Growing Importance of Color in a World of Displays and Data

Color in displays

Standards for color space and their importance

The television and monitor display industry, through numerous standards bodies, including the International Telecommunication Union (ITU) and International Commission on Illumination (CIE), collaborate to create standards for interoperability, delivery, and image quality, providing a basis for delivering value to the consumers and businesses that purchase and rely on these displays. In addition to industry-wide standards, proprietary standards developed by commercial entities, such as Adobe RGB and Dolby Vision, drive innovation and customer value.

The benefits of standards for color are tangible. They provide the means for:

- Color information to be device- and application-independent
- Maintaining color fidelity through the creation, editing, mastering, and broadcasting process
- Reproducing color accurately and consistently across diverse display devices

By defining a uniform color space, encoding system, and broadcast specification relative to an ideal “reference display,” content can be created almost anywhere and transmitted to virtually any device. In order for that content to be shown correctly and in full detail, the display rendering it should be able to reproduce the same color space. While down-conversion to lesser color spaces is possible, the resulting image quality will be reduced. It benefits a consumer, whenever possible and within reasonable spending, to purchase a display with the closest conformance to standards so that they are assured of the best experience in terms of interoperability and image quality.

The Color IQ optic that is referenced as Annex 3 of Exemption 39(b) allows displays to meet these standards, and does so at a lower system cost and higher energy efficiency than alternative solutions. Displays using Color IQ optics not only meet current standards, they often exceed them, making them potentially compatible with future standards and reducing the need for consumers and businesses to upgrade their older displays.

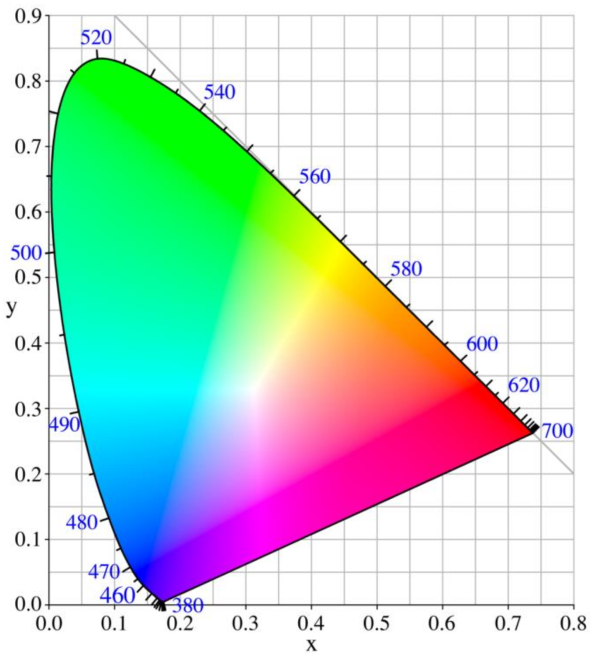
For years, televisions, computers, and handheld device displays all served different purposes. With the widespread adoption of always-on, high-bandwidth data networks, and the near ubiquitous connectivity of devices, the lines have blurred between these screens: broadcast television is available on mobile phones; movies can be downloaded or streamed and played on computers or game consoles; and televisions can be used to surf the web. The proliferation and widespread availability of content across devices highlights the importance of the screen, and brings increasing focus to the quality of the display.

