The Evolving Digital Workflow in Cinema

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Abstract

Full-length feature films for the cinema have been produced by photochemical methods for over 100 years, based on a three-step workflow: *original photography*, *post-production*, and *release printing*. In the last decades of the 20th century digital methods were first introduced for limited special-effects tasks, and subsequently adopted for many routine processes in the post-production phase of the workflow. Improvements in imaging technology are enabling feature-quality digital methods to be used in all three steps of the traditional motion picture workflow, as *digital capture*, *digital intermediate*, and *digital cinema* projection, respectively. This paper describes how digital methods are being incorporated into motion picture production, with a particular focus on color reproduction issues.

Introduction

When discussing workflows for cinema, it is important to recognize that there is no single production pattern that fits all projects. Motion picture production is a complex collaborative task involving art, craft, and technology within strict schedule and budget constraints. Workflows vary from fairly simple to extremely complex. Where all methods come together is at the final result: a large-screen presentation in a darkened theatre, a finished creative work.

DVDs, tapes, and broadcast TV versions of a movie are important derivative products. They are distinct from cinema due to the more limited color reproduction and different viewing environment in these applications, which requires additional color rendering.

A minimalist workflow would consist of original photography, followed by editing selected shots together in sequence, and finally duplication and projection. Already, issues of color consistency arise in each of these steps.

In reality, the post-production step includes much more than just simple editing. In subsequent sections we will use *compositing* and *tonal manipulation* as examples of such work. In compositing, two parts of a scene (e.g. foreground and background) which were photographed separately are combined into a single image. In tonal manipulation, image contrast may be raised or lowered, overall brightness, hue, and saturation may be shifted, etc.

The body of this paper is structured in three sections. First we review the color reproduction issues in cinema, with an emphasis on the aspects which distinguish it from conventional photography or graphic arts applications. Second, we introduce the elements of the traditional photochemical workflow, providing a context in which the digital methods can be understood. The third section discusses the evolving digital workflow in more detail.

Overall, the intent of this paper is to introduce color specialists from other disciplines to the processes involved in filmmaking, and to open issues in digital color management.

Color Reproduction in Cinema

While cinema may be considered a branch of photography, methods which work well for snapshots and magazine spreads cannot be imported blindly to this realm. Historically, the motion picture industry has developed color workflows and color management methods independently of the graphic-arts industry. Attempts to combine digital methods from these differing disciplines have had mixed success. In part this is due to the special characteristics of cinema discussed below.

Dark Surround

Theatrical presentation can approximate a true dark-surround environment. Psychophysically, there is no independent “reference white”: the eye adapts to the light level which is currently on the screen.

High Contrast

The luminance ratio between full-white and full-black screen conditions can reach 10000:1 in a well-maintained screening room, although 500:1 would be more representtative of a good commercial theatre. Because of the dark surround and viewer adaptation, the lower end of the tone scale can be quite visible; shadow detail rendition is very important. Furthermore, because of the wide visual angle subtended by the screen, small highlights in one area of the screen do not necessarily restrict the audience from attending to shadow information in another portion of the scene.

Unstable Adaptation

As alluded to above, the viewer’s state of adaptation depends on the scene content. During a movie, the viewer’s adaptation state is constantly changing; this may be used as the basis of intentional artistic effects.

Absolute Luminance Level

There is a specified screen luminance which appears on the screen of a correctly-aligned theatre when no film is in the projector. As a result every presentation at every theatre should have approximately the same light level.

Headroom in Production

Camera negative and color intermediate films record a substantially wider range of exposure than can be effectively transferred to the screen. (The contrast-boosting rendering transform required by a dark-surround presentation contributes to this situation.) However, the extra range is definitely not wasted; it allows manipulation of the image during postproduction. As in artistic still photography, creative decisions (or "fixes") regarding brightness, color, and tone reproduction may be made late in the workflow. Also, even simple dynamic effects such as fade-to-black require considerable highlight headroom. The fact that, during postproduction, the working format is effectively a high-dynamic-range (HDR) image which contains several more f/stops of dynamic range than can be displayed on screen raises fundamental questions about "soft proofing" in the workflow and about an appropriate Profile Connection Space.

Fine-Art Paradigm

In many practical applications, the goal of color management is to obtain "a pleasing reproduction of the original scene". In a feature film, in contrast, the Director of Photography (DP, or Cinematographer) aims for a particular visual "look". This look may be neither the most accurate nor the most pleasing reproduction of the scene in front of a camera. What the DP demands, as an artist, is precise, repeatable control over the final image. Furthermore, this final, approved, image should appear consistently across different theatres.

