Designing Camera Origination Films for Scan-Only Applications in Television and Digital Intermediate

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With the growing popularity of digital intermediate in the feature film market and the continuing development of improved telecine technologies for television, the notion of traditional camera origination film design optimized around direct optical or contact printing is radically challenged. For scan-only film image capture systems where the camera film will be scanned exclusively to video or data and never directly printed, a very different approach is taken to sensitometric curve design. Rather than focusing on tonal characteristics, which yield acceptable and preferred results for overall contrast, grayscale neutrality, and shadow and highlight detail in a traditional printing paradigm, the film curves must instead be drawn to optimize the quality of signal provided to the digitization step in the film scanner. Further, standard constructs of color reproduction are also open for modification as the film's spectral sensitivity and color-enhancing chemistries are changed to better mesh with digital color-processing capabilities.

As an integral component in the television or digital intermediate process, a scan-only film must be designed to deliver superior digital data when compared to a traditional optically printable film. Such quality can be delivered in the form of improved noise structure (lower grain), higher spatial resolution, extended dynamic range, or enhanced color reproduction. Further, the additional benefits of traditional film image capture such as format independence, equipment compatibility, and archivability, among others, must not be compromised. When paired with intelligent digital image processing, the superior capture capabilities of the scan-only film can be used to deliver improved creative and technical content.

An obvious application for such a system would be to render the classic color and tone reproduction characteristics of any existing traditional film, but with quality enhancements above and beyond what is available in the more classic workflows such as direct optical or contact printing. Beyond traditional camera origination film emulation, scan-only film systems can be further manipulated to allow the reproduction of other desired color positions. These might include true scene color (perfect matches to the human visual system) or more novel alternative color such as might be achieved with less common chemical processing techniques on more traditional films—cross-processing (chemically developing reversal camera films in negative film laboratory processes), black-and-white, retained silver (skip-bleach processing), etc.

Characteristic Curve Definitions for a Scan-Only Film

Most traditional color motion picture films are designed with preferred contrast and color reproduction for optical or contact printing. In the case of scanning applications, however, further manipulation of the film's characteristic response can be made to enhance image quality during digitization. Specifically, the film's tone transfer function can be lowered in contrast and reduced in gross fog density or minimum density to maximize signal quality for the electro-optical sensor in a typical scanner. Most film scanning technology is based on analog capture by way of photomultiplier tubes or CCD sensors. When combined with analog-to-digital converters and signal processing electronics they yield a video or digital signal proportional to the optical density of the captured and processed optical film image at any particular pixel measured by the sensor. Whether the film-optical image is described as negative (where the transfer function of the film is such that reproduced optical densities are directly proportional to the level of incident light from the scene) or reversal (where the transfer function of the film is such that reproduced optical densities are inversely proportional to the level of incident light from the scene), the optical density representing image content on the film is transferred to the scanner's sensor. This is done by way of a source light being focused through the emulsion layers of the film and onto the sensor. The sensor, in turn, measures the signal of incident intensity from the attenuated source light and renders a response level inversely proportional to the measured optical density on the film. As is the case with most photon-counting devices such as scanner sensors, there is a baseline dark current noise at low incident light levels (high film densities), which is generally constant, and a photon shot-noise component, generally proportional to the level of incident light. By designing a film characteristic transfer function with a lowered contrast and lowered minimum density, high reproduction densities, which will translate to low incident photon levels on the sensor, can be avoided. Subsequently, if the scanned film image is manipulated to a given grading for color and contrast, a starting image with lower raw contrast will provide a superior electronic signal-to-noise in the final rendering.