Important Notes on Color

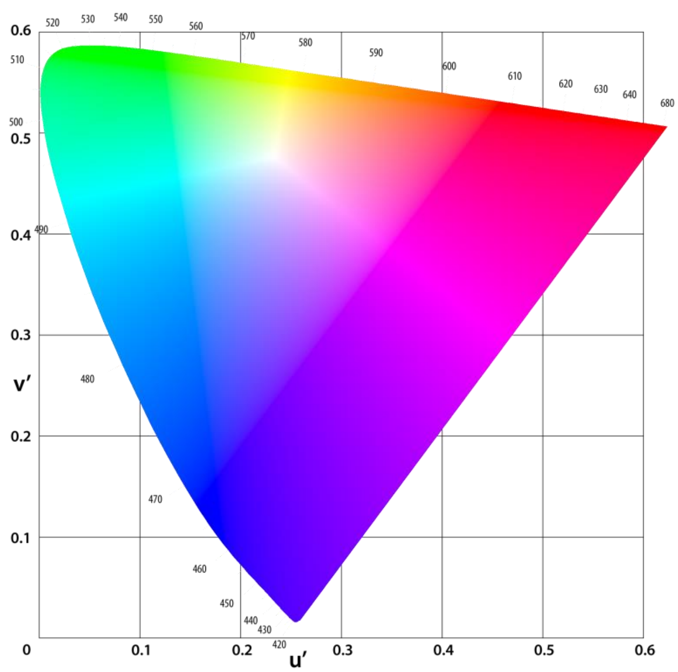
CIE 1931 xy and CIE 1976 u’v’ chromaticity diagram

Color is made up of two components: chromaticity and luminance (sometimes called brightness). Chromaticity describes the component wavelengths of light that make up the specific color.

In 1931, based on color research performed in the 1920s, the International Commission on Illumination (CIE) created the CIE XYZ and CIE RGB color space. These were used to define the xyY color space, separating the chromaticity of a color (xy) from the luminance (Y). This color space defines all of the chromaticities visible to the human eye, and the following illustration shows the CIE 1931 xy gamut as a plot:



Research done in the early 1940's by David McAdam showed that the CIE 1931 XYZ color space did not provide uniform color perception. Basically, McAdam's study showed that a test subject's perception of the value of a color did not match the measure chromaticity for that color. This led to a revision in 1976 called the CIE 1976 Luv color space. The following illustration show the CIE 1976 u'v' chromaticity diagram:

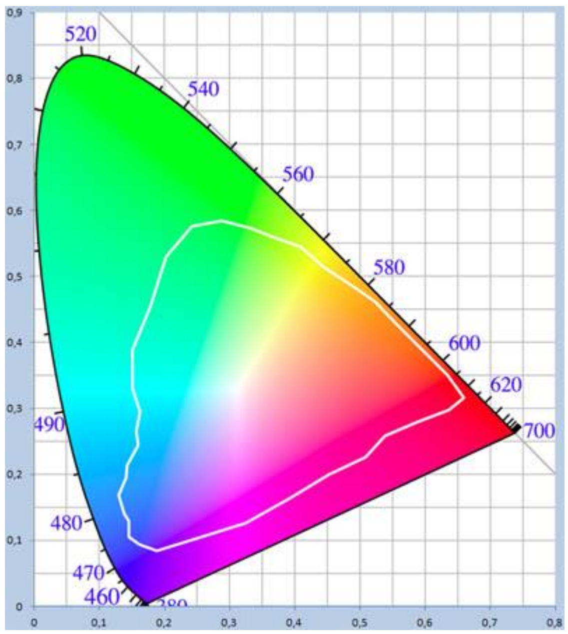


The CIE 1931 xy chromaticity diagram remains the standard, though some companies use the CIE 1976 u'v' diagram instead. It is possible to map measured RGB primaries to either gamut to accurately compare results.

Pointer's Gamut

The Pointer's gamut is an approximation of the gamut of real surface colors as can be seen by the human eye, based on the research by Michael R. Pointer (1980). What this means is that every color that can be reflected by the surface of an object of any material is inside the Pointer's gamut.

The following illustration shows Pointer's Gamut, mapped against the CIE 1931 xy chromaticity diagram:



Older wide color gamut standards like NTSC, Adobe RGB, and DCI-P3 achieve < 86% coverage of Pointer's gamut, necessitating the development of still wider gamut standards.   As part of its ongoing efforts to drive standards that can faithfully reproduce the entire gamut of naturally occurring colors, the ITU-R developed the Rec. 2020 standard in 2012, which can cover 99.9% of Pointer's Gamut and is backwards compatible to encompass >99% of the other major gamut standards (e.g. NTSC, DCI-P3, sRGB, and Adobe RGB).

