the camera, on the lens, or on the CCD's is another challenge. Dust can cause inaccurate results and should be avoided wherever possible. Although it is difficult and often not recommended for most people to attempt to clean a CCD, this must be considered before hand.

The evaluation methods are the most challenging part of camera testing. Not only is the evaluation difficult in order to determine if a camera's quality is acceptable, it is also necessary to have something to compare it to. Therefore, it is necessary to have value metrics in place, and these metrics should be categorized by camera type, such as 35mm, medium format, 4x5 single shot, and scanback.

Also, it is important to have a quality cut-off metric that would provide a point where it could determine a camera is absolutely no good. Professionals who are familiar with the evaluation methods must derive these types of metrics. It would also serve this

industry well to have user-friendly evaluation methods; this include methods that could be explained to photographers and methods that users can easily execute themselves. Although there are some software programs available, they still require operator computation to determine the final result. "Only when off-the-shelf software for this purpose becomes available can the full promise of digital imaging for institutional photograph collections be realized" (Frey, Reilly, 1999, p. *vi*).

Museum Photography

After looking over the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s case study videos, it is clear to the researcher that the most significant need in the museum photography world is a standard operating procedure (SOP) or any sort of standardized workflow guidance. The lack of this has lead to a situation where each museum has to formulate its own workflow.

Every museum photography department is driven and influenced by its people, equipment, budget, goals, skills, art handling, conservation, politics, and purpose. Within the imaging component itself, all other factors aside, a number of technical variables exist, and they must be considered for each institution and for each camera set-up.

The technical imaging variables include: cameras, lighting, profiles, color balancing, color-spaces, rendering intents, sharpening, color corrections, monitors, file formats, metadata, digital asset management (DAM), and backup storage media.

Because there are so many imaging variables, and because these are affected by and decided upon by each museum's people and purpose, workflows have become somewhat idiosyncratic. There is a general understanding that institutions are trying their best to navigate each of the variables and that they are doing the best they can, or perhaps know how to. The problem lies in the fact that because there are so many elements, and so many options per element, it has been difficult to set something in stone or to determine one "best" way. Not only has the technology been changing rapidly and new devices of higher quality are always being introduced, but user skill and understanding is also increasing over time, and a new "best" workflow could be created everyday. Table 4 lists both the technical variables museums face when developing an SOP and influential variables that may affect the technical decision-making.

Table 4: Museum Photography Variables.

Technical variables that must be considered when developing a SOP	**Other variables affecting museum photography departments**
Cameras	Staff
Lighting	Skill sets
Profiles	Budget
Color balancing	Equipment
Color spaces	Goals
Rendering intents	Art Handling
Sharpening	Conservation
Color Corrections	Politics
Monitors	Purpose
File formats	
Metadata	
DAM (Digital Asset Management)	
Backup storage media	

At some point, each museum should define and document a workflow for itself. This will allow it to maintain consistency across all of the imaging variables. It is important to note that, depending on the initial purpose of an image, different qualities may be deemed satisfactory. For example, when doing an installation shot, a 35mm digital camera may be the camera of choice, but when imaging a painting for the archive, a high-end 4x5 digital camera should be used. Images that are to be included in a "Master

Archive" may be repurposed at any time for specific reproduction objectives, and these files must be of the highest, unaltered quality possible.

Is it possible to create an SOP that can be applied to every museum imaging workflow? Perhaps yes, in theory. However, because each museum will have chosen a camera brand, monitor, profiling software, and such, it may be difficult to say this way is the only way. Rather what is helpful is a recommended "best practices." As of now, some best practices include saving the RAW camera file, not sharpening archival images, being mindful of profiles and color spaces, being consistent, keeping up with DAM systems, and backing up files on DVD or CD (and closely monitoring their stability).

Back-up storage is a large consideration for archive building projects. Not only is monitoring back-up media important, but upgrading file formats is a large concern. If manufacturers maintain consistent file format options, such as TIFF, then this problem may be minimized, but if proprietary file formats, such as camera file formats, are relied upon for future use, this could become very problematic. It is also a good idea to store back-up files off-site, or in a fire- and flood-proof safe.

Museum Photographers

Most cultural institutions began using digital photography in 1996, and currently most, if not all, imaging is done using digital cameras and digital workflows. Although digital photography has been accepted and implemented, findings from the *Direct Digital Image Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Need*s project indicate that some photographers feel they could benefit

from more knowledge of these new digital technologies. The benchmarking survey found that about 50% of museum photographers have a "perceived lack of knowledge about the new technologies" (Berns, Frey, 2005, p. 10).

Such a situation must lead to investment in retraining staff members and also to updated considerations when hiring new employees. Currently a background in photography and knowledge of art history are considered the most important characteristics necessary for working within a museum photography department. In order to keep up with new digital technologies and to hire and train staff, it is the recommendation of the researcher that newly hired persons have knowledge and or skill sets relevant to digital imaging.

To begin, a broad understanding of color science would be very helpful. A broad understanding of color science can provide one with a comprehension of digital imaging that goes beyond specific devices or current technologies. This knowledge of color science does not require one to be an expert; rather, if one understands color science in a broad manner, then he or she can understand how digital imaging methods are derived from color science theories. It is very important at this time to bridge the gap between scientist and photographers. If scientists share information in a manner that can be understood and useful to museum photographers, then it would facilitate learning about color science, and this will enable photographers to feel more knowledgeable about digital imaging technologies.

Along with a broad understanding of color science, it would be beneficial if one has knowledge of the human visual system and CIE color matching functions; skills

relating to color management and ICC profiling are essential. Photographers must be able to create profiles, and they should be equipped to do so in-house. Understanding of issues like illuminant variation and metamerism is also important, and knowledge of viewing standards is also an asset. It would also be helpful if photographers have an understanding of color space and RGB to CMYK conversions. It may also be an advantage to have knowledge of print applications in order to assist with the creation of publications. Table 5 lists the skill sets that are currently recommended for museum photographers.

Table 5: Knowledge and Skill Sets Needed for Museum Photographers.

Knowledge Museum Photographers Should Have
A broad understanding of Color Science
An understanding of the Human Visual System
CIE Color Matching Functions
Metamerism
Viewing Standards
Camera quality metrics
Color Space
Recommended Skill Sets for Museum Photographers
ICC profiling
Illuminant variation
Camera testing
RGB to CMYK conversions

The skills needed to be a museum photographer today have changed drastically within the past decade. For working photographers, training and continuing to learn about color science, digital imaging, and color management is essential. For younger photographers, this is a way of life; one must keep in mind that, in just a few years, the industry will be flooded with people who only used digital imaging, for film was before their time.

Because it is the responsibility of today's museum photographers to build archives of digital files that are the best they can possibly be and that will serve well into the future, the need for acquiring the necessary skills is a most urgent issue. Photographers working today are doing the best they can with the knowledge they have, but the continuation of learning and building skill sets is essential in order to ensure the best possible outcome. This is how camera testing and the usability of camera tests can be incorporated into a photographer's workflow. If photographers can conduct camera tests on their own, it will aid them in understanding how image quality parameters can and are affected by digital imaging technologies.

