Color Matters

Why Full-Gamut Color is a Required Capability for LCD TVs
Full-gamut color refers to the ability of an LCD device to display the entire range of colors available within 100% overlap of a color space defined by the content creation community. Examples include NTSC, Rec. 709, Adobe RGB, and DCI. While many consumer display announcements refer to “wide-gamut color,” expected performance and picture quality benefits are ill-defined. Foggy definition of color-gamut results in new products with disappointing partial-gamut color, and in confused consumers whose preferences and willingness to pay for color are difficult to discern.

While the pressure to respond to improved picture quality extends beyond color-gamut (as we are seeing in the current 4K UHD resolution battle), powerful market forces will inevitably punish LCD TV brands that fail to provide full-gamut color experience. Competition is rapidly expanding for LCD technology suppliers, with players entering from new geographies, and threats remaining from alternatives such as OLED. The most significant change, however, is that consumers now expect LCD TV picture quality to match the best-in-class capabilities of second and third screen devices. The new requirement is to accurately and vividly display all video content, not just broadcast television. Mindful of the cost and price implications of various aspects of improved picture quality, TV product planners face difficult choices. Accordingly, this paper examines the psychology and biology associated with color to establish its central role in perception of picture quality. It also demonstrates that full-gamut color is necessary to achieve both dimensions of viewer preference: colorfulness and color accuracy.

The most compelling argument for immediate implementation of full-gamut color is the commercial viability of quantum dot optics. Quantum dots enable OLED-quality color at product costs well within the range of LCD TV targets. Quantum dot optics ship in volume today, delivering warmly received full-gamut color in both television and tablet LCD displays. This paper identifies the benefits of 100% NTSC color for LCD TVs intended primarily to display more limited Rec. 709 broadcast content, and we demonstrate the extensibility of quantum dot color-gamut performance into home theater formats such as DCI. Finally, we discuss additional benefits made possible by the unique properties of quantum dots, such as precise and easy tune-ability to LCD TV design goals, and to constraints in supply without major cost ramifications in manufacturing.

This whitepaper explains why full-gamut color is a required capability for LCD TVs; why there are stunning and award winning televisions containing QD Vision Color IQ™ optics on retailer shelves today; why we will see new full-gamut LCD TVs with quantum dot optics announced in 2014; and why full-gamut color will inevitably follow the same rapid market penetration path as LED backlighting.
Display Industry Dynamics

Pressure Intensifies to Innovate in Picture Quality

The TV supply chain has decades of experience competing to differentiate products for buyers primarily focused on price, picture quality, and screen size. However, even as succeeding generations of competitively priced LCD panels have escalated screen-size and resolution battles, the color-performance aspect of picture quality has actually degraded relative to the FCC’s original 1953 NTSC color-gamut definition. Contemporary consumers bring high expectations and ravenous appetites for premium-quality content and visually-exquisite viewing experiences. This intensifies pressure on LCD TV suppliers to quickly close the color-gamut gap that exists between the ubiquitous and limited-gamut Rec. 709 color standard, and the promise of full-gamut color performance.

Today, consumers access video content in different mediums and forms. Phones, tablets, laptops, game consoles, monitors and televisions all play a role, as does a wide variety of image and video content, all of which may be displayed on each of these delivery platforms. This tectonic shift in use cases for video means that consumer expectations for capability, most especially picture quality, will be set across consumer device types. In other words, LCD TV display suppliers must inevitably match picture quality improvements that occur on any and all consumer screens.

This dynamic is evident in the market penetration of new display technologies such as OLED. Well-known technology barriers resulting in prohibitive cost disadvantages for large format displays have limited OLED volume to small-screen mobile phones. OLEDs now account for about 20% of smartphone screens, with brisk growth expected in the tailwind of Samsung’s market leadership. Picture quality is the core of the OLED value proposition, particularly the delivery of full-gamut 100% NTSC color. The resulting war of “wide-gamut” claims in new device announcements, from tablets to readers to high-end televisions, includes the criticism heaped on Apple for the partial-gamut implementation of its otherwise spectacular new Retina iPad Mini. Clearly, if LCD TV suppliers want to continue to stave off OLED technology, they must respond immediately by taking the initiative on full-gamut color performance.