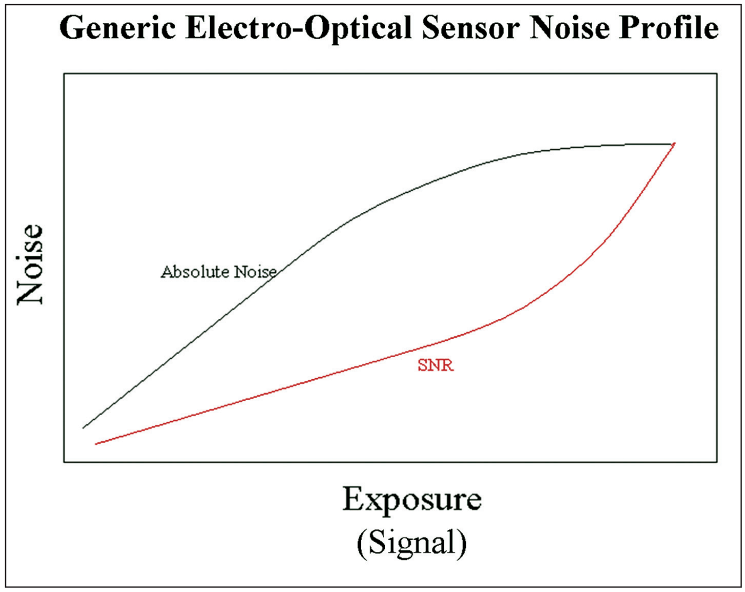

Figure 1. Typical electro-optical scanner noise profile.

By examination of dark current and photon shot noise theory, it can be concluded that electronic scanning noise in typical telecines increases as a function of increased exposure on the scanning sensor. The signal-to-noise ratio of the system, however, generally improves with increased exposure (Fig. 1) as the total noise increases via a typically exponential function with exponent significantly less than 1. Generally, dark current noise is a constant in linear terms, independent of the incident exposure level on the sensor, while shot noise increases as the square root of exposure. Therefore, by placing as much of the film image as possible on a higher exposure space for the scanner, electronic signal-to-noise performance is greatly improved. Added noise can be minimized in subsequent image processing or color grading.

As further argument to the premise of creating superior signal from lower contrast camera films, the concept of recorded image dynamic range is introduced. Images captured on a traditional color motion picture film that is designed for optical or contact printing can exhibit a loss of detail in the highlights of high dynamic range scenes after an electro-optical scan. This loss is commonly a result of white "clipping," wherein the electro-optical image path in the scanner system is incapable of recording the full range of optical densities reproduced on the piece of film. Additionally, many film scanners use light sources that are deficient in blue light output. Conventional films have relatively high minimum blue optical densities resulting from the presence of color compensating chemistries and other formulation elements to produce a desired optical print. Thus, they can exhibit excessive blue channel noise in an electro-optical scanner.

Despite the simplicity of the preceding arguments, the practice of designing films with lower contrasts to yield maximum scanner signal-to-noise performance does have limits. Specifically, as film contrast is lowered, analog-to-digital quantization sampling comes into play, relative to acceptable contouring artifact levels. The lower the contrast of the scanned film, the more likely that two consecutive digital sample levels will represent film densities and, further, scene exposures that are separated by more than the human visual contrast threshold.[1] As a consequence, a practical lower-bound to the contrast of a film can be defined for scanning applications by the following equation (1).

$$\Delta D/\Delta E \geq (DR/n)/\Delta E_i \quad (1)$$

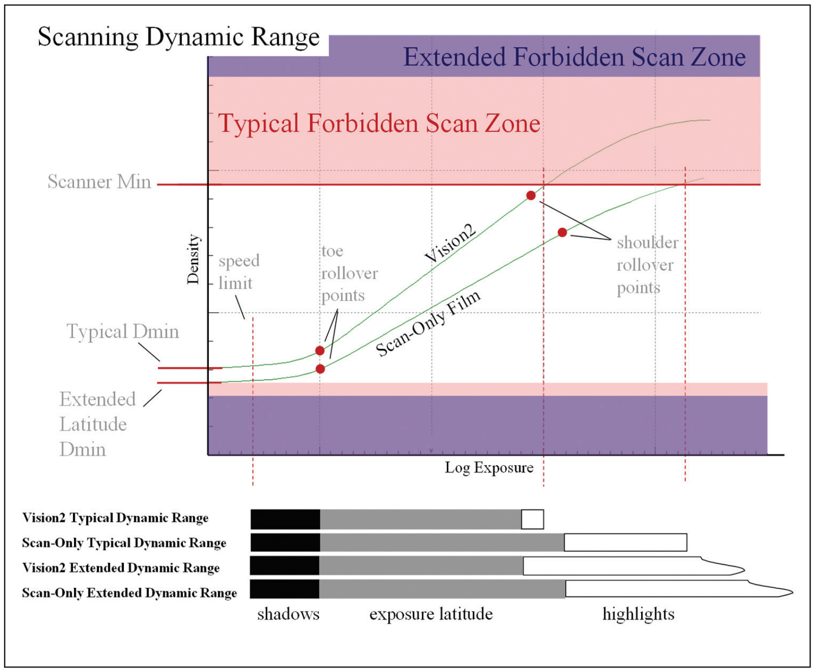

Figure 2. Characteristic response of camera negative films to various scan setups.