Photochemical Workflow

The traditional, and still dominant, workflow in motion picture production is based on photographic film (Table 1). A guide to film-based postproduction is given by Case.[1]

Table 1. Types of motion picture film

OCN (original camera negative) **sensitivity** **gamma (contrast)**	Camera film stock High Low, 0.6 typical
Color Intermediate **sensitivity** **gamma (contrast)**	Laboratory film stock Low 1.0
Color Print **sensitivity** **gamma (contrast)**	Release print stock Low High, 3 typical

After the OCN from original photography is developed, it can be contact-printed directly to color print stock, which can be projected. Until the 1980's, editorial work was done primarily by physically splicing together such "work prints". After considerable trial and error, a fully assembled work print was approved, and the locations of all the splices were noted. Only then was the OCN taken out of safekeeping and "conformed" by splicing it to match the approved work print. In current practice, the editorial work is often done using lower-resolution video proxies, resulting in an approved edit decision list (EDL). The OCN is then conformed to the EDL. The conformed (or "cut") negative can now be printed, resulting in "answer prints" which are screened for quality control purposes.

Color intermediate is designed for image duplication: its 1.0 gamma does not distort the tonal scale. When OCN is contact-printed to color intermediate, the result is a low-contrast positive image which is useless for projection or viewing; this is called an interpositive (IP). Printing the IP again onto color intermediate produces a duplicate negative, with the tonal scale undistorted from the OCN.

When image manipulation in postproduction is required, IP's and duplicate negatives are commonly used. For example, building a composite requires two passes in an optical step printer, a device in which the background and foreground are exposed onto color intermediate using precisely aligned masks. The final result is a composite negative image, on color intermediate, which can be conformed along with OCN when the final negative is cut together.

Color timing ("grading", in British English) is another step in postproduction. Because of variations in lighting and processing, there are always slight color-balance variations between film rolls which are shot on separate locations or different days. Such variations become very noticeable when scenes are spliced together in sequence, so scene-to-scene matching is always necessary. Color timing is achieved by precisely controlling the relative amounts of red, green, and blue light during contact printing. The same method can be used to introduce intentional color casts into scenes for artistic effect. The conformed negative is printed onto color intermediate, using the scene-to-scene color adjustments, resulting in a "timed IP".

Tonal manipulation such as contrast changes, saturation adjustment, and hue rotation are difficult to perform photochemically. Special developing conditions (e.g. retained silver process) and/or individual color separations on black-and-white film stock are used.

For commercial distribution, the timed IP is contact-printed to an internegative (IN), which is finally contact-printed at high speed onto color print film. For a wide release, many release printers may be running simultaneously with identical INs, producing thousands of final prints.

As in other subtractive systems, motion picture color reproduction is strongly nonlinear. Characteristics of OCN and color print are typically designed in a proprietary manner so that, in tandem, a good end-to-end rendering transform is obtained.

Digital Workflow

A digital workflow involves representation of the full-resolution, full-color moving image by numerical values rather than by physical film. Historically, digital postproduction has preceded digital capture and digital distribution; it is discussed in the first subsection below. A major factor limiting adoption of digital methods has been the expense of moving, storing, and processing the large quantities of data. A typical "2K" postproduction frame is 2048 x 1556 pixels, RGB, with 10 bits per primary per pixel[2], occupying some 12 MB; this corresponds to 288 MB per second of program or several terabytes for a single feature film. Image compression techniques are not commonly used during postproduction. These quantities of raw data continue to stretch the capabilities of computing workstations and storage networks.

Attempts at theatrical presentation using electronic projectors date back at least to the 1930's with work by Baird[3]. However, only recently have electronic projectors been able to provide images which consumers accept as equivalent to 35mm film. The second subsection discusses digital cinema, i.e. digital content distribution to such projectors, and the corresponding workflow implications.

The commercialization of High Definition Television (HDTV) during the 1990s made equipment available which could record video images at resolutions up to 1920 x 1080, leading to much experimentation. The third subsection discusses how adoption of electronic capture influences the cinema workflow.

Digital Intermediate

Digital Intermediate (DI) as currently practiced may be described as "digital filling sandwiched between photochemical bread". The basic premise of DI is that film is an excellent capture medium, and an essential distribution medium, but that digital postproduction methods provide artistic flexibility and, especially in complex effects sequences, provide image quality which is unattainable with the traditional photochemical process.

The precursor to DI was digital effects. Initially, digital computation allowed "impossible" visual effects, but due to the high cost and extended processing times only short, high-profile scenes could be executed. In this environment of "insert" shots – short segments of effects intercut with conventionally produced negative – there is a high priority on matching of the color and tonal scale between OCN and digital effect. The industry widely adopted a standard interchange format[4,5,6] based on 10-bit encoding of the RGB printing density of the developed OCN image.