NTSC is an RGB color space that was introduced in 1953 by the FCC. The NTSC color-gamut is much wider than Rec. 709 gamut, which was specified by the ITU in 1990 and used for almost all television content today. More vibrant colors outside the Rec. 709 area are not accurately reproducible on partial-gamut displays.
The bottleneck, and currently the protective competitive barrier, for TV picture quality innovation is the Rec. 709 broadcast distribution infrastructure. If consumers can only receive Rec. 709 TV content, what is the value of investment in display capabilities beyond that? In the case of color, as OLED TV entrants tout, meaningful Rec. 709 picture quality improvements are possible using a 100% NTSC full-gamut color display. 100% NTSC display technologies are also well positioned for expansion to full-gamut color overlap with standards such as DCI to support consumer home access to a digital theater experience.

Relentless Pressure to Reduce Costs

Innovation investment has to be considered in the context of recent single-digit TV set market growth. LCD panel makers’ response to this stagnation has been to add capabilities, such as color-gamut expansion, to large format displays to justify price so that fewer but larger and more valuable screens are manufactured. In order to protect profit, it is imperative that panel designers close the color performance gap completely, but do so at the lowest possible cost of technology and integration.

The economics of LCD TVs are driving increasing specialization and internationalization of supply as the industry innovates to reduce cost. In order to take advantage of the price and flexibility advantages of supply chain specialization, TV system makers have to address increased complexity in design and production. Backlight unit (BLU) designs incorporate many types of non-standard components, from LEDs to light guide plates and more. Likewise, panels include non-standard color filters among other specialized components. LCD integrators must meet specifications that tradeoff color volume, brightness, cost, and power efficiency. The more precision offered by the optical components, the less limitation imposed by yield issues, and the easier it is to tune the design, the more likely it is that the resulting front of screen color performance will match design goals.

The advantages of precise and easy tuning of BLU optical components are even more valuable once the TV system is in production. The ability to re-tune color-gamut and maintain front of screen performance without major production changeover is critical to cost effectively respond to component availability or quality issues, or to maximize the opportunity to switch to lower cost sources of component supply.

Color Telepathy

Recent neurobiological studies explore why humans are trichromatic, asserting that the primary purpose of our wide perceptual color palette is to read minor changes in skin tone as indicators of blood flow and oxygenation. Low blood volume skin appears yellow, less oxygenated blood turns our skin greenish, and high volume blood flow makes the skin appear blue; all indicators of potential disease or internal trauma.

The red tones associated with highly oxygenated skin are so varied and critical to survival, from mating availability to anger, that researchers have found that humans must use contextual cues to interpret red skin. In these cases we are using color for unconscious communication of inherited meaning rather than conscious learned association.

All trichromatic mammals have hairless faces, perhaps because much of our success or failure depends on getting along with those in our social group. Skin is not merely something we see, but something of supreme value in our lives.

Excerpted from The Vision Revolution by Mark Changizi
Perceived Picture Quality

The Role of Colorfulness

The eyes of all animals use specialized photoreceptors to process color. Photoreceptors cross-reference each other to process additional hues, so creatures with only one type of photoreceptor can only see shades of grey. Humans are trichromatic, seeing combinations of short wavelength colors (blue), medium wavelength (green) and long wavelength (red). Nature uses color for communication of basic purposes that are critical to survival: to attract or repel members of the same species, and to attract or repel members of other species. This is why we are most attracted to vibrant colors such as red and yellow – we are tuned to distinguish these hues and have consciously learned to associate survival experience with color, such as with venomous snakes or poison plants. There is a reason STOP signs are highly saturated red, and crosswalks are vivid yellow.

In the last 10 years, rigorous research has been published – notably Elena Fedorovskaya’s work demonstrating that colorfulness is the main perceptual attribute underlying image quality – that links highly saturated colors, enabled by expanded color-gamut, to both viewer attention (dwell time) and preference. To check this theory qualitatively, engage any television retail professional in this discussion, and he or she may open up about the common practice of “toasting” – showroom manipulation of TV controls to pump up saturation in high ambient light conditions.