where ΔD is the total range of film reproduction density over a logarithmic exposure range of ΔE;

DR is the dynamic range of the scanner in terms of film density;

n is the number of quantization levels in the scanner A-to-D;

and ΔE_i is the human visual threshold for exposure difference (logarithmic again).

In this equation, $\Delta D/\Delta E$ is the intended film transfer function contrast over a given exposure range. The premise of this equation is that any two consecutive digitized film densities should differ by an equivalent log exposure range less than the human visual threshold. The equation is extensible to any specific luminance level and exposure range over which a defined response is desired. Similar relationships can be drawn for display encoding systems to prevent visual contouring in rendered images as well.

Optimum film contrast for scanning is thus bounded by building a characteristic transfer function of minimum contrast to promote the maximum electronic signal-to-noise profile and dynamic range transfer from scanning. It is also bounded by controlling the contrast reduction to a level that still qualifies under the limits of equation (1), thus preventing contouring artifacts from developing during the digitization process. Figure 2 presents a summary of the practical implications of the preceding arguments.

When a scanner is set-up for typical transfer, RGB minimum and maximum data points are set, corresponding to specific minimum and maximum film densities. However, it should be noted that actual density limits can be variable in practice; a function of scene content based on flare considerations within the scanner optical path. For any given film, these minimum and maximum densities can be translated back through a sensitometric curve to derive the total scene dynamic range preserved in the scanned signal.

For comparison, a typical sensitometric reproduction is represented by the curve labeled "Vision2." Further, the scene exposure dynamic range translated to a differentiable electronic signal is summarized at the bottom of Fig. 2, in the first bar chart. Regions of the scene are defined as either "shadows" (nonlinear toe of the sensitometric curve), "exposure latitude" (linear portion of the sensitometric curve), or "highlights" (nonlinear shoulder of the sensitometric curve). The new sensitometric response is proposed and labeled as "Scan-Only Film." This film system has a lower Dmin, lower contrast, and a longer linear curve section. This enhances both overall scene dynamic range translated to differentiable electronic signal and total linear exposure latitude. By not utilizing the full density dynamic range of a typical color negative film for production of an electronic signal, the typical calibration scheme could be described as "scanner-limited," with respect to scene reproduction dynamic range. This practice is by no means uncommon, because density limits are usually set to represent the full shadow to highlight dynamic range of most average scenes. This takes full advantage of digital bit depth in the scanner data path.

For normal scanning applications, it must also be recognized that a typical calibration scheme is not the only available option. Scanners are designed with dynamic range profiles capable of discriminating film densities present in positive, high-contrast reproductions. Therefore, the "forbidden zone" of scanning can easily be opened wider than the typical density range represented by a low-contrast color negative film. The blue forbidden zone in Fig. 2 represents one such calibration scheme. As is evident, it is unlikely that any density reproduced by the Vision2 sensitometric curve will not produce a final differentiable electronic signal. In this case, the calibration scheme could be described more accurately as "film-limited," relative to scene exposure dynamic range. The bottom bar graphs in Fig. 2 summarize the difference in a film-limited dynamic range scheme versus the scanner-limited scheme for the two film curves shown. By virtue of possessing a longer positive slope before the final maximum density plateau, the scan-only film system will still enjoy an advantage over the typical Vision2 reproduction.

In addition to the benefits already outlined here, films with lowered contrasts may also be augmented with additional features including reduced blue minimum densities (to help with blue-deficient scanner sources), reduced sensitivity to radiation or physical pressure damage, improved sharpness, and reduced grain.