Broadcast Color Standards

The ITU

The International Telecommuncations Union (ITU), based in Geneva, Switzerland is a United Nations agency responsible for managing information and communication technologies. Among its many roles, it assists in the development of worldwide technical standards, including those used for broadcasting. The Radiocommunication sector, or ITU-R, is responsible for the broadcast standards used in creating, mastering, and transmitting visual content.

ITU-R BT. 709 (Rec. 709)

First approved in 1990, Rec. 709 defines and standardizes the format for high-definition television. It includes all of the information needed to encode, broadcast, and display HDTV, including the RGB primaries relevant to displays. It covers just 33.5% of the CIE 1931 xy chromaticity diagram and less than 70% of Pointer's Gamut.

Here are the values for the Rec. 709 color primaries:

Primary	CIE 1931 xy chromaticity diagram			CIE 1976 u'v' chromaticity diagram	
	x	y		u'	v'
Red	0.640	0.330		0.451	0.523
Green	0.300	0.600		0.125	0.563
Blue	0.150	0.060		0.175	0.158

DCI (Digital Cinema Initiative) P3

The DCI-P3 color space is part of a voluntary specification for digital cinema projectors among select content producers (Disney, Fox, Paramount, Sony, Universal, and Warner Bros.). The DCI-P3 RGB primaries were selected based on the color rendering capabilities of DLP cinema projectors that utilize Xenon bulbs and color filters and is only intended for theatrical playback of digital cinema content. The DCI color space covers 41.7% of the CIE xy chromaticity diagram and 85.5% of Pointer's gamut. DCI was never intended for consumer displays and as such there is no DCI-graded consumer content today, nor are there plans to make DCI-graded content available to consumers in the near future.

Primary	CIE 1931 xy chromaticity diagram			CIE 1976 u'v' chromaticity diagram	
	x	y		u'	v'
Red	0.680	0.320		0.496	0.526
Green	0.265	0.690		0.099	0.578
Blue	0.150	0.060		0.175	0.158

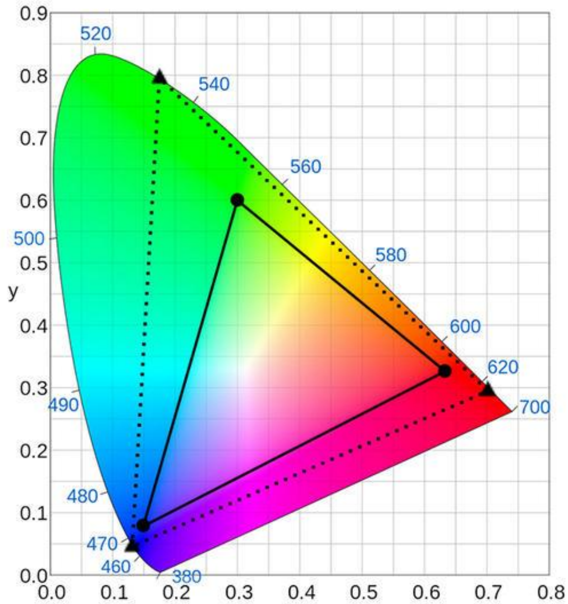
ITU-R BT. 2020 (Rec. 2020)

The newer Rec. 2020 specification advances the aging Rec. 709 version, defining and standardizing the format for Ultra High-Definition Television (UHD TV). The UHD TV standard features higher resolutions (up to 8K) and significant improvement over the Rec. 709 color gamut standard, nearly doubling the size. Rec.2020 specifies monochromatic RGB primaries with wavelengths of 630, 532 and 467 nm respectively, delivering a very wide color gamut standard that covers 63.3% of the total chromaticity and 99.9% of Pointer's gamut in CIE 1931 xy space. Rec. 2020 also encompasses Rec. 709/sRGB, Adobe RGB, DCI-P3, and NTSC (1953) color spaces, making it possible to display nearly all available content with accurate colors. This is a significant advance that promises to match modern digital imaging capabilities with displays across a wide range of devices.