This printing-density encoding, commonly referred to as "Cineon format", does not fall neatly into either the input-referred or output-referred image state. It thus occupies an ambiguous place in an architecture for color image encoding[7] such as that being standardized in ISO TC42[8]; it is best discussed as an additional, *intermediate* image state[*]. By encoding the properties of the negative film itself, this method makes possible a "transparent" film-to-digital-to-film process based on densitometric calibration of the film scanner and film recorder. This is important for effective intercutting of digitally processed negative with original negative.

Cineon format has proven valuable for compositing separately-photographed scene elements, blue-screen wire removal, restoration, and similar tasks based on photographic originals. Another important type of compositing, in which photographic elements are combined with computer-generated imagery, has required additional effort. In order to make the composite image realistic, the computer-generated and photographic images must be brought into the same color space. Two possible alternatives are (1) rendering the computer-generated image through a film-simulating transform into Cineon space, or (2) "unrendering" the scanned photographic element into a scene-referred, linear-light representation matching the computer graphics. Both of these techniques require an accurate characterization of the OCN behavior over its full 3-dimensional gamut.

Resizing and other spatial manipulations benefit from computations performed in a linear-light encoding, either scene- or output-referred. Digital effects houses continue to refine 3D-LUT and other techniques to transform between computational color spaces and film input/output spaces.

If *digital effects* constitute a replacement for "opticals" – the processes traditionally performed on an optical step printer – then *digital intermediate* constitutes a replacement for negative cutting.

In the DI method *all* the OCN needed for the final movie is scanned at high resolution, and the entire finished picture is output to color intermediate on a film recorder. This is true even for those simple scenes which require nothing more than color timing. Since the entire film is digitized, there is no intercutting of OCN with digitally processed scenes. One side effect of this is that "transparent" film-to-digital-to-film behavior is less critical than in digital effects. DI can provide a consistent look, meeting the cinematographer's requirements, without precisely encoding film negative's characteristics the way Cineon format does.

[*] "Workflows associated with particular applications may include additional colour encodings that may correspond to image states different than the standard image states defined in this image-state-based digital imaging architecture. For example, it may be useful to define a colour encoding for representing colour negative scans, or an intermediate colour encoding for partially colour-rendered images."[8] (sec .4.1).

The vast increase in data volume – a DI production handles hours of content rather than seconds – required a change of technology. Traditional film scanners, taking many seconds per frame, are replaced with telecine equipment originating in the film-to-video transfer industry and operating at near real time. Digital video standards[9,10] have been adopted in many cases.

Color encoding for DI is an area of active experimentation; Cineon and Rec. 709[10] coexist with methods based on logarithmic or linear representation of scene light. Integer and floating-point[11] formats are in use. Many facilities have developed proprietary image encoding methods for computer graphics, effects, and animation work, some of which are now being considered for DI. The exact colorimetry, and especially the image state, of these encodings is often unclear, as implementors focus largely on tradeoffs among file size, efficient image processing, dynamic range, and quantization resolution.

In-process monitoring, or "soft proofing", is a persistent problem area in digital postproduction. In practice, decisions must be made while looking at workstation displays or HDTV monitors. However, there is an enormous difference between the workstation viewing environment and the final theatre, as well as differences in the reproducible gamut and contrast; critical material requires periodic "reality checks" using actual 35mm projection. Digital cinema projectors are now being deployed, especially in color correction suites, as real-time monitors in addition to CRT displays. Rendering transforms used for soft-proofing range from simple per-channel nonlinearity to full 3D LUTs.

Cross-fertilization from the telecine (video transfer) industry to feature film production has introduced sophisticated color correction as a creative tool for cinematography. Dramatic use of dynamic digital color manipulation has become a commonplace in advertisements and music videos; video color correction equipment is being adopted and adapted for long-form cinematic use, despite the fact that it is commonly engineered for use primarily with broadcast color standards.

There is great business interest in taking advantage of the color-corrected digital intermediate as a basis for near-automatic generation of a home video version. This would bypass the traditional telecine film-to-video step and the skilled colorist who supervises it. A skeptical color scientist might view automated conversion between theatrical and video media as an impossibly complex dynamic gamut-mapping problem; nonetheless there are real gains in workflow efficiency when DI production feeds supervised video conversion.[12]

Digital Cinema

Digital cinema is the replacement of release printing and projection by digital equivalents. Digital cinema is in a pilot phase, with worldwide interest, over 100 installations, and many studios experimentally producing digital versions of major feature films.

Transferring data files into local theatre storage, rather than shipping film reels to theatres, is expected to reduce cost and increase business flexibility. Image compression techniques are used to reduce distribution files to less than 100GB in size, but no single compression method has been universally adopted.

High performance electronic projectors are able to produce screen brightness and color gamut which rivals 35mm film projection. In this pilot phase, a group of electronic projectors sharing a common micromirror-based "projection engine" has demonstrated stable performance over time and consistency from theatre to theatre. The principal concern for color management to date has been obtaining a satisfactory appearance match between digital and 35mm film presentations.