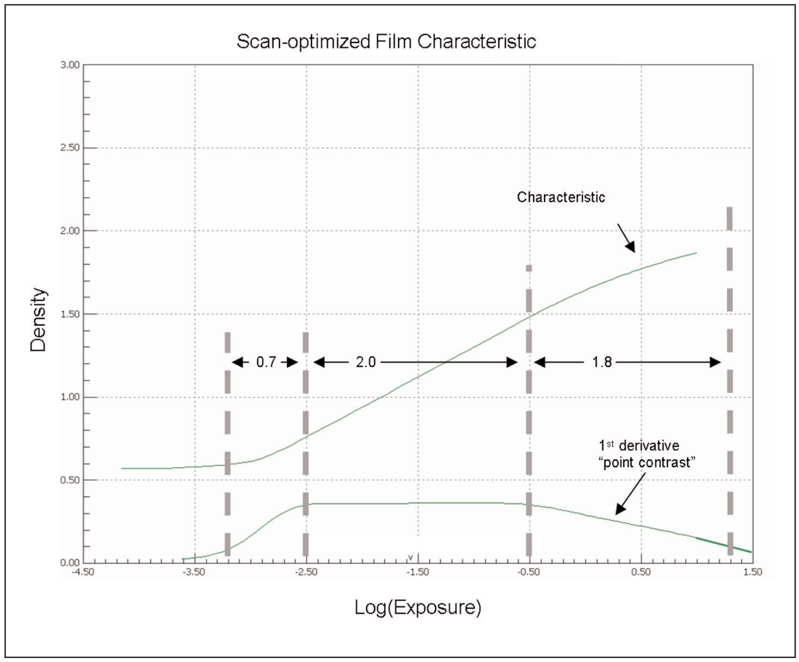

Figure 3. Basic linearity definitions for scan-only film system.

Extending Usable Dynamic Range

An important aspect of this system concept is the creation of a film characteristic transfer function with extended linearity to maximize capture dynamic range. A proposed design comprises a negative color film with red-sensitive, green-sensitive, and blue-sensitive imaging layers. This adheres to the following transfer shape definitions:

(1) A photographic speed equivalent to current Kodak EI 500 motion picture negative films.

(2) A nonlinear density response versus the logarithm of exposure that is at least 0.7 logE units wide between a point where the contrast is 25% of the mid-scale contrast and the onset of the linear mid-scale contrast.

(3) A roughly linear mid-scale contrast that is at least 2.0 logE units wide, and (4) a nonlinear contrast roll-off that is at least 1.8 logE units wide between the end of the linear mid-scale contrast region and the point where the contrast has dropped to 25% of the mid-scale level (Fig 3).

The upper-scale specification is especially significant as it addresses the problem of faster contrast roll-off in conventional motion picture films. By defining a higher contrast farther into the upper end of recorded dynamic range, the proposed design offers significant improvement in the quality of rendered highlight information upon electro-optical scanning. Rather than being generically defined by standard ANSI statusM optical density specifications, the preceding design features are also defined exclusively to scanner density specifications, calculated as the integral product of film dye spectrophotometry and electro-optical system spectral response.

A final important point to be made regarding this concept is that the absolute level of contrast is not important, relative to the creation of a first-generation aesthetically pleasing image. Instead, it is defined exclusively against the creation of superior electronic data upon scanning. Further, color reproduction techniques incorporating masking, inhibition, and contamination strategies can be widely modified from the general hue, saturation, and neutrality control objectives representative of normal color negative films. Typical color negative printing or scanning steps would lead to very flat and potentially non-neutral image reproduction using the proposed film curve, if subsequent contrast enhancement were not utilized. However, this film is intended to be used exclusively in combination with digital image processing, which yields a pleasing final look. Thus, the aesthetic of the raw translated image is not a factor for this design. Instead, the proposed tonescale adjustments here are intended to enhance the quality of scan data, relative to scene dynamic range and electronic noise.

Impact of Color Chemistry

Beyond tonescale design, further optimization of the scan-only film is accomplished by removing color chemistry components such as masking couplers and inhibition couplers. These are designed to impart specific preferred color and tone reproduction characteristics in traditional direct print image capture and distribution systems. With these elements removed, the film system can be designed to maximize light-capture efficiency and minimize image noise or graininess. Color-control components built into traditional image capture films can degrade image quality by reducing the efficiency of light capture and subsequent amplification during chemical processing. By utilizing digitization and manipulation steps subsequent to the capture of the image by the film, any desired image look can be introduced into the final display and distribution chain.