Chapter 6

Summary and Conclusions

The Four Selected Tests

The goal of this research was to simplify camera testing procedures for museum photographers by providing them with a selection of test that are most applicable to their goals. The four camera tests selected by the researcher as recommended tests for museums or institutions are tone reproduction using the OECF, noise, resolution and target based color accuracy. It is the researcher's belief that each of these parameters be tested for in order to ensure that a camera's capability meets the expectations of the photographer.

The research paper, *Digital Imaging for Photographic Collections: Foundations for Technical Standards*, discusses the topic of image quality. Specifically the researchers pose the question: What is image quality? The answer given is:

> According to The Focal Encyclopedia of Photography, the basic purpose of a photograph is to reproduce an image. One of the three basic attributes of a reproduction image is the reproduction of the tones of the image. Also of importance are the definition of the image (the reproduction of edges and detail and the amount of noise in the image) and the color reproduction (Frey, Reilly 1999, p. 10).

Tone reproduction, resolution, noise, and color reproduction accuracy are listed here as the attributes that constitute image quality. Is it coincidence that these same tests

have been selected as the most important and recommended camera tests? The answer is No. These test were selected because the parameter they evaluate is absolutely essential to image quality; thus, it is important to test a camera's ability to achieve each of these parameters. A coincidence it is not, because image quality and the characteristics that make a make a good image have always been one and the same. Digital technologies have simply presented new way of achieving image quality; hence, the performance of an imaging device should be tested for, especially when the camera is being used to photograph cultural heritage.

Of all the camera tests considered only four are essential in the context of this investigation. These tests, including tone reproduction, resolution, noise, and color reproduction accuracy, represent photographic quality metrics, and good pictures account for these characteristics. Due to the complex evaluation methods, and the probability that the cameras being used by museums for fine art reproduction are of high quality, the following tests are not considered required at this time: system spatial uniformity, dynamic range, spatial crosstalk, color-channel registration, and depth of field
If evaluation methods improve, and more photographers consider this type of testing, then perhaps a larger group of tests may be recommended. Also if a camera is being used for purposes other than art reproduction, different tests may be required. At this time it would be helpful to develop a testing kit specific to museum photography camera testing needs. Table 6 specifies what should be included in this type of testing kit based on the selected recommended tests.

Table 6. Recommended Camera Tests.

Quality Metric	**Standard**	**Target**	**Evaluation Method (Including Reference Points)**
Tone Reproduction (OECF)	ISO 14524	ISO OECF Chart	Software to calculate gamma and plot OECF curves
Resolution – Spatial Frequency Response (SFR)	ISO 12233	ISO Resolution Chart, or Siemens Star	Software to plot SFR Curves and calculate cy/pixel
Image Noise	ISO 15739	ISO Noise Chart	Software to calculate Image Noise and Signal to Noise Ratio (SNR)
Color Reproduction Accuracy – Target Based	ISO 1732-1	Gretag Macbeth Color Checker Charts	Software to compare Imaged target to Original and to calculate ΔE

For each test the appropriate standard is given, along with the target needed. The evaluation column represents the methods needed to determine the quality metric. It would be best if the evaluation methods were simplified by software that can calculate the final metric. It would also be helpful to include quality metric reference points so that testers can understand the camera's performance in relation to the determined metric. Also, it would be useful to include guidelines for storing any metadata generated from the tests. If kits like this were made available, it would encourage and enable photographers to do camera testing.

Should Camera Dealers do Testing?

Most often, when a photography studio is considering a new equipment purchase, the studio will liaison with an equipment dealer. Dealers will often times allow photographers to borrow cameras and equipment prior to purchase. This brings up an interesting question: Should dealers be doing camera testing? And, if customers demand this type of metric, would it be performed by the dealers? If dealers did camera testing, this would allow a customer to know, almost absolutely, the quality metric of the device. These are interesting questions, and a topic which provides a wide array of potential.

Testing Services

It is important to make mention of some existing camera testing services. These are companies that provide camera-testing services to interested parties. Image Engineering in Germany can be found on-line at http://www.image-engineering.de. Applied Image Inc. Precision Imaging of Rochester, NY can be found on-line at http://www.appliedimage.com. Quality Logic an American company, provides testing services geared towards manufactures. Quality Logic can be found on-line at http://www.qualitylogic.com. Digital Benchmarks of Newfoundland, PA also offers camera-testing services. The website http://www.digitalbenchmarks.com offers a wide range of information about camera testing, as well as published camera test results. These websites (in effect at the time of this writing) provide a plethora of useful information for anyone interested in camera testing.

Museum Conclusions

Given the drastic change in imaging technologies and workflows within the last decade, it is wonderful that museums have had enough funding to make these changes in a timely fashion. Digital imaging technologies themselves are impressive and complicated. Continuing education about digital imaging, color science, and color management are essential for successful digital imaging initiatives. Within the museum setting, it is most important to create the best possible digital images, to have a good DAM system in place for storage and retrieval of the file, and to keep back-up files stable and formatted correctly.

Museums themselves are complicated places that sometimes are restricted by budget and politics, but what is absolutely un-deniable is the fact that photography is now digital. Accompanying digital photography is the need for appropriately skilled photographers, large storage servers, DAM systems, and money continually allocated for new and improved technologies and also for archive maintenance. A museum that does not budget for digital imaging is doing itself a disservice, because there is no turning back, and there is no cutting corners. Museums who embrace these changes and keep up with the technology are on their way, creating great digital images that may very well stand the test of time. Preserving and now being able to share cultural heritage with the world through the Internet and museum databases is an awesome thing. Digital imaging has made this all possible; it is now time for scientists and photographers to come together and to help each other understand the needs and limitations of both the science and the reality of photographing cultural heritage.

Camera Testing Conclusions

It is important to realize and to understand that the entire color reproduction field is restricted by one thing: the gamma of any given device. Whether it be a camera, monitor, projector, scanner, film material, digital printer, digital press, or litho press, each device is limited by it own specific ability to reproduce colors. Thus, it is actually remarkable that digital color mapping techniques have lead to the "profile connection space" within "color" space that can allow the capability of each medium to be represented and reproduced.

That being said, camera testing itself is the investigation into the variables of one specific device within the entire color reproduction family. Knowledge of camera testing is important for photographers because it provides an in-depth look at how digital imaging device are engineered and manufactured, what quality components are required, and what compromises are made in order to maintain reproducibility within the color reproduction workflow.

It is best for any professional to fully understand the element with which they work, and because photography has experienced a recent "medium" shift, now is the time for photographers, especially those who document cultural heritage, to take a closer look at how to achieve the best possible image.

Chapter 7

Recommendations for Further Research

Further investigation into the area of camera testing for color accurate reproduction within museums and institutions, may begin with the development of a testing kit that would contain the recommended camera tests and simplified evaluation procedures. This would be useful for museum photographers because it would serve as a tool that could be easily used, and thus ensuring the consideration of camera testing.