Currently, motion picture features are often completed photochemically, and the digital cinema release is a subsequent process beginning with a timed IP. The workflow is similar to an HDTV transfer, supervised by a colorist and monitored on an electronic projector in the color correction suite.[13] Difficulties arise because the color gamut, and contrast range of these projectors exceeds that of HDTV, and the transfer function ("gamma curve") consequently differs from television standards. At least one projector manufacturer has introduced nonlinear enhanced color correction hardware,[14] largely so as to work effectively with the available postproduction equipment.

Projector performance developments have focused on improved contrast (lower black levels) and increased spatial resolution. Anticipating further improvements, as well as introduction of additional display technologies such as liquid crystal on silicon (LCOS) and grating light valve, there is a possibility that the consistency of presentation seen in the pilot phase will be lost. It is strongly desired to distribute just one digital motion picture dataset ("single inventory"), even when there is a variety of fielded projectors with different contrast ranges and color gamuts. While standardizing digital cinema at today's limited performance level would establish consistency, it is preferable to allow each projector to provide its best possible rendition of the original creative intent. This calls for some amount of color management in the projector itself, and for a production workflow which allows creative control of how that color management behaves. This is an area currently under investigation within the industry, and a wide-gamut color image encoding standard for digital cinema is under development within SMPTE's DC28 technology committee.

Digital cinema must coexist with conventional celluloid for some time. This places a burden on the postproduction process which must produce two equivalent versions of a movie in different color spaces and formats. Under the DI process, digital color transforms which render appearance-matched output for film recording and digital distribution would be valuable. Since these media have similar gamuts and identical viewing conditions, this problem is considerably more tractable than the video rendering task mentioned previously.

Digital Capture

Digital capture, or digital cinematography, refers to real-time “scene to digital” conversion. Current electronic cameras for cinematography are based on 3-CCD sensor technology developed for the HDTV broadcast market, typically modified for 24 frame-per-second operation and with different lens arrangements. The color-selective filters may be similar or identical to those used for Rec.709-based HDTV.

The spectral sensitivity curves of television cameras do not exactly match the sensitivity curves of OCN emulsion layers; thus an electronic camera exhibits different capture metamerism and “sees” differently from film. However, as long as film and electronic capture are not being closely intermixed, consistent colorimetry within the medium is much more critical than matched response. It is routine to use a single emulsion batch for all the OCN shot during a particular production, in order to ensure consistent color reproduction; the same level of consistency is needed among all electronic cameras used during a production.

The most prominent shortcoming of current electronic capture devices is their limited highlight headroom. In one study[15], OCN exhibited a highlight saturation level 4000 times higher than a comparison HDTV camera. Commercial HDTV tape recording systems employ compression which has been problematic for some feature-quality work. Alternatives to television-standard recording methods and interfaces are in use, and the choice of an optimum bit depth, transfer function, and color representation for digital cinematography remains uncertain. The trend in electronic capture appears to be to operate in a simple scene-referred color encoding, free of the nonlinear cross-channel interactions that are endemic to OCN, and free of the compression and partial rendering features inherited from television practice.

Because electronic cameras provide limited dynamic range, a DI workflow based on digital capture faces fewer color-management difficulties than one based on OCN origination. There is a correspondingly reduced capability for creative image manipulation in postproduction. Similarly to the case with compositing computer graphics and film-originated images, compositing of digitally-captured material with such other media requires color rendering or unrendering transforms in order to bring the scene elements into a common color space. Accurate characterization of the camera response is needed. In general, as electronic camera capabilities improve, DI postproduction for film-based and digital cinematography will become more alike.

Summary

Feature motion picture production has been undergoing a transformation for some time, in which digital methods are replacing photochemical ones in a piecemeal fashion. Fully digital postproduction – digital intermediate – is just becoming practical, but is able to build on prior art from feature digital effects and from telecine color correction for television. Digital capture and digital distribution are poised for wide adoption despite rapid technological changes and absence of accepted standards. Production workflows will continue to mix film and digital methods for the foreseeable future.

In this dynamic environment, one of the greatest challenges is maintaining accurate and reliable creative control over color rendition. This paper has surveyed the place of digital color management operations in the evolving cinema workflow. High-dynamic-range soft proofing, standardized intermediate-state image encodings, and projector-specific color management have been raised as some active areas for investigation.

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Biography

Chuck Harrison studied Electrical Engineering at the Massachusetts Institute of Technology, where he also worked on lithographic tonal reproduction at the Visible Language Workshop in 1976. At Associates and Ferren in Wainscott, NY, he designed equipment for motion picture production and presentation, including an optical effects printer which received an Academy Technical Award in 1987. As a principal at Far Field Associates in Snohomish, WA, his current activities include Digital Cinema system standardization, including color encoding specifications. He is a member of IS&T and the Society of Motion Picture and Television Engineers.