Introduction

Three Layer Stack: Color Management, Color Rendering, Color Enhancement

The primary focus of this course is color rendering and color enhancement. Both of these are built on top of a color management foundation. Color management provides the repeatability and predictability of the image creation and reproduction process that is essential for color rendering and color enhancement to work reliably enough for feature and game production.

Distinctions between the three layers along with pointers to resources for those interested follow in the next few sections.

Color Management

The ICC defines color management as “communication of the associated data required for unambiguous interpretation of colour content data, and application of colour data conversions, as required, to produce the intended reproductions.” It follows that if the associated data are not communicated, then interpretation of the color content becomes ambiguous at best, and just plain wrong at worst; and accurate conversion between representations becomes improbable if not impossible. Much of this section of the course will emphasize the need to know and communicate color image encoding metadata such that color can remain unambiguous from scene to screen.

Color management is a topic in itself. In fact, it has been a topic in itself at SIGGRAPH four times in the last decade:

- 2000  *Color Science and Color Management for CGI and Film* – Charles Poynton, Maureen Stone, Michael Bourgoin, Arjun Ramamurthy and Dave LeHoty.
- 2004  *Color In Information Display* – Maureen Stone
The most comprehensive work on digital color management is the 2nd Edition of Edward Giorgianni & Thomas Madden’s *Digital Color Management: Encoding Solutions* (John Wiley & Sons, 2009). Anyone who is serious about color management should have this on their desk. Most of the Academy of Motion Picture Arts and Sciences’ Image Interchange Framework (IIF) comes from an original design by Giorgianni.

Also recommended is Glenn Kennel's *Color and Mastering for Digital Cinema* (Focal Press, 2007). This book also includes almost all the contents of Tom Maier’s articles on color processing for digital cinema which appeared as a series in the *SMPTE Journal*.


A second work that deserves mention as an introductory color science text is *Color Imaging – Fundamentals and Applications* (A. K. Peters, 2008) by Erik Reinhard, Erum Arif Khan, Ahmet Oğuz Akyüz and Garrett M. Johnson although it should be noted that this latter book does not really concern itself with photochemical processing, as Hunt’s work does.

Densitometry and basic colorimetry can be automated; they involve no human judgment, no consideration of the complex factors the brain weighs in forming an image when that image is presented in a set of viewing conditions. Those considerations left unchecked, however, can derail a color management system. The reference work here is the second edition of Mark Fairchild’s *Color Appearance Models* (John Wiley & Sons, 2005). Provision for color appearance factors is a notable feature of the Truelight system, although the separation and naming of the relevant concepts may be different there.

The practical use of color management in postproduction prior to the handoff to Digital Intermediate (DI) is documented largely by the vendors of application or plug-in products for that market, and the odd chapter in books on production tools. Other than in compositing tools, color management tends to be missing from the CG artist’s toolkit.

**Color Rendering**

Color images at the moment of capture are a very literal representation of the subject material, in an image state termed ‘scene-referred’. Prior to display, the scene-referred image is converted to an image more agreeable, according to established convention, to the human eye, and this ready-to-view state is termed ‘output-referred’. The conversion from scene-referred to output-referred is the task of (in fact, it is really the definition of) color rendering.
Much of color rendering is concerned with accommodation of differences in the viewing conditions at the time the original image was created (where the viewing conditions are those of the scene itself) and those of the reproduction environment. A lesser part of color rendering is an agreed-on diversion from ‘accuracy’ of reproduction in favor of established user preferences. Hunt identified six types of color reproduction: spectral, colorimetric, exact, equivalent, corresponding and preferred. While not a strict progression along every dimension, these reproduction types can loosely be said to be ordered from what instrumentation would claim was a ‘perfect’ match to what a human would say was an ‘ideal’ match. Reproduced skies are often preferred when appearing clearer and more blue than the original, and similar preferences can be cataloged for grasses and some skin tones.