Here are the values for the Rec.2020 color primaries:

Primary	Wavelength	CIE 1931 xy chromaticity diagram			CIE 1976 u'v' chromaticity diagram	
		x	y		u'	v'
Red	630	0.70792	0.29203		0.55649	0.51651
Green	532	0.17024	0.79652		0.05573	0.58674
Blue	467	0.13137	0.04588		0.15983	0.12558

Here is a CIE 1931 xy diagram comparing Rec. 709 and Rec. 2020:



High Dynamic Range (HDR) / DolbyVision

Dynamic range refers to the TV's contrast ratio (range from highest luminance to lowest luminance), which is typically around 2000 to 3000:1. High Dynamic Range (HDR) has just been defined by the Consumer Electronics Association as "a range of luminance levels that exceed conventional display system capabilities", and it relies on the HDR10 Media Profile, which adopts the Rec. 2020 color primaries.

Note: The HDR10 Media Profile is defined as:

- EOTF: SMPTE ST 2084
- Color Sub-sampling: 4:2:0 (for compressed video sources)
- Bit Depth: 10 bit
- Color Primaries: ITU-R BT.2020
- Metadata: SMPTE ST 2086, MaxFALL, MaxCLL

Dolby Vision is an end-to-end solution that incorporates various technologies to create life-like image quality. It spans the entire content pipeline from video capture and encoding to distribution and display hardware. Dolby Vision is focused on creating and delivering "better pixels", meaning Dolby does not stop at improving the quantify of pixels (e.g. 4K), but also incorporates other picture quality enhancements like high dynamic range and wide color gamut.

Dolby views Dolby Vision as a "Super Set" of all other 4K HDR approaches. Dolby's approach is "to master in the largest color volume possible … The larger the color volume, the greater the range of both color and contrast … From that highest quality master, [Dolby] can derive any needed output version including International Telecommunications Union (ITU) Rec.709 standard dynamic range (SDR) as well as HDR10 [Rec. 2020] and anything in between ..."

In addition, Dolby's goal is "to deliver the largest color volume content possible … The Dolby Vision ecosystem is designed to enable this level of quality all the way to the end display and then allow the final display to effectively map that content to its native capabilities to provide the best experience possible. This is true for all device classes such as TV's, tablets, mobile devices etc."

Monitor Color Standards

sRGB

The sRGB standard, developed by Microsoft and HP in 1996, was designed to bring a standard color space to the computer display industry and the Internet. The goal was to provide a device-independent color standard for displays, operating systems, applications, image capture devices such as cameras, and to allow color information to be accurately shared between applications.

By matching the Rec. 709 standard for RGB primaries, sRGB was able to bridge between television and computer displays standards, helping push its successful adoption. sRGB is now used across an incredible wide range of displays and devices. Many image capture devices, such as digital cameras and scanners, used sRGB as their standard color space, as did consumer-grade inkjet printers.

As image capture and printing technologies have progressed, sRGB, which has its roots in cathode-ray tube (CRT) displays and the 1990 Rec. 709 standard, is beginning to show its age. Most digital cameras now use the RAW format to capture the full color gamut that modern image sensors can capture, converting to sRGB only for lower resolution, lower fidelity JPEG images. Newer standards, such as Adobe RGB or Rec. 2020, provide a larger color gamut more appropriate to the technology available today.

AdobeRGB

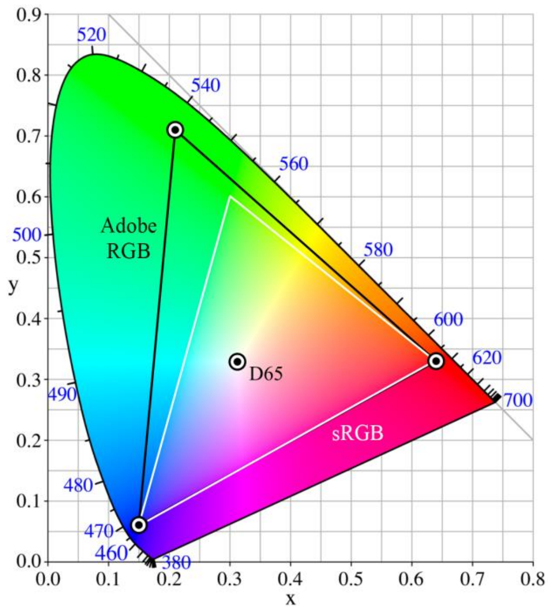
Adobe Systems, through its Creative Suite and Creative Cloud software products, has a market penetration of more than 80% of the worldwide market for illustration, photo manipulation, video editing, and publishing. As the driving force in the creative software business, Adobe saw an opportunity to correct a major problem: how to resolve the significant color gap between transmissive RGB computer displays and reflective CMYK printed materials.