Color Accuracy as Quality Metric

Fedorovskaya also found that perceptual quality of images is closely related to the “naturalness” of the image. How does our attraction to highly saturated colors square with naturalness, when humans are capable of perceiving about 1 million different colors, only about 4000 of which are found in nature? Research finds that viewers do care about the accuracy of colors for which they have an experience-based expectation; these are termed “memory” colors, but how do we judge the accuracy of an unnatural color?

Video content creators define accuracy by agreeing on various color space dimensions (e.g. DCI) within the total area of perceivable color and declaring accuracy to be the correct display of colors exactly as they were intended within a standard color-gamut. TV industry consultants and technicians calibrate and measure the degree to which a consumer device accurately displays colors within the area of a particular color-gamut standard. While these standards are important in that they give TV designers a metric of compliance to content creator choices, is this definition of accuracy important to viewers? The answer is yes, and no.

Over the last several years, researchers at the Munsell Color Science Lab at The Rochester Institute of Technology have been studying the relationship between color-gamut or saturation and viewer preference. Research finds that preference rises with saturation up to the point at which skin tone appears unnatural. 2012 findings by Philips Research likewise report median preference for saturation as a 20% boost over Rec. 709, but that desirability was hue dependent. Researchers concluded that these findings reinforced viewer desire for colorfulness, but also memory color and skin tone accuracy.
The Value of Full-Gamut Color

Full-Gamut Enables Attention-Grabbing and Accurate Displays

A common misconception about wide-gamut and full-gamut technologies hitting the market today is that increased color-gamut infers a tradeoff with color accuracy. In fact, full-gamut displays enable a wide variety of display modes that can be tailored to both user preferences and content.

100% NTSC full-gamut displays are the widest gamut available on the market today, so the range of colors that can be displayed, from the deep reds of berries and blood, to gorgeous green grass on the golf course, to ocean scenes of the Caribbean, can all be attractively displayed. These colors at the full-gamut periphery are colors that occur in nature with some frequency, appearing on the Munsell Color palette for this reason. Saturated colors are also widely used in man-made artificial content, such as cartoons, video games, eye-catching art and signage in our cities’ nighttime skylines. Without full-gamut, all such scenes are rendered inaccurately – that is, they are displayed in colors less saturated than they actually appear in a natural environment. However, a full-gamut display device is only part of the solution to accurate color display.

The concept of display-color accuracy is also intimately tied up in the display gamut standards that are proliferating today. NTSC, Adobe RGB, sRGB, Rec. 709, or DCI may not be household names, but they are the pipe through which most digital content reaches us. So while the berries and the Caribbean golf course are indeed very colorful, they are likely reaching you through a partial-gamut broadcast standard such as Rec. 709. In the content encoding process, original colors are de-saturated to match the standard, reaching the display device without the as-captured saturation information. Simply rendering this partial-gamut content on your full-gamut color display without regard to the specific gamut differences may indeed make the berries red again, but certain memory colors and skin tones may also be expanded inappropriately, producing inaccurate colors. Generally, there are two approaches to addressing this issue.
First, while full-gamut color displays offer expanded capability, by no means is it necessary to exclusively use the expanded color space. Users that are dedicated to accuracy and want to view content exactly as encoded (not as is in nature) may do so. Many wide-gamut TVs allow users to tune the TV to Rec. 709 mode through device settings, resulting in increased accuracy with respect to the more limited-gamut standard. A full-gamut TV, on the other hand, provides the color space to ensure 100% overlap of a limited gamut (i.e., all colors in Rec. 709 are contained within the DCI standard). Through color management software, Rec. 709 content can be reproduced on a full-gamut display with perfect accuracy. Additionally, a full-gamut display provides TV designers with more flexibility to achieve full Rec. 709 front of screen performance, given a myriad of multi-sourced component combinations (e.g., color filter arrays, LEDs, etc.), and a range of ambient light viewing conditions.

Alternatively, color management algorithms can be used to map limited-gamut content to a full-gamut color display, which viewers may prefer for viewing content such as animation. Using gamut expansion software, similar to the up-conversion that was common in early HDTVs before HD content became pervasive, the Rec. 709 signal can be expanded to utilize the full-gamut capabilities of the display hardware. Expansion can be achieved imperfectly with linear algorithms, or more often use advanced non-linear gamut expansion algorithms. More sophisticated algorithms account for the regions of the gamut where expansion can create an unnatural appearance (e.g., skin tones and memory colors) and perform very little expansion in those regions. These algorithms give users the ability to experience the vivid, saturated colors of full-gamut color display without introducing unnatural color distortion.