When the preferences are nearly universal, it is convenient to build them into the image reproduction process, and the usual spot for this is in what is termed the color rendering phase of image reproduction. With an inexpensive digital still camera (DSC), the difference between the internal unprocessed camera raw file and the sRGB file presented to the user includes internal-to-the-camera color rendering. Control of color rendering for the inexpensive DSC is effectively done by the camera designer and realized in silicon.

In film-based workflows, color rendering is done as part of film processing, in accord with the film’s photochemical and physical structure. As with the inexpensive DSC, color rendering is a locked process where the rendering behavior was determined by the emulsion and processing designers.

The Jones Diagram at right shows the color rendering performed by properly developed Kodak original camera negative and print stocks when processed according to Kodak standards. (This image was created by Doug Walker, is used by permission, and is best appreciated in the context of the April 2005 issue of American Cinematographer, where it is accompanied with a wealth of useful information in an article titled The Color-Space Conundrum – Part Two: Digital Workflow.)
Incidentally, when searching for technical data such as the curves defining the relationship between exposure and density, or spectral dye densities, or anything else about a film, the following two links may be useful:

http://motion.kodak.com/US/en/motion/Products/Production/index.htm

and


Color Enhancement

As I am not a colorist by profession, I would be hard pressed to recommend a set of books for those new to the field. Fortunately Patrick Inhofer, a colorist working in New York City, maintains a useful list of such books on his website, which can be found here:

http://www.fini.tv/primaryshots/learn_color_correction/

Scope of these course notes

These course notes discuss color management. Though they might occasionally mention color rendering or even color enhancement, their main focus is the bottom layer of the stack. The other authors in today’s course are providing content regarding the middle and upper layers.

Note that I have no background in gaming and can’t speak to color management there, other than to say that in preparing this course I have been impressed by the resources the game industry has dedicated to color management in the last few years.

Color Image Encodings and Standardization

On the spine of Giorgianni & Madden, the words read Digital Color Management; on the cover the subtitle is “Encoding Solutions”. Color Image Encodings are the *sine qua non* of color management. Without knowing the color image encoding, you are at best guessing what the pixels in the file represent, and how they should be transformed for display.

Color image encodings, to be genuinely useful, need to be the product of some standards organization. Without this blessing, hardware and software organizations will ignore them. The good part about standardization is that the documents become publicly available; the bad part is that they are not free. Buying standards documents from SMPTE or from ISO can be done over the web, and a well-written standard can serve as a model for a good in-house document on encodings or practices.

That said, SMPTE or ISO documents are not cheap, and for an independent or small shop, Charles Poynton’s *Digital Video and HDTV — Algorithms and Interfaces* (Morgan Kaufmann, 2003) is a useful compilation of the salient points of dozens of standards—encoding primaries, encoding equations, data metrics, and so on.

One ‘meta-document’ deserving of greater recognition is ISO 22028-1:2004, *Photography and graphic technology: Extended colour encodings for digital image storage, manipulation and interchange—Part 1: Architecture and requirements*. The Terms and Definitions section of this document has become the terminological anchor for many recent documents. This publication is decidedly **NOT** free, but is sufficiently useful to be worth the price.
A Color Image Encodings Taxonomy

In the discussions that follow, color image encodings, color space encodings and color spaces are related to each other as depicted in the hierarchical diagram below. As much as possible the terminology is that of ISO 22028-1:2004.

Rather than go into each component of the hierarchy individually, the best way to explain it is by example, using a color image encoding that should be fairly well known to most readers: Adobe RGB (1998).

Colorimetric Encodings

There are four color space or color image encodings which every CG artist should at least be able to look up, the last of these being new. These encodings are:

- sRGB – similarly well-covered in those same two books.

Beyond these four colorimetric encodings two others are worth a mention.
Rec. 1361 - this is notable because it allows negative amounts of color primaries. The virtue of negative primary amounts is that they allow one to go outside the triangle of chromaticities defined by the color primaries, achieving a wider gamut.