What would also be useful are educational training sessions specific to color accurate reproduction. A course that would cover background information such as color science and colorimetry would be helpful, so that museum photographer may understand the science behind the technology.

Also with the recommended camera tests, it would now be an appropriate time to define a new step-by-step workflow that includes camera testing as the starting point for color critical photographic reproductions.

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Appendix A

A Case Study:

The Digital Imaging Workflow of Photographer Allen Phillips

at the Wadsworth Atheneum Museum of Art, Hartford, CT

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Abstract

This paper is designed to document the workflow of the digital imaging system at America's oldest public art museum, the Wadsworth Atheneum Museum of Art in Hartford, CT. Allen Phillips is Director of Photography for the Museum, and he has created an all-digital workflow which allows for highly accurate art reproductions. A description of the workflow is recorded and illustrated within this case study.

Background

The Wadsworth Atheneum Museum of Art received a $400,000 grant to implement a digital imaging initiative in the early part of 2002 from the Hartford Foundation for Public Giving. A small team of Wadsworth Atheneum staff members headed by Cindy Roman, the Associate Curator of European Paintings, did extensive research to put together an imaging project plan, and they then requested funding for the plan. After a search, Allen Phillips was hired in June of 2002 to direct the project.

After a staff needs assessment was completed, Allen started to purchase equipment. The BetterLight camera system was purchased, as well as all the supporting equipment necessary to establish a system capable of fine art reproduction.

Because the Wadsworth has a large collection of Hudson River School paintings that were on the verge of traveling to seven different venues, it was decided that a catalogue should be created to accompany the exhibit. This catalogue was the first large-scale project undertaken by the newly established imaging department, which consisted of Allen Phillips and his assistant, Natalie Russo.

This particular group of paintings presented unique challenges, as the paintings each had very large tonal scale, luminance highlights such as bright skies (in some cases looking directly into the sun), and deep, dark shadows full of detail. Upon visual examination of existing transparencies and reproductions from the transparencies of these works, it was found that the extremely long tonal ranges fell beyond the capability of conventional film. This was quite apparent within the transparency archive because often, the bracketed exposures were kept, and they revealed great detail in the highlights of the under-exposed images and great detail in the shadows of the over-exposed images.

It was also discovered that the transparency archive was in various states of decomposition; often the only remaining transparencies of a given image were the duplications, or they were suffering from aging and simple wear and tear.

Therefore, these works had never been accurately reproduced. The challenges faced with this body of work aided in the creation and solidification of the imaging workflow described within this paper.

With the successful completion of the first publication, *Hudson River School Masterworks from the Wadsworth Atheneum Museum of Art 2003*, another book, *Renaissance to Rococo Masterpieces from Collection of the Wadsworth Atheneum Museum of Art 2004*, was under way. *Hudson River School* was the first book published by Yale University Press New Haven to be created with all digital files, with a digital-to-plate workflow. The book was printed by Butler and Tanner of the UK, and has been re-printed a number of times, and plans are underway to publish it in Germany. Allen has continued to create high-resolution digital images for many exhibit catalogues and other museum needs. The workflow established is a success, and Allen continues to build an archive of master images.

This paper is a documentation of the unique workflow developed, implemented, and executed by Allen Phillips while working at the Wadsworth Atheneum. The information that follows is a description of the steps necessary to photograph a painting and to create an archival digital image. First presented is a list of the equipment, followed by a step-by-step description of the image creation process. This is followed by a brief explanation of the advantages of the BetterLight camera system, as well as an explanation of how the images are reproduced. Some closing remarks conclude this paper.

Case Study Painting

During the documentation of this workflow, a 20th Century Surrealism and Modernism painting by Peter Blume, *The Italian Straw Hat*, 1952, was imaged. The painting is oil on board, and the credit line reads: The Henry Schnakenberg Fund,

Wadsworth Atheneum accession number 1955.32. This painting was chosen for the case study documentation because it poses similar challenges as faced by Mr. Phillips on a daily basis. This is a very colorful work, has a large tonal range, and contains many little details.

Figure A1: Blume, Peter, *The Italian Straw Hat*, 1952, Oil on board, The Wadsworth Atheneum Museum of Art, 600 Main Street, Hartford, CT 06103, The Henry Schnakenberg Fund, 1955.32.

Equipment

The following equipment list describes both the equipment and, in some cases, how it is used.

- K-Lite – 6 high frequency daylight fluorescent lamps.
  - Output Intensity: 23,200 Lumen.
    Corrolated Color Temperature (CCT): 5,000 Kelvin
    Frequency of Energization: 27 kHz nominal (flicker-free for electronic imaging).
  - Color Rendering Index (CRI): 98 (5000K lamps installed).
  - Light Meter Reading (ASA100,1/60th): F11 measured at 50cm (20 in.), (similar to a 1000W tungsten light source).

Note: Depending on image lighting requirements, 4 or 6 lights may be used. Polarizing filters are optional, but not preferred, because they adversely affect the contrast range, increasing the contrast. This is hard to correct for, because it is hard to compensate for the altered tonal range. Polarizing filters also severely cut down the amount of light which defeats the battle for depth of field, because the light and the lens must both be polarized in order for polarization to effectively work. More information can be found at: www.intelab.com/klite/klite_data.shtml.

- Sinar 4x5 p2 view camera with a bag bellows lens shade

- Schneider – Kreuznach APO-Symmar 5.6/180 Multicoating lens with a rear mounted Daylight Infrared Filter 2.0mm thick: Figures A2 and A3.

Figure A2: Rear mounted Daylight Infrared filter.

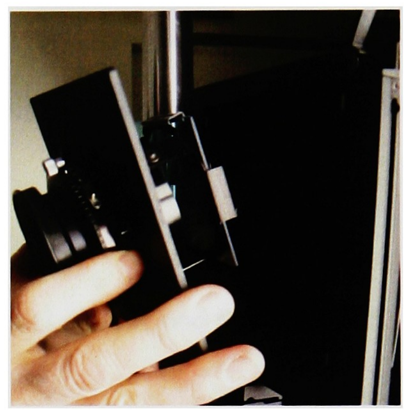


Figure A3: Rear mounted Daylight Infrared filter.

- BetterLight Super 8K-2 digital scanning back with a native resolution of 100% = 8,000 x 10,600 pixels. 244 MB maximum file size 24-bit RGB (8 bits per color channel), 488 MB maximum file size in 48-bit RGB (16 bits per color channel).

- BetterLight ViewFinder 5.2.2 digital camera controller software

- Johnson Magnetic Angle Locator: Figure A4.

- BetterLight Focusing Aids – The focusing aid has two squares that are made up of very fine lines. One square has vertical lines, and one square has horizontal lines. This is important because later in the workflow, when the image focus will be

digitally verified, the proper line direction must be selected in order for the focusing to properly take place: Figure A5.