Another accuracy benefit of full-gamut color display is that as alternative color-gamut spaces proliferate via initiatives like UHD and Rec. 2020, digital cinema in the home, and over-the-top distribution, full-gamut color displays can accurately render them all. As defined here, technology that enables 100% NTSC full-gamut color capability can be tuned to achieve 100% overlap with DCI, Adobe RGB and other wide color-gamut spaces, thus ensuring enhanced colorfulness and 100% accuracy.
Full-Gamut Implementation Must Address Material and Supply-Chain Costs

Several technologies exist today that enable full-gamut-capable displays: lasers, OLEDs, and quantum dots. Laser-based displays have been much discussed, but remain a curiosity due to the lack of an efficient green light source. While OLED technology has matured, high-capacity manufacturing requires large infrastructure investments which increasingly make less business sense as LCD technology steadily improves. Also, the rapid degradation rate of blue OLED sub-pixels has persisted for more than a decade without a solution. The new entrant to the list is quantum dot technology, now found in displays down to 7” tablets and up to 65” UHD TVs. Remarkably, in the first year of quantum dot displays’ commercial launch, quantum dot displays reached a similar total display area shipped as that of OLED, despite OLED having a decade-long head start in the market.

Quantum dot semiconductor nanocrystals are tiny chunks of luminescent material that can emit saturated light in colors that are dependent on the material composition and size of the dots themselves. Blended together to form the red and green light channels of an LCD display, quantum dots can be meticulously tuned to a display manufacturer’s specifications during the engineering design process both for quantity of light and for color precision. This degree of freedom in optical design is unprecedented for LCD displays, and it presents a critical advantage in the display supply chain where lack of standards is the rule, and where every display maker battles to differentiate their products from the competition.

There are a variety of blue LEDs, color filter arrays, cell gaps, and even liquid crystal geometries that persist in the supply chain. Standardization of components is absent from the display supply chain for a host of business and technology reasons – the result is that no general specification exists for light-emitting material performance, white point, or even color-gamut. Surprisingly, many display devices made today do not even adhere strictly to limited-gamut standards such as Rec. 709. The tunable nature of quantum dot technology enters as an ideal solution for this diverse and untamed industry.

LCD module design is a custom business where differentiation depends on trading off color-gamut with brightness and power efficiency. Designers focused on making green, energy efficient sets can choose wavelengths which maximize brightness while using less power. Displays targeted for digital cinema content can be designed to display DCI gamut with perfect accuracy. Mobile devices can achieve Rec. 709 gamut while optimizing for power consumption and battery life. And all this can be done at the BLU component level, without making any changes at the LCD fab, where they would lead to extensive and expensive development/qualification time and potential yield reductions.

Brands that source panels from multiple vendors can buy different components with slightly different quantum dot formulations to consistently achieve specified front of screen performance requirements despite the use of different color filter arrays from various panel makers. Front of screen performance can even be tuned mid-production if for any reason final display performance in manufacturing differs from the design specification.
Conclusion

The LCD industry is positioned to close the color-gamut performance gap, significantly improving the single most important perceptual factor in viewers’ estimation of picture quality. Full-gamut color displays enabled by cost-effective quantum dot technology deliver vibrant colorfulness and 100% accuracy, and are poised for universal adoption in the coming years.

As with the transition from standard definition to HD, there are short-term gaps to address in content distribution standards, content availability, and the software layer to better support the new optical components capability, but these challenges are readily addressable by several large-ecosystem communities that are incented to tackle them. Content creation and processing equipment makers, as well as display suppliers, are anxious to offer consumers the next level of performance after 3D failed to gain widespread adoption. Studios have learned how to capture profits from movies in the home, and are now focused on bringing cinema quality viewing experiences to mainstream, affordable home theaters. Traditional content delivery services like cable will profit by upgrading services, and newcomers in the over-the-top distribution world will accelerate innovation in this domain. All of the ingredients are available to make full-gamut color display a reality, and like prior display technology transitions, including the transition to LEDs themselves, better consumer value will drive surprisingly rapid penetration.

Reference Materials


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