PhotoYCC - an early example of scene-space encoding, this standard provided for two types of reconstruction of the original scene colorimetry, one which emphasizes colorimetric accuracy and one which sacrifices accuracy to retain some of the ‘flavor’ of the capture system. The two methods are termed product-specific and universal, and are both covered in Giorgianni & Madden’s book.

Densitometric Encodings

The densitometric encodings most likely to be encountered by SIGGRAPH attendees are Cineon (which is ever less common) and ‘the encoding without a name’: the unnamed densitometric encoding based on the unnamed printing density whose foundation is the spectral condition described in SMPTE RP-180.

Typically this unnamed encoding is misidentified as its containing file format, namely, DPX. Since DPX can also contain images encoded colorimetrically, handoffs—especially those that cross organizational boundaries, such as delivery for DI—are too often followed by a game of guess-the-encoding.

ADX (the Academy Density Exchange Encoding) remedies this ambiguity. It has a well-defined relationship and direct relationship to scene colorimetry through the ‘unbuild’ transform, and a well-defined indirect relationship to displayed colorimetry through the Reference Rendering Transform (RRT) and the appropriate Output Display Transform for a particular device.

The unpublished spectral condition defining Cineon Printing Density was appropriate for the print stocks in wide use in 1993. SMPTE RP-180 defines a spectral condition appropriate for the print stocks which came out in the mid 1990s. The spectral condition defining Academy Printing Density (APD) was developed by the Academy (largely as a cooperative effort between the two major vendors of motion picture print film (Kodak and FUJIFILM) to support print stocks of the 2010s and beyond

As mentioned in passing above, there is a well-defined transform converting APD values (which can be derived from ADX values) to ACES values, through what is known as the ‘unbuild’ transform. Here is an illustration showing the various color encodings and transforms used in an IIF workflow; the reader’s attention is drawn to the left-hand side of the diagram, specifically to the box labeled ‘apply unbuild’: 
An Example of Converting from Densitometric to Colorimetric encoding: 3D LUTs for DI

At the present time, without any sort of widely-accepted relationship between original scene and reproduced colors, common practice is to work with reference not to the scene but to the reproduction of the scene, that is, to work with output-referred images.

In a Digital Intermediate (DI) session, a motion picture stored as RGB triplets — typically in a DPX container, and purportedly representing printing densities defined according to the spectral condition laid down in SMPTE RP-180 — is edited by digitally projecting those RGB triplets to provide a preview of how a film-recorded version of them would appear when printed and projected. The RGB triplets are manipulated in real time, by a colorist doing his or her best to accommodate the stated wishes of the director, until creative desire, patience, or time is exhausted, at which point the goal of the DI facility is to replicate on projected film the theatrical viewing experience that was approved by the production.

This demands a high degree of accuracy in the preview. In particular, it demands that the digital projection system, which is optoelectronic and virtually free of crosstalk, emulate the photochemical processes of film, which are deliberately full of crosstalk. As the film is multilayer (typically more than a dozen layers are present in modern motion picture films) occurrences of such crosstalk are termed ‘interlayer effects’.

There are really three ways in which 3D LUTs incorporating the interlayer effects of the film chain can be made.

1. Use spectral measurement ‘all the way’, directly measuring the spectral transmission of a filmed-out-and-printed color cube, then indirectly measuring the projector illuminant as spectrally reflected by the theater screen, and with those results in hand, performing the required calculations to determine projected colorimetry. This leads to a result optimized for a particular combination of film stocks, laboratory, and screening room.

2. Measure the densitometry of a similarly recorded and filmed-out print, then use published spectral dye densities to infer what the transmission spectra of the print must have been to have produced the measured densities. This has a few interesting ancillary points:
• The published spectral dye densities for commercial motion picture print films are widely believed to be inaccurate. There are published techniques for inferring these dye density curves, however; an example can be found in the paper from Fairchild, Berns and Lester, “Accurate Color Reproduction of CRT Displayed Images as Projected 35mm Slides”, from the 2nd Color Imaging Conference (1994).