In 1998, Adobe created Adobe RGB 1998 to encompass most of the colors achievable on CMYK printers, using just the RGB primaries available on a display. To accomplish this, they extended the value of the green primary, matching the one specified in the NTSC 1953 color space. This better mapping of colors between the display and output makes it easier for creative professionals and consumers to get a true WYSIWYG (what you see is what you get) experience, with the obvious benefit that this simplifies the workflow by reducing the chance for error due to color mismatches.

Here is a table showing the specific values of the Adobe RGB 1998 primaries:

Primary	CIE 1931 xy chromaticity diagram			CIE 1976 u'v' chromaticity diagram	
	x	y		u'	v'
Red	0.640	0.330		0.451	0.523
Green	0.210	0.710		0.076	0.576
Blue	0.150	0.060		0.175	0.158

Here is a CIE diagram comparing the sRGB and Adobe RGB 1998 color gamuts:



"CIExy1931 AdobeRGB vs sRGB" by Mbearnstein37 - Own work. Licensed under CC BY-SA 3.0 via Commons - https://commons.wikimedia.org/wiki/File:CIExy1931_AdobeRGB_vs_sRGB.png#/media/File:CIExy1931_AdobeRGB_vs_sRGB.png

The role of color in displays

Mastering

Creative / artistic

According to a recent Barclays Bank report on Adobe Systems (NASDAQ: ADBE), more than US$15B is spent worldwide each year by businesses and individuals on software for creating and manipulating digital images. The creative pipeline, from photography to illustration and layout, from printing to online and traditional advertising, has gone digital. Displays have traditionally been the weak link in the creative chain by failing to provide an adequate color gamut to properly render the full color of the content. This is especially true today the color information captured by digital video and still image cameras, scanners, and even mobile phones far exceed the capabilities of displays to accurately reproduce them.

Standards such as Adobe RGB (1998), which define display performance directly aligned with the content do provide a solution to the problem, but have been prohibitively expensive for all but the largest companies. As new materials, such as CdSe-based quantum dots make their way into monitors, displays with >99.5% Adobe RGB (1998) coverage are becoming available at consumer price points, making Adobe RGB-compliant monitors affordable to virtually anyone using applications such as Photoshop, Illustrator, or Gimp.

E-commerce and color accuracy

Color is a key component of the purchasing decision for apparel and home décor items. With the growth of e-commerce in Europe—which has grown to nearly €424B, or 2.4% of the GDP, according to the non-profit eCommerce Europe Foundation—returns for color mismatch can be a significant economic issue. While specific return rates were not specified in the 2014 eCommerce Europe report, Kathleen Fasanella of Fashion Incubator and publisher of the bestselling book, The Entrepeneur's Guide to Sewn Product Manufacturing, said:

> *"Of total returned apparel products, 60% is due to the wrong size, 15% due to hand properties of fabric, and >7% is due to color matching.*
> *source:* http://www.fashion-incubator.com...
>
> *Returns due to color matching are inevitable because you have little control over visitor monitor calibration."*

The University of Regensburg[1] made a study for the reason for returns[2] which implicitly gives similar results. The study allowed to give several reasons for wanting to return a product. The most prominent reason remais the fact the product didn't fit however 7% indicated they found the aspect (looked cheap which is clearly a discrepancy in the visual) a criterion for returning the product. The same study indicates that most e-retailers in fashion have margins between 11-15% so that decreasing the return rate is a primary driver between profit and loss.

The need for calibration is greatly reduced when the full color gamut is supported by the display, which opens the possibility of reducing expensive returns due to color-mismatching. As e-commerce continues to grow across Europe and around the world, matching display capabilities with the full color available in content is a key part of increasing customer satisfaction and decreasing costly returns.