Practical Applications for a Scan-Only Film Design

One of the primary benefits of a scan-only film system is that it permits the combination of the superior light capture capabilities of a photographic film, with the enhanced flexibility and efficiency of digital post-production techniques. By trading off the requirement of having an image origination film stock produce an optical image embodying a preferred look when directly printed or scanned/transferred to video, a single scan-only film can be created and optimized to capture additional information from a scene. Additional scene information allows various existing camera negative film looks to be applied with a processor, employing algorithms that represent select film color and tone characteristics. Multiple film origination stocks are not needed to achieve the various film looks exhibited by conventional origination stocks. Looks are primarily achieved with photoscience image processing algorithms rather than with the specific emulsion chemistries that provide each film with its own unique look. This concept is easily extendable to either television or digital intermediate applications.

Alternate Color Reproduction Concepts Enabled by Scan-Only Systems

Being able to render the tone and color qualities of any past or present color film stock from a single starting film image offers significant benefits to creative and technical content producers. However, it is clearly not the only potential advantage of a scan-only film. Marrying a scan-only film with more advanced processing algorithms that simulate optical or chemical effects, otherwise cost- or time-prohibitive (such as cross-processing, skip bleach processing, etc.), allows users to do much more with their images in far less time. Further, alternative color reproduction paradigms could also be explored. One such application which deserves special attention focuses on designing a film that offers completely accurate color reproduction across the full gamut of visible colors.

A significant difference between traditional color origination films and the human visual system is the specific relative spectral sensitivities each has to regions of red, green, and blue light. Figure 4 illustrates the difference. In Fig. 4, the spectral sensitivities have been normalized to equal area to provide equivalent color balance. In practice, the film will be exposed through some typical lens on the camera, and the short wavelength sensitivity of the film will be removed by the UV absorption of the lens. This leaves the film and human eye blue sensitivities reasonably close. Film and human eye green sensitivities peak at about the same wavelength. However, the film sensitivity possesses a much higher peak, because the film sensitivity is much narrower than the human eye sensitivity. The two sensitivities differ the most in the red region. The human eye red sensitivity overlaps the green sensitivity significantly, whereas the film red sensitivity is shifted to longer wavelengths with considerably less overlap.

There are several reasons why traditional color origination film sensitivities differ from the human eye. One can be found in the image processing done in the human brain versus that done chemically in the film. The currently accepted color processing model for the brain is the Opponent-Color theory.[2] This model involves three channels of color, but not the red, green, and blue channels that are captured by the cones in the retina. Instead, the signals from the cones are combined to produce three signals representing a function of (1) red + green + blue (2) red-green and (3) red + green-blue. These three signals simplify to define a total signal, a redness-greenness signal, and a yellowness-blueness signal. In the classic chemical processing model found within color film, it would be impossible to provide for these transforms of the original red, green, and blue captured signals. Additionally, because color origination film is printed onto a color print film, the captured red, green, and blue signals must be transferred to complementary print film dyes, not color difference signals.

Another reason for the difference between color film and the eye can be found in the arrangement of the sensors in the two different systems. In the human eye, the cones are packed adjacent to each other and each cone has a red, green, or blue sensitivity. In film, the layers are stacked on top of each other. To understand the consequence of these different arrangements, take for example a 580 nm photon. In the eye, this photon could hit either a red-sensitive cone or a green-sensitive cone and produce a signal from that cone. The probability of producing a red or a green signal depends on the relative number of red and green cones and the relative sensitivities of the red and green cones as shown in Fig. 4. There are many photons at normal viewing luminances; therefore the red- and green-sensitive cones