• Commercial densitometers only approximate the spectral conditions defining the densities which they claim to measure.

• That said, densitometric measurement is used in making 3D LUTs for Filmlight’s Truelight system, and has achieved great acceptance in their targeted marketplace. If generic spectral dye densities are used this approach may not be as accurate as direct spectral measurement, but if the actual spectral dye densities are determined, the approach may yield superior results, as densitometers are often capable of handling higher spectral dynamic ranges than spectroradiometers or like instruments.

3. Spectrally model the processes of exposure and printing that lead up to the film print, as well as the downstream processes from the print to the screen. This approach is used by at least one widely-used desktop production suite, and in Gotanda-san’s segment of this course. The approach trades accuracy away for generality; on the other hand, if the material is going to go through a downstream DI, the magnitude of color enhancement is likely to exceed the magnitude of inaccuracy as compared to the direct spectral measurement of print, or the densitometric measurement of print.
Measuring the film chain

In both direct spectral measurement and indirect densitometric measurement, a few considerations are key:

- The lamp used to back-illuminate the film must be extremely stable over periods of measurement that, depending on the number of samples in the cube and the maximum density of the film, can take as much as a day to measure.
- The measurement geometry should emulate that of projection.
- The detector should be shielded from stray light that could swamp the transmitted light from a very dense frame on the print; and

- The portion of the frame being measured should be consistent from frame to frame, at least in the edge-to-edge dimension (since commercial release printers sometimes exhibit an intensity gradient across the exposing slit).

The system shown above has been used commercially, across two generations of hardware, to measure the transmission of filmed-out patches and to capture the raw illuminant.

Most of the mechanism is there solely to transport roughly 3000 filmed-out patches, at reasonable speed and with relatively constant tension, between the regulated light source at left and the spectroradiometer at right. The considerations outlined above are addressed by

- using a beamsplitter, photodiode and a small amount of custom electronics to provide regulating feedback to the microscope illuminator that backlights the film,
- collimating the light coming out of the randomizing fiber bundle before going through filtration and before entry into the beamsplitter,
- isolating the point of measurement from outside light by essentially having the film measured while in an enveloping velvet-lined slit, and
- allowing for small lateral (that is, direction of film travel) movements while preventing almost any perf-to-perf wavering at all.
The result of the multiplication of patch transmission by measured projector open-gate illumination is a set of spectra which can be converted to points in CIE XYZ space. As CIE XYZ is not particularly perceptually uniform, the result is a tallish narrow angular volume. CIE LAB is a better space with which to visualize the nonlinear tonal response and interlayer effects in the film chain. The curving lines shown are a result of interlayer effects but also the nonlinear CIE LAB equations; the ‘bunching up’ towards the end of the lines represent the toe and shoulder of the film.

Measuring or modeling the digital projector

In addition to characterizing the path from RGB values in a DPX file to the screen colorimetry of recorded and projected film, the same must be done for RGB values in a DPX file digitally projected. Assuming a cinema-quality device (a 3-chip DLP, or a Sony SXRD), there should be no inter-channel contamination, and no toe or shoulder. The result is a quite regularly shaped and spaced set of points in CIE LAB space:

The TI Digital Cinema color processing engine is so good at producing regularly spaced points, in fact, that it became easier and more accurate to model it rather than to measure it. (The color processing engine is documented in a 2001 Color Imaging Conference paper from Brad Walker and Greg Pettitt: *DLP Cinema™ Technology: Color Management and Signal Processing*, which along with a small amount of vendor provided information on data layout provided everything required to build a successful DLP simulator.)