Figure A4: Johnson Magnetic Angle Locator.

Figure A5: BetterLight Focusing Aid.

- 8x Loop
- Center post camera stand with a Majestic model 1200 tripod from Modern Builders Co. Chicago IL
- Painting Easel: Figure 6.
- GretagMacbeth 24 Color Checker with Bogen stand
- PowerMac 3.6 Power PC G4 866 MHz Dual processor
- Mac OS 9.2.2 (OS 9 is preferred because the camera software is problematic in OS 10)
- LaCie Electron 22 Blue IV (22" monitor) with light hood: Figures 6 and 7.
- LaCie Blue Eye (Sequel Imaging) Calibration Hardware device

Note that the monitor is set to a calibrated state that is described in terms of its brightness, gamma and white point temperature. This calibration is performed using the Blue Eye calibrator, which directly controls the electronic output of the monitor phosphors. An ICC monitor profile is created that is then used by the operating system to properly display RGB values. The ICC profile translates the

RGB values to absolute color metric measurements, which are expressed in CIELAB. The profiles describe the color that the RGB values actually represent, and they relate device-dependent RGB values to device- independent CIELAB values.

- Gamma 2.2
- Color Temperature 5500 Kelvin
- White Luminance 85 cd/m2
- Black Luminance- some adjusting is often necessary; the process of setting black and white point is one that requires careful attention to detail.

  Note that LaCie Blue Eye Hardware calibration sets the white point and the gamma by adjusting the guns of the digitally enabled monitor. Then it creates a monitor profile.

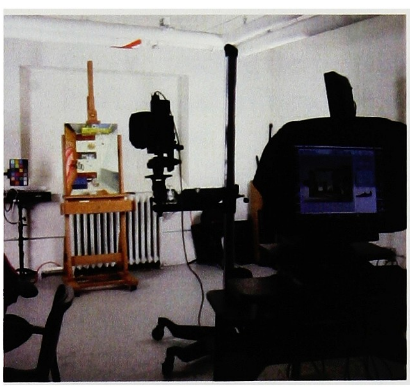


Figure A6: Studio set-up with LaCie monitor.

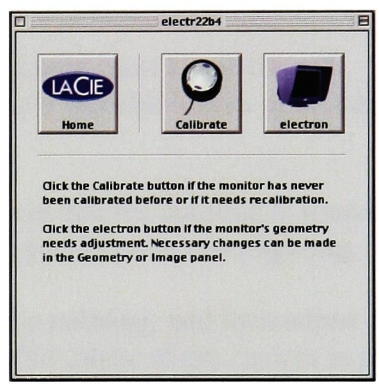


Figure A7: LaCie Calibration menu.

Image Acquisition

The image acquisition chapter of this paper documents and explains the step-by-step procedure of the workflow. Imaging a painting ranges from three to eight hours, depending on the size of the painting, the condition it is in, and whether or not the studio must move to the painting's location. Included in this case study is an example of a set-up in which the process of moving the equipment and the size of the painting lends itself to a full day's work. It is apparent from the scale of the painting shown, that this process can sometimes be lengthy. The steps for digitally imaging the painting within this case study are:

1. Prior to placing the painting on the easel, the painting must be un-framed. Professional art handlers who are trained to handle valuable works of art complete this process.

2. Place the painting on the easel, with care to ensure that the painting is square on the easel. The paintings are placed vertically to enable more even lighting.

3. First, use the angle locator to find the angle of the painting, and then adjust the camera with a global tilt adjustment so that the film plane of the camera is parallel to the artwork: Figure A8.

4. Place the artwork square in the frame of the camera's ground glass using the graduated lines as reference guides.

5. Place BetterLight focusing aids at opposite corners of the painting (for example, the upper left corner and the lower right corner). The focusing aids are very thin plastic cards which should be placed on the surface of the painting. A tool (created by Allen Phillips) has enabled the placement of the upper aid without adhesive contact to the painting. The tool is simply a small piece of wood the focusing aid it attached to; this rests on the upper edge of the painting: Figure A9.

Figure A8: Angle locator and camera.

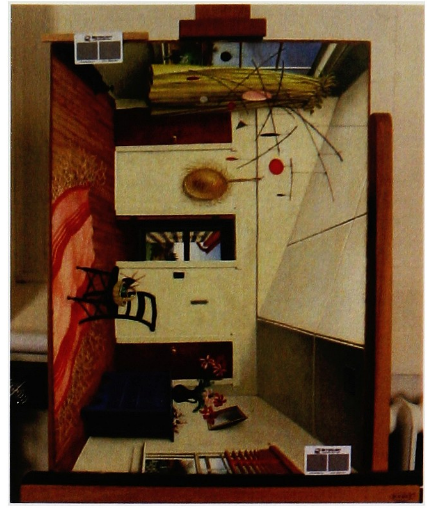


Figure A9: Focusing aids at either corner of painting.

6. Fully open the lens; using a loop on the ground glass, focus the camera on the lower focusing aid. Then check the focus on the upper one. If the upper focusing aid is not on the same focal plane as the lower aid, an adjustment of the front standard of the camera is required. Adjust until both aids are in physical, visual focus. (It is important to note that the rear standard adjusts the shape of the image seen on the ground glass, and the front standard adjusts the focal plane). The focus knob is the lower knob below the rear standard; adjusting this makes slight movements in the rear standard, while maintaining a parallel relationship to the artwork.

7. Then, switch focusing aids to the opposite corners of the artwork, and verify that they are in focus. Now the artwork is in visual focus and parallel to the film plane.

8. Turn on the BetterLight camera system by flicking the little switch in the rear of the camera's hard drive. This must be done prior to launching the BetterLight software: Figure A10.

9. Next. insert the BetterLight digital camera back: Figure A11.

Figure A10: BetterLight camera hard drive.

Figure A11: Inserting the BetterLight digital back into the 4 x 5 camera.

10. Stop down the lens to approximately f11.

11. Place the Macbeth 24 Color Checker on its stand in the image area.

12. Launch BetterLight ViewFinder software.

13. First select Prescan, which will create a low-resolution image. At this time. no adjustments have been made to the digital capture commands: Figure A12.

    The first objective with the prescanned image is to digitally verify the focus of the image. This process happens by selecting the focus tab panel in the ViewFinder main control window, select the green channel, set magnification according to the size of the focusing aid in the prescan, and select the sound symbol. Then press the "go" button. A focusing rectangle will appear within the prescan image area once inside the focusing window; the size depends on the selected magnification. Place the focusing rectangle on one of the focusing aids within the area of the lines within one of the squares: Figure A13.

    It is important to place the focusing rectangle on the lines of the focusing aid that are perpendicular to the movement of the imaging CCD array. Once the sound symbol has been selected, a noise that can be heard will begin: Figure A14. The goal is to adjust the fine focusing knob on the camera until the highest pitched sound can be heard. (Numerical and graphical information is also available as a focusing tool). Once this is achieved, stop the sound by selecting the "stop" button. Then repeat this process for the other focusing aid, making sure to select

the appropriate line direction. (It should be the same square on both focusing aids). Then focus on the second card. The goal is that both focusing aids focus at the same point on the focusing knob on the camera. Any discrepancy in this will hinder the focus of the image; thus, it is extremely important that both aids focus at the same point. Hence, there is zero variation tolerance: Figure A15.

It is also important to repeat this process for the other two corners to ensure that the painting is not warped and that all corners are focused; this requires a second prescan. If the focusing aid does not focus on the same point on the knob, camera adjustments will be required, and this whole process will need to be repeated until all corners are in exact focus. The importance of this step is supported by the camera's capability of achieving excellent results. This system is capable of focusing at 1/16 of an inch.

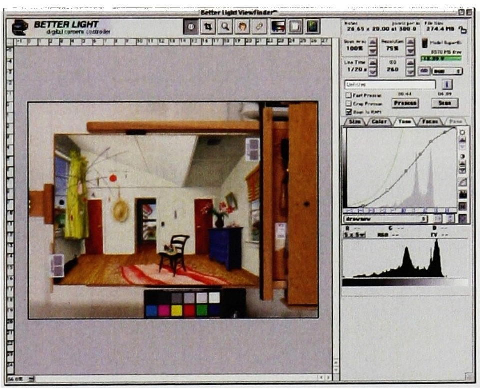


Figure A12: The prescanned image.

Figure A13: Focusing rectangle.

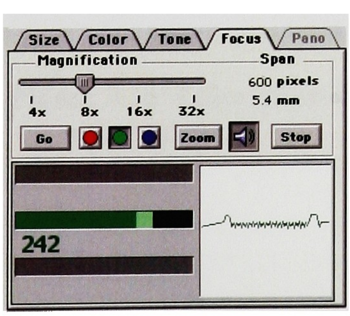


Figure A14: Focusing window.

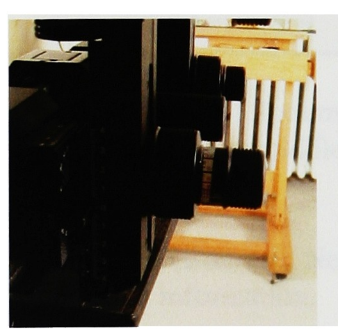


Figure A15: The fine focus knob the camera.

14. The next step is to gray balance the image; this is the only time the GretagMacbeth 24 Color Checker is used during this process. Select the color tab in the ViewFinder main control window: Figure A16.

    Once in the color window, the spot meter cursor will appear. Four different spots may be simultaneously addressed. Place a spot meter spot on each of the four middle gray patches in the Macbeth Color Checker: Figure A17.

    Then click the auto balance button. The reading should be averaged within the tolerances of the Color Checker card itself: Figure A18.

    Then select the clear meter button. Now the image has been balanced for the light source used. The color checker can now be removed from the imaging process. This custom gray balanced setting will be saved and used when the final image is created.

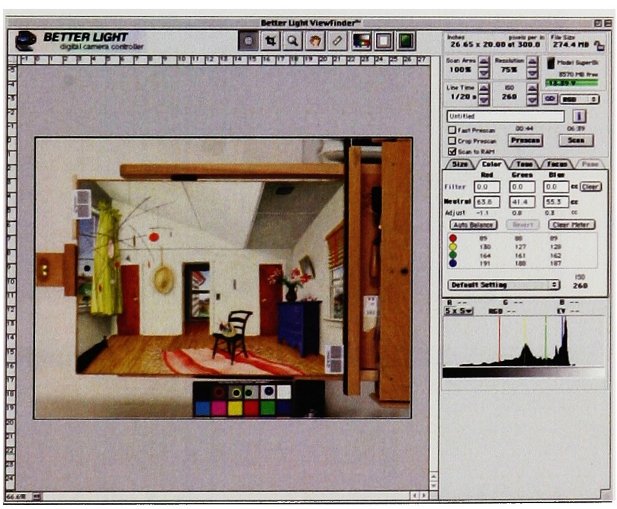


Figure A16: Color tab in the ViewFinder main control window.

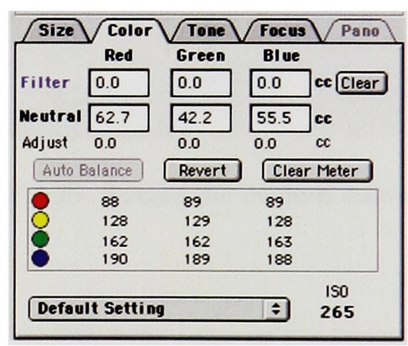


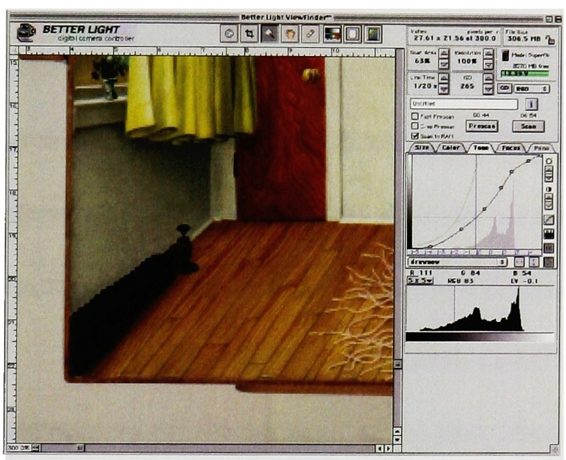
Figure A17 (Top): Spot meter spot on each of the four middle gray patches.

Figure A18 (Bottom): Neutralized gray patch information.

15. Next, the tonal range of the prescanned image is adjusted and the custom curve is saved. Select the tone tab in the ViewFinder main control window; this is where

tonal adjustments can be made to the prescan. In a very fluid and intuitive manner, adjustments are made between the ISO and the tone curve; this can be done by either global adjustments in contrast and or brightness, or manual adjustments can be made to the curve itself. Many times it is necessary to make adjustments in all of these ways, with the goal at this stage being the replication of the tonal scale of the original artwork (disregarding for the moment the affects these adjustments have on the color).

Before the color is adjusted, the tonal scale must be correct. This is a subjective process that requires practice. Examine the shadow areas and the highlight areas, and make sure detail is visible. Also, do an overall assessment of the mid-tones, ensuring that the overall impression of the painting is captured. When a desirable curve is achieved, it is saved and named accordingly. Figures A19 and A20.



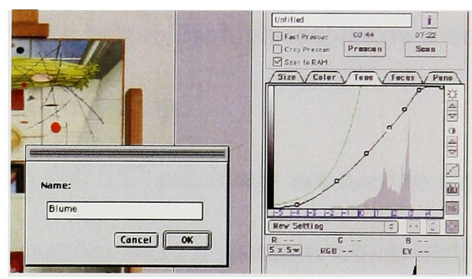


Figure A19: Tone tab in ViewFinder window. Figure A20: Saving the custom curve.

16. Once the curve has been determined, it is time to adjust the color of the image. This process requires alteration of the original camera profile in order to create a custom profile for each painting. First, the camera profile: early on when the camera was first set up, a camera profile was created using the studio lighting condition, the normal working aperture f11, and an average curve, which was created by Allen. The GretagMacbeth 24 Color Checker target was photographed; the profile was generated using Kodak Color Flow profiling software.

Allen purchased GretagMacbeth Profile Maker 4.0 professional and tested it.

After several attempts to create a profile that was acceptable by visual examination, Allen

was not satisfied with the results, and the resulting profile was rejected. Using Kodak Color Flow Profile Editor version 2.1 software, a new camera profile was created using the 24 patch Color Checker. This profile was then adjusted until Allen was satisfied with the results. This then became the basic camera profile, which is still the starting point, used in the imaging process.

It is very important to understand that this is just the starting point in imaging the works of art, because with time and experience, it is very clear that individual paintings require color adjustment for accurate reproduction. This is because the spectral reflectance values of the pigments used in works of art are more complex and vary greatly from the Color Checker target. These differences have to be compensated for in some way, and Allen prefers to create a custom profile before the high-resolution scan for each painting, rather than adjusting the files later in Photoshop.

Note that the GretagMacbeth Color Checker DC 237-patch was not used to make the camera profile because, at the time, the glossy patches were a problem which had not been addressed. Allen initially thought he would be using polarizing filters, and it was understood that problems existed between the DC checker and a polarized workflow. The polarizing workflow was later abandoned.

The steps to creating a custom profile are:

1. Using the custom curve as described above, the artwork is imaged using a low-res setting, less than 50 MB. This file has the basic camera profile imbedded in it, and the image is rendered with the respective tonal curve. The tonal curve translates the CCD's "raw" luminance data into "finished" brightness data in 16 bit RGB values.

2. To make color adjustments by creating a custom profile, the following procedure is used: First open the Kodak Color Flow Profile Editor version 2.1 software with

the starting camera profile: Figure 21. Then open the low-res 16-bit file that was just created, in the drop-down menu select View>Image> and select the respective image: Figure A22. Once the image is open, the necessary color adjustments can be made. In the drop-down menu, select ColorTools>Selective Color: Figure A23. This will bring up a color-editing window that allows for specific color adjustments; colors needing adjustment based on visual evaluation are selected with an eyedropper tool: Figure A24. This window allows for adjustments of color hue, saturation, and lightness.

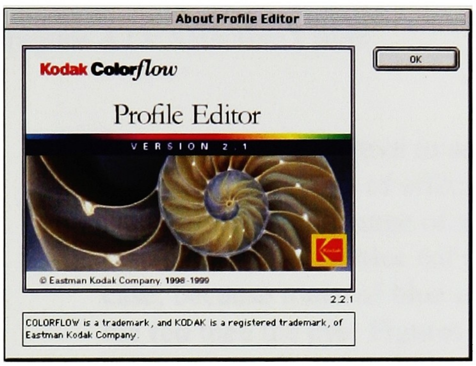


Figure A21: Kodak Color Flow Profile Editor version 2.1 software.

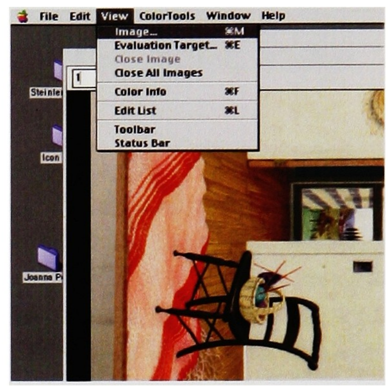


Figure A22: Opening the respective file.

Figure A23: Selective Color.

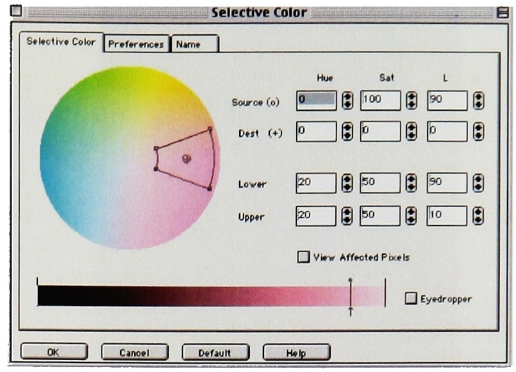


Figure A24: Color Editing window.

3. Use the eyedropper tool to select a color. View the Affected Pixels by checking the box; if the range of affected color requiring adjustment needs to be larger or smaller, adjust the range of affected pixels. In this case, the most obviously skewed color is the blue (of the chest of draws and the area of sky), as often is case, because tones of blue contain red, and the camera is much more sensitive to the red then the eye: Figures A25, A26, A27, & A28. The camera sees the red that the eye doesn't and therefore picks it up. (This phenomenon can clearly be seen in the reproductions of Edward Hopper's watercolor skies). Once the color has been corrected save the adjustment, the adjustments will be compiled in the edit list.

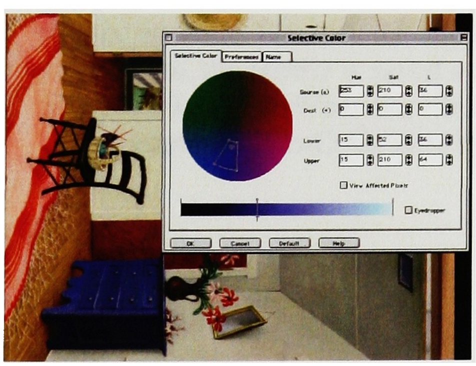


Figure A25: Eye dropper tool.

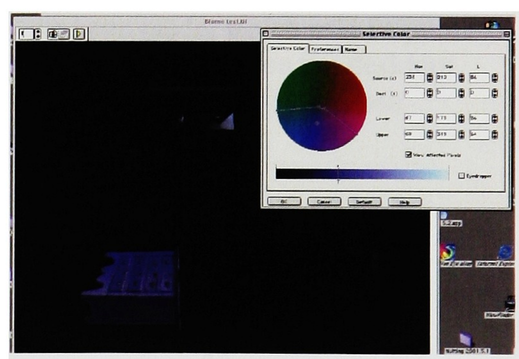


Figure A26: Selected color.

Figure A27: Color before adjustment.

Figure A28: Color after adjustment.

4. The next color adjustment was the yellow of the curtain. The hue did not need adjustment, but an increase in saturation was necessary; again, this correction was saved and added to the edit list: Figure A29. Next, the straw hat was selected; the color is pale beige. A color like this creates a challenge, because in order to affect the pixels in the straw hat, many other pixels are affected. This becomes a balancing issue. Once all the adjustments have been made, which may require many edits, the profile is saved as an ICC file and will appear on the desktop: Figures 30 and 31. When the file appears, it must be moved to Macintosh HD>System Folder>ColorSync Profiles: Figures 32 and 33.

Figure A29: Color corrected image with edit list.

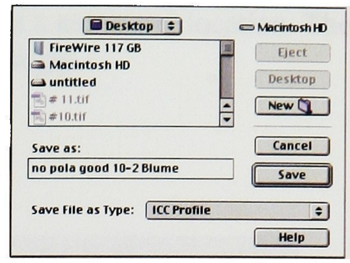


Figure A30 (Top): Saving ICC profile.

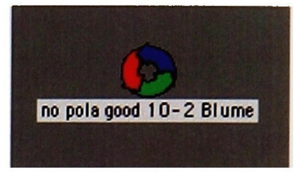


Figure A31 (Middle): ICC profile as it appears on the desktop.

Figures A32& A33 (Bottom): Moving the profile to the ColorSync folder.

5. The next step is the high-resolution digital image-scan. This requires imbedding the custom profile within the software prior to scanning. Launch the BetterLight ViewFinder software. In the drop-down menu, select Edit>Preferences, the preferences window will appear: Figure 34. Next, click the Choose Profile button and select the custom profile created for the artwork; click the Open button: Figure A35. Once the profile is in the Preferences window, click OK: Figure A36. At this point, double-check the pre-scanned image to ensure the image appears, as it should. Now, you are ready to make the high-resolution scan with the imbedded custom profile. Select the resolution desired in percentages, often 92%: Figure A37. The file will now be scanned with the custom curve and the custom profile. Press the Scan button to activate the camera: Figure A38. When the camera has

completed the scan, a save menu will appear and request a name and location. The file will be save in TIFF format. Name and save accordingly.

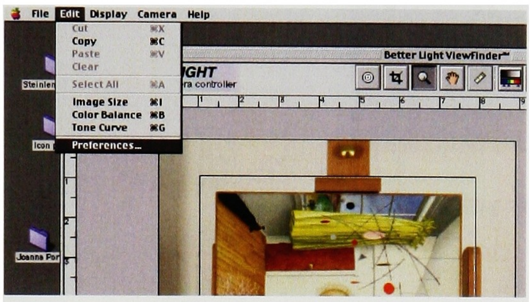


Figure A34: Select preferences to find profile.

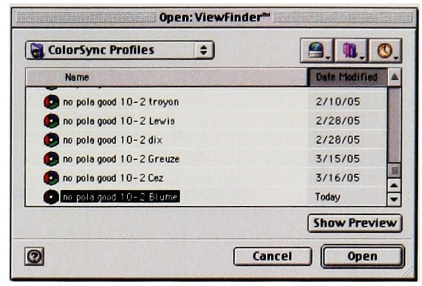


Figure A35: Select profile.

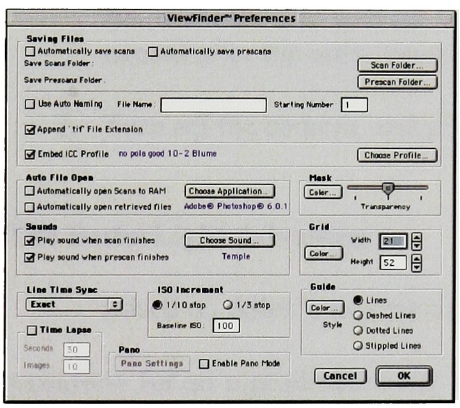


Figure A36: Verify the proper profile is selected.

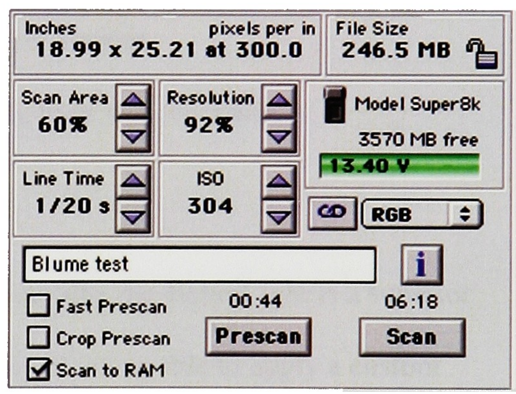


Figure 37: Set high-resolution image scan.

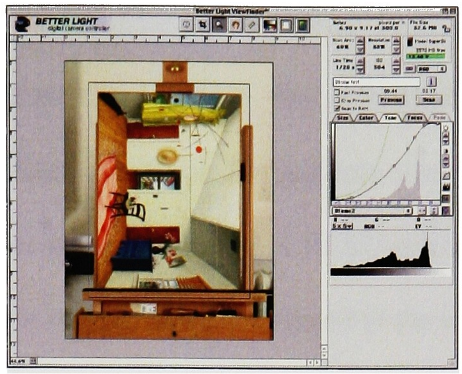


Figure A38: Scanning the high-resolution digital image.

6. The next step is to open the file in Photoshop with the embedded adjusted camera profile, do not convert to the working space. Once the file is opened with the embedded profile, first check to see if all of the corners are in focus, rotate the image accordingly; visually assess the appearance of the image. Select File>Save As, name the file with the museum accession number, place the file in a directory named after the artist including the accession number.

7. Turn off the camera, and place the scanning back into its cradle.

The BetterLight Advantage

Based on Allen's experience, the two reasons why the BetterLight is a superior workflow for art reproduction are: 1) The capability of being able to apply a custom profile to the prescan, and 2) It gives the photographer total control of the tonal curve. Because of these two advantages. The photographer is allowed to make both color and tonal adjustments to the file prior to the high-resolution imaging; therefore, fewer, if any, adjustments need to be made to the file once it has been created. The goal is to make no adjustments to the file once the high-resolution file has been made. This will ensure the highest possible image quality and will prevent the need to make color adjustments when the original is no longer available for referencing.

Image Output

The images acquired are saved as TIFF files in RGB color mode, with their custom profiles embedded. Each file is saved in multiple sizes within their own directories. The high-res files are always saved in 16-bit with the custom camera profile. A version is also prepared for output, and it is cropped to the edge of the painting, reduced to 6000 pixels across the length, 8-bit, RGB, custom profile, and some minimal amount of sharpening is done to account for the decrease in size. Each painting directory is stored on multiple hard drives and DVD's. The DVD's provide back up and are stored in a fire-safe box within the museum. The images can be easily accessed through the hard drives they reside on for immediate use.

As mentioned at the beginning of this paper, most of these images are intended for reproduction purposes. Allen has successfully worked with printers all over the world; his department is responsible for fulfilling Rights and Reproduction requests for the entire museum and for outside parties who request images. Allen will send out RGB files with a request for a proof. Most often this request is granted. Allen has received some interesting results, but the proofing process allows some time for corrections.

When Allen was working with Yale University Press on the two publications titled *Hudson River School Masterworks from the Wadsworth Atheneum Museum of Art 2003,* and *Renaissance to Rococo Masterpieces from Collection of the Wadsworth Atheneum Museum of Art 2004*, the RGB to CMYK conversions were done through a pre-press house in Rockford IL, called ProGraphics. They were responsible for providing

the proofs to Allen, at which time suggestions for improvements were made, until the proofs were accepted.

Allen has also developed a close relationship with a local printer responsible for printing many of the museum's regular publications, such as the annual report, members' quarterly, and the events calendar. Allen profiled the printer's calibrated proofing device, and with this profile, Allen converts his images from RGB to CMYK. The images are then printed on the proofing device, and are returned to Allen for approval, more often then not with much success. It is then the burden of the printer to match the proof on press. Having a profile for the printers proofing device also allows Allen to soft-proof the images, in which case he can make image adjustments prior to the proofing process in order to avoid repeated rounds of proofs.

Closing Remarks

I have been fortunate enough to have worked with Allen for four years before returning to RIT for a Master of Science Degree in Print Media. (Figure A39 shows Allen at work at the Wadsworth Atheneum.) Allen is a person who is in pursuit of technical excellence, as can be seen from his diligent determination evident within his imaging workflow. Allen insists on excellence when imaging artwork, and in all aspects of technical marvel. The Wadsworth Atheneum is very happy to have Allen, and I am grateful to have worked with him.

Figure A39: Allen Phillips in one of the Galleries at the Wadsworth Atheneum Museum of Art in Hartford, CT, imaging a large painting, requiring an on-location shoot.

Appendix B:

Reference Tables of Standards and Parameters

Appendix B

Reference Tables of Standards and Parameters

Table B1: List of standards that are summarized in this standards review.

Title	**No.**	**Date**	Organization	**Form (in ISO terms)**	**Edition**	TCs
Viewing conditions – Graphic technology and photography	3664	02/02/2002	ISO	FDIS	2nd	ISO/TC 42 (Photography), ISO/TC 130 (Graphic Technology)
Photography- Illuminants for sensitometry – Specifications for daylight, incandescent tungsten and printer	7589	09/01/2000	ISO	FDIS	2nd	ISO/TC 42 (Photography)
Photography – Electronic still picture cameras- Terminology	12231	06/15/1997	ISO	FDIS	1st	ISO/TC 42 (Photography)

Title	**No.**	**Date**	Organization	**Form (in ISO terms)**	**Edition**	TCs
Photography- Electronic still picture cameras – Resolution measurements	12233	09/01/2000	ISO	FDIS	1st	ISO/TC 42 (Photography)
Graphic Technology- Displays for color proofing- Characterization and viewing conditions	12646	05/30/2002	ISO	DIS	N/A	ISO/TC 130 (Graphic Technology)
Photography- Electronic still picture cameras- Method for measuring opto-electronic conversion functions (OECFs)	14524	12/15/1999	ISO	FDIS	1st	ISO/TC 42 (Photography)
Photography- Electronic still picture imaging – Noise measurements	15739	05/01/2003	ISO	FDIS	1st	ISO/TC 42 (Photography)

Title	**No.**	**Date**	Organization	**Form (in ISO terms)**	**Edition**	TCs
Graphic technology and photography- Colour characterization of digital still cameras (DSCs) – Part 2: Methods for determining transforms from raw DSC to scene-referred data	17321-2	10/10/2003	ISO	WD	N/A	ISO/TC 42 (Photography) ISO/TC 130 (Graphic technology)
Photography and Graphic Technology- Extended color encodings for digital image storage, manipulation and interchange- Part 1: Architecture and requirements	22028-1	08/30/2002	ISO	DIS	N/A	ISO/TC 42 (Photography) ISO/TC 130 (Graphic technology)

Title	**No.**	**Date**	Organization	**Form (in ISO terms)**	**Edition**	TCs
Multimedia systems and equipment – Colour measurements and management- Part 8: Multi media colour scanners	61966-8	02/2001	IEC	FDIS	1st	IEC/TC 100 (Audio, video and multimedia systems and equipment)
Multimedia systems and equipment – Colour measurements and management- Part 9: Digital cameras	61966-9	06/2000	IEC	FDIS	1st	IEC/TC 100 (Audio, video and multimedia systems and equipment)
Graphic Technology- Color reflection target for input scanner calibration	IT8.7/2	06/21/1993	ANIS	FDIS	1st	IT8 Subcommittee 4
Colorimetry	15.2	1986	CIE	N/A	2nd	CIE/TC 1.3 (Colorimetry)
A method for assessing the quality of daylight simulators for colorimetry	51	1986	CIE	N/A	2nd	CIE/TC 1.3 (Colorimetry)

Title	**No.**	**Date**	Organization	**Form (in ISO terms)**	**Edition**	TCs
Data Dictionary- Technical Metadata for Digital Still Images	N/A	06/01/2002	NISO	DIS	N/A	N/A

Table BII: A reference table for the digital image quality parameters of the discussed standards.

Standards Information			Digital Image Quality Parameter							
Title	**No.**	**Organization**	**Spatial Uniformity**	**Tone Reproduction**	**Color Reproduction Accuracy**	**Noise**	**Dynamic Range**	**Spatial crosstalk**	**Resolution**	**Non-Image Quality**
Viewing conditions- Graphic technology and photography	3664	ISO								X
Photography- Illuminants for sensitometry- Specifications for daylight, incandescent tungsten and printer	7589	ISO								X
Photography- Electronic Still picture cameras- Terminology	12231	ISO								X
Photography – Electronic still picture cameras- Determination of ISO speed	12232	ISO								X
Photography- Electronic still picture cameras – Resolution measurements	12233	ISO							X	
Graphic Technology- Displays for color proofing- Characterization and viewing conditions	12646	ISO								X
Photography- Electronic still picture cameras- Method for measuring opto-electronic conversion functions (OECFs)	14524	ISO		X						
Photography- Electronic still picture imaging – Noise measurements	15739	ISO				X	X			
Graphic technology and photography – Colour characterization of digital still cameras (DSCs) – Part 1: Stimuli, metrology, and test procedures	17321-1	ISO			X					

Graphic technology and photography- Colour characterization of digital still cameras (DSCs) – Part 2: Methods for determining transforms from raw DSC to scene-referred data	17321-2	ISO			X					
Photography and Graphic Technology- Extended color encodings for digital image storage, manipulation and interchange- Part 1: Architecture and requirements	22028-1	ISO			X					
Multimedia systems and equipment- Colour measurements and management- Part 2-1: Colour management- Default RGB colour space - sRGB	61966-2-1	IEC			X					
Multimedia systems and equipment – Colour measurements and management- Part 8: Multi media colour scanners	61966-8	IEC	X	X	X			X		
Multimedia systems and equipment – Colour measurements and management- Part 9: Digital cameras	61966-9	IEC	X	X	X					
Graphic Technology- Color reflection target for input scanner calibration	IT8.7/2	ANIS			X					
Colorimetry	15.2	CIE								X
A method for assessing the quality of daylight simulators for colorimetry	51	CIE								X
Data Dictionary- Technical Metadata for Digital Still Images	N/A	NISO								X