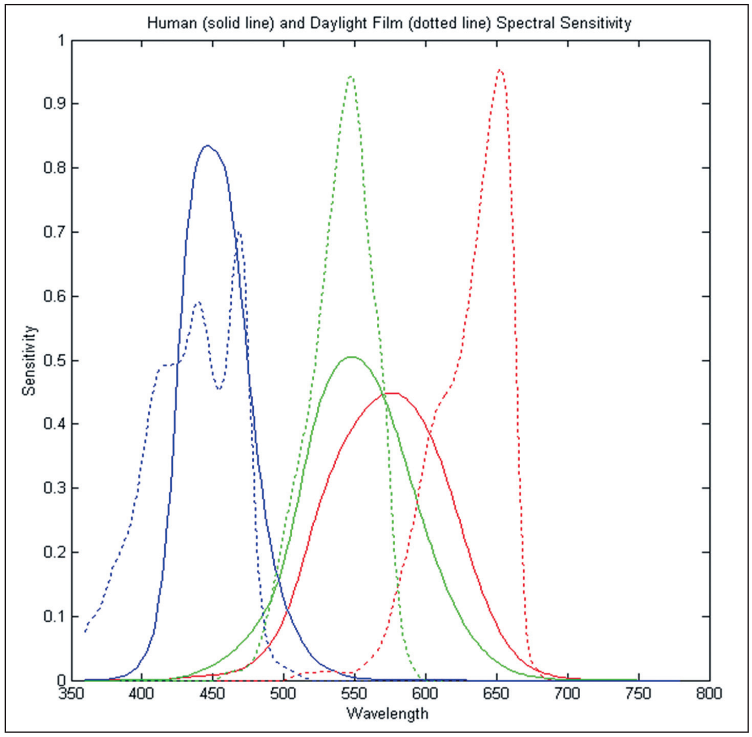

Figure 4. A comparison of human and a daylight film spectral sensitivity.

will absorb enough photons to allow a person to perceive the correct color. However, in film, the layers are stacked on top of each other with the green-sensitive layer above the red-sensitive layer. Therefore, any photon absorbed in the green-sensitive layer will not reach the red-sensitive layer. So, if the 580 nm photon is absorbed as it passes through the green-sensitive layer, there is zero probability that it will be absorbed in the red-sensitive layer. This forces a film design that minimizes the overlap of the red, green, and blue sensitivities. However, it is the overlap in sensitivities that allows an observer to distinguish between two wavelengths of light that differ by only 1 or 2 nm in the human visual system.

The film system cannot match the human eye spectral sensitivities or perform the processing that is performed in the brain. Color film historically produces colors that are not exactly the same as those perceived by a human observer in the original scene. In fact, although film colors are reasonably accurate, they have actually been optimized historically to offer the most pleasing color rendition, as determined by a large number of viewers averaging reproductions over all possible scenes. This is traditionally accomplished with a careful engineering of the spectral sensitivities and color processing chemistries found in modern color films to develop a desired full-system color reproduction.

If complete color accuracy in film reproduction is desired, it is theoretically possible to produce the same or very nearly the same colors on film as the human observer sees. This is accomplished by replacing the classic film spectral sensitivities with another set that is a linear combination of the human spectral sensitivities. To recover the same information as was captured by the human eye, the reverse of the specific linear transform chosen needs to be applied to the film captured image in processing. Again, this is impossible in the traditional chemical technologies available with film. With digital image processing following a scan step, however, the transformation becomes trivial.

A color film designed in this manner would not necessarily offer classically preferred image reproduction if it were to be printed directly onto a color print film. Further, an altered spectral sensitivity film, although capable of producing more accurate color reproduction, will not be able to produce the color reproduction of existing films. Such is the disadvantage of designing a film for a very specific application. Once spectral scene information is integrated and recorded with a set of sensitivities not linearly convertible to another known position, no amount of image processing will bring the color reproduction back to the same point.

The image processing needed to produce images that match the colorimetry of the original scene is not difficult. If a linear combination of the human eye sensitivities was used in the film, the film densities would need to be converted to film exposures using the characteristic film curve. Following this, a 3 x 3 matrix should return the exposures to values representative of those captured by the human eye. Because the color matching functions used to calculate the CIE XYZ tristimulus values are a linear combination of the human eye sensitivities, another 3 x 3 matrix would provide these. With tristimulus values known, several recognized scene-referenced output algorithms could be used to generate appropriate data for creating a reproduction colorimetrically equivalent to the original scene. The final result would be a film system that offers truly accurate color reproduction as an alternative to more classic preference-based color film systems.

Conclusion

With the advent of newer and better scanning technologies for motion picture film, a new paradigm for film design is required. The elimination of the classic requirements of direct optical printing and chemically derived color reproduction open the door to allow film to be a better sensor of light and a better starting point for high-quality images. By taking advantage of the power and flexibility of digital image processing, the imaging benefits of silver halide capture can be augmented to produce truly superior digital data for any present or future imaging application.

References

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