Computing the transformations

Once the two devices have been characterized, they are each reduced to a form which allows for translation of any point in device RGB space to a corresponding CIE LAB point: the volumes are cut into tetrahedra with a Delaunay triangulation, allowing any point in device RGB space to be expressed with barycentric weights as the sum of neighboring vertices.
Then for each point in a regular lattice sampling of the film chain RGB cube, where that sampling corresponds to the desired DI LUT dimensions, a point in the film chain RGB cube is determined, its neighboring vertices are found, the barycentric weights are computed and then applied to the corresponding set of points in CIE LAB space. The film chain RGB point has now been mapped into CIE LAB.

Next, the CIE LAB volume associated with the DLP characterization is probed to find a set of points which happen to be the transported DLP device RGB points for one of its tetrahedra, in particular a tetrahedron containing the CIE LAB coordinates produced above. Once the containing volume in the DLP’s CIE LAB characterization is found, the barycentric weights are computed and applied to the corresponding DLP device RGB points. The film chain RGB point has now been mapped into CIE LAB and taken back into DLP device RGB space.

This DLP device RGB point corresponding to the film chain device RGB point is stored in the result lattice and the process continues until all samples from the film chain sampling have had their DLP device RGB point counterparts computed.

The resultant 3D LUT is ready to be used. All scanned imagery is passed through this 3D DI LUT on its way from the colorist’s intermediate storage system to the DLP, resulting in the displayed digital projection accurately previewing the colors of the eventual projected film print.

Gamut mapping

The just-described approach has a glaring hole in it, however: there are colors which can be produced by the projection of film which cannot be produced by a digital projector.

In the illustration above, many intense cyan colors in the film projection gamut have no counterpart in the digital projection gamut. This situation requires some form, however crude, of what is termed gamut mapping.

Gamut mapping is a complex subject, and these notes will do no more than touch on it. The interested reader is urged to find a copy of Ado Ishii’s *Color Space Conversion for the Laser Film Recorder*, from the Nov 2002 SMPTE Journal. The illustrations to follow were inspired by that paper.
When considering the gamut mapping problem, it is traditional to do so by looking at a particular hue angle, that is, to examine the problem as transported to a cylindrical coordinate system where the height dimension of the cylinder represents luminance and the angle relative to some zero angle indicates hue. CIE LCH (Luminance, chroma and hue) space satisfies these requirements so we can look at our illustrations of the problem there:

The Problem

Here we see the blue hull representing the source gamut and the orange hull representing the destination gamut. Points outside the destination gamut but inside the source gamut are going to be a problem. We want to map those problematic points to the destination gamut somehow (rather than just letting those points go, say, black).

Moreover we don’t want those points going just anywhere. We want some sort of sensible relationship between the luminance of the source point and the destination point. The way this is done in the Ishii paper (and in the implementation illustrated here) is to pick a particular luminance and map each source point on a line between the source point and the horizontal projection of the destination cusp onto the luminance axis, a practice called ‘cusp mapping’.

The most obvious solution is just to project the problematic points onto the surface of the destination gamut. This works, but it means that objects with that source hue and luminance, regardless of saturation, are mapped to the same point. The result could be loss of detail.

Graphically, the clipping solution looks like this:
Clipping can be avoided by mapping all the points in the problematic area to distinct new points inside the volume, by a simple scaling operation whose coefficients are computed for each source point. This has the awkward side effect of affecting colors all the way in to the luminance axis, however, which can have unpleasant effects on colors ‘in the way’ such as skin tones, grass, sky or other ‘memory colors’. Graphically this looks like:
So the solution used by Ishii (and others) is to *fade on* the scaling. Colors in the ‘core’ of the hue plane, near the luminance axis, are left alone. Colors at the very edge of the source gamut are mapped to the very edge of the color gamut. Colors between the edge of the source gamut and the edge of the destination gamut are compressed into a region of the source gamut allocated for this purpose in such a way that compression is maximized near the destination edge, and nonexistent as the destination gamut ‘left alone’ colors are reached.

This solution also has the appealing characteristic that it is (ignoring issues of numerical precision) in principle invertible.

For those who want a more comprehensive (or comprehensible) exploration of the possibilities, the Ishii paper is again recommended, and beyond that, Ján Morovič’s *Color Gamut Mapping* (John Wiley & Sons, 2008) is the reference work on the subject.

Writing tools for tasks such as these can be rather tedious. It usually makes sense to seek out commercial or open-source solutions nowadays rather than writing something from scratch, as will be covered shortly.

Checking your work

The best way to evaluate the quality of a DI 3D LUT is to do what is known as a ‘butterfly test’. This allows digital projection’s emulation of film to be compared to the actual projection of film. A test frame is filmed out to sufficient length (usually a dozen feet is sufficient) to be ‘looped’ by the projectionist. One half of the projected image is masked off by placing an opaque object on that side of the projector port glass.
On the other side, the test frame is digitally flopped (that is, mirrored horizontally) and run through the DI 3D LUT, then projected with half of its projected image masked off – the complementary half to whichever side was masked on the film side. The result is that the two images, one from film projection and one from digital projection, are symmetrically displayed:

Center-to-corner vignetting can approach 40% in some theater projection systems. Vignetting is, however, usually symmetrical, and so by reflecting around center, similar portions of the image receive similar lamp intensity falloff.

Using a commercial or open-source color management system for motion imaging

In the wider marketplace, there are several color management systems out there one might imagine using: the ICC tools built into the Adobe suites, LittleCMS, SampleICC, OpenICC, Argyll, Cinespace and Truelight. In production it seems to come down to two (or possibly three). The two most used color management systems for production are Truelight (from FilmLight) and Cinespace (from Cine-tal, originally from Rising Sun Research). Use of the Adobe suite with its ICC support was pioneered by The Orphanage, but it’s unclear to me the degree to which the ICC workflow really got traction in motion picture workflows.

The Truelight documentation is phenomenal. It really does a nice job of explaining the various factors involved in going from scanned negative to the projected image, and to emulations of that projected image on other monitors. The Cinespace documentation is comprehensive but — no doubt this will sound strange — if one is to read one set of documentation or the other, without the intent of using either product, then read the Truelight documentation.
The primary difference between the two systems is that the Truelight system is a bit more flexible. Both have what might be termed fixed color processing pipelines, but within the pipeline stages, Truelight allows one to inject arbitrary formulae, whereas Cinespace makes assumptions about how color data should be processed solely on what it finds in the XML files that are Cinespace profiles. Both handle the most common cases for visual effects work.

The Academy Image Interchange Framework (IIF)

An alternative color management architecture that may become available in the second half of 2010 is the Academy of Motion Picture Arts and Sciences’ Image Interchange Framework (IIF). This framework grew out of a rather humble initial quest to match the output of scanners at several Los Angeles-area scanning and recording service bureaus; as the effort progressed the scope widened and the associated talent pool grew considerably.

Today the IIF is a fully-imagined color management architecture with a preliminary implementation. Several of the internal documents are scheduled to be presented to SMPTE as candidate international standards; others will be moved along that track when current testing of the relevant parameters and equations is completed.

The rest of these course notes is dedicated to the IIF, as it is a strong candidate for adoption by camera manufacturers, service bureaus, visual effects houses and game developers.

Revisiting the IIF architectural diagram

We touched on the IIF architectural diagram earlier when discussing its ‘apply unbuild’ module, the conversion between densitometrically encoded ADX images and colorimetrically encoded ACES images. Now we take a more wide-angle view of the diagram.

The center of the diagram is the volume storing scene-referred ACES images. This is ‘where the action is’; compositing happens here, as does the application of ‘Look Management Transforms’ or LMTs (interactive modifications of the scene data to affect the final look).

To the left of center are input paths to ACES from the original scene.
In the top left path, a digital motion picture camera system captures a scene and produces RAW images (which are assumed to be black-subtracted and demosaiced). An Input Device Transform takes these black-subtracted and demosaiced data and turns them into ACES RGB relative exposure values.

In the bottom left path, a film camera captures that same scene and produces OCN which is scanned. The scanner is set up to produce ADX directly (an alternative [not shown] would be to produce the scanner’s native color image encoding and convert to ADX). The resulting ADX values are passed through a film ‘unbuild’ transform to become ACES RGB relative exposure values.

If the camera were colorimetric in its response and the film unbuild transform was ‘perfectly tuned’ for that film stock, then the ACES data from the two paths, upper left and lower left, would be identical. As it is, however, characteristics of the IDT and of the unbuild transform bring some of the digital camera or film stock ‘flavor’ into ACES as part of the captured scene. This is not a bug, it’s a feature: cinematographers choose particular film stocks and digital cameras for many reasons, including the associated intangible ‘look’.

The next two sections provide more detail on IDTs and the unbuild transform; after that, the right-hand side of the diagram leading to displayed imagery will be explained.

Input Device Transforms

There are many forms a digital camera IDT could take but the presumption is that following current practice and applying a 3x3 matrix to the demosaiced RGB stream will allow real-time, in-camera IDT application and be ‘reasonably close’ to optimum IDT output on the way out.

The difficulties in creating IDTs come in two areas:

1. the definition of ‘optimum’
2. the computation of a 3x3 matrix that implements that notion of ‘optimum’

Considerations in the definition of ‘optimum’ include

- handling of the highly probable case that the camera’s spectral response is not colorimetric, that is, it does not capture some linear transformation of the human visual system’s color response. This becomes a problem in error minimization and the placement of error — methods that improve one area of the camera performance must come at the cost of increased error in some other part of the color space. Typically one favors accuracy in the capture of flesh tones, for example, over the accurate capture of chartreuse.

- handling of the case where neutral objects are captured under illumination sources whose chromaticity differs from that of the ACES neutral colors - namely, the chromaticity of CIE Standard Illuminant D60, more or less halfway between the 5400K CCT of film projection and the 6500K CCT of video display. Should a neutral object be captured with equal R, G and B relative exposure values? If so, and the RAW capture was not one producing equal RGB values, how should the adjustment of colors be made? Simple linear channel scaling, or something of medium complexity like chromatic adaptation? Or something yet more sophisticated, e.g. an attempt at ‘re-illuminating’ the scene?
The correct behavior is in many cases ‘do what the cinematographer wanted’, and presenting the variety of options available on-set to the cinematographer may be so intimidating (or at least, so varied) as to push towards having the choices be made offline when RAW frames are converted to ACES frames.

That said, real camera vendors are producing real IDTs for use in IIF testing, and at least one vendor (RED) has publicly announced they will support ACES output, either as direct camera output, or RAW converter output, or both.

Film scanning and the unbuild transformation

The alternative path to ACES for live-action material is to shoot on film, scan the film to produce ADX imagery, and ‘unbuild’ the resulting ADX RGB values to ACES RGB relative exposure values.

The Academy has designed, as part of the Image Interchange Framework, a set of scanner setup films known as Academy Scanner Analysis Patches (ASAP) rolls. An ASAP roll is accompanied by an index file listing for each patch the nominal ADX value for that patch — derived from measurement at time of manufacture — so that users of an ASAP roll can verify that a scanner or scanning service bureau is accurately delivering ADX values from the test negative. In some cases, it may be possible to use the output of a scan of an ASAP roll to derive transforms so that the output of scanners not producing conforming ADX output (e.g. scanners delivering DPX frames whose image data is that printing density whose spectral condition is given by SMPTE RP-180) may be transformed to conformant ADX.

The Reference Rendering Transform (RRT)

The ACES data that originated as digital camera capture results, as film scanner output or as CGI must be transformed from scene-referred to output-referred data prior to viewing. This is done in two steps: first the scene data are color-rendered using the Reference Rendering Transform (RRT), and then the transformed, output-referred data are processed for a particular type of device with an Output Device Transform (ODT).

The RRT contains those elements of a transform from a scene-referred image state to an output-referred image state that are common to all devices, while deferring to the ODT elements of such a transformation that are particular to a device class. For example, the RRT embodies a contrast-enhancing tone curve with a gentle toe and shoulder to avoid ‘blocking up’ shadows or ‘blowing out’ highlights, because such a response is desirable for all displays, but omits conversion to a final primary set because such a set would be device-type-specific. The RRT similarly delegates to the ODT any clamping to a limited device tonal range or compression to a limited device gamut volume.

Output Device Transforms (ODT)

As alluded to during discussion of the RRT, the ODT is responsible for all components of the transformation between scene- and output-referred space which are not common to all devices. This includes

- any additional compression and/or clamping of tonal range beyond that done by the RRT
• clipping or compression from the unlimited color gamut of RRT output to the gamut of a type of a particular type of display device.

• any chromatic adaptation used to account for differences between the neutral chromaticity of RRT output and the neutral chromaticity of a particular device type.

The output of the ODT is image data ready for presentation on a particular type of device. (Particular instances of a type of device are presumed to be calibrated such that they behave nominally for that device type.)

What’s this LMT then?

As previously mentioned, two types of manipulations take place wholly while the image data are encoded as ACES RGB relative exposure values: compositing and the application of Look Modification Transform (LMTs). What are LMTs used for? LMTs are for modifications of the scene-referred ACES data that produce desired results in the output-referred displayed data.

An LMT might apply, for example, lift, gamma, and saturation operations specified as an ASC CDL [American Society of Cinematographers Color Decision List]; or to provide another example, an LMT might be applied to scene-space data to provide a ‘day-for-night’ look.

Why so much time and space dedicated in these notes to the IIF?

In the interests of full disclosure the author of these notes should reveal that he has served as editor on one of the IIF documents (the ACES document), contributed to several IIF documents written by others, and is writing at least three IIF documents from scratch. That said, it is (not surprisingly) the consensus opinion of the IIF designers that the system will be genuinely useful for CG artists, for producers, and for colorists:

• IIF for CG artists:
  - ACES images are unambiguously stored in scene space, which is the type of space to which most CGI renderers are targeted. This in itself could justify adoption of an IIF workflow in some facilities.
  - Better camera-to-camera consistency through IDTs
  - Easier blending in of film elements (such as high-speed pyro) to CGI scenes.

• IIF for producers:
  - Foundation for a color pipeline which doesn’t need replacement after each show.
  - ADX images are based on a modern printing density metric better tuned to today’s stocks. This should enable better scanner-to-scanner and facility-to-facility scan matching, avoiding single-point-of-failure dependence on any one service bureau.
  - ACES scene data should provide better digital-camera-to-CGI matching than most facilities have been able to achieve so far.
  - An open-sourced reference implementation means an investment in a color-managed IIF workflow isn’t vulnerable to vendor collapse.

• IIF for colorists:
- a fixed RRT means no more guess-the-encoding games in the DI suite; it’s ACES in, and the path forward from there is locked. Color correction is Look Modification, that is, modification to scene data visualized through the RRT and ODT(s).
- This should also make it easier to match shots from different sources (such as digital camera systems and film chains).
- The HDR and wide-gamut nature of the system preserves tonal and chromatic latitude all the way to DI.

A recap

So, just to get back to those three key points:
1. Judge the color where your audience is going to judge the color.
2. Understand your color encoding. Read the relevant documents. Keep track of color encodings as they flow through the production process.
3. Use a color management system designed for motion imaging. This realistically means TrueLight, or Cinespace, or the IIF. Take the IIF seriously — the vendors are doing just that.

Good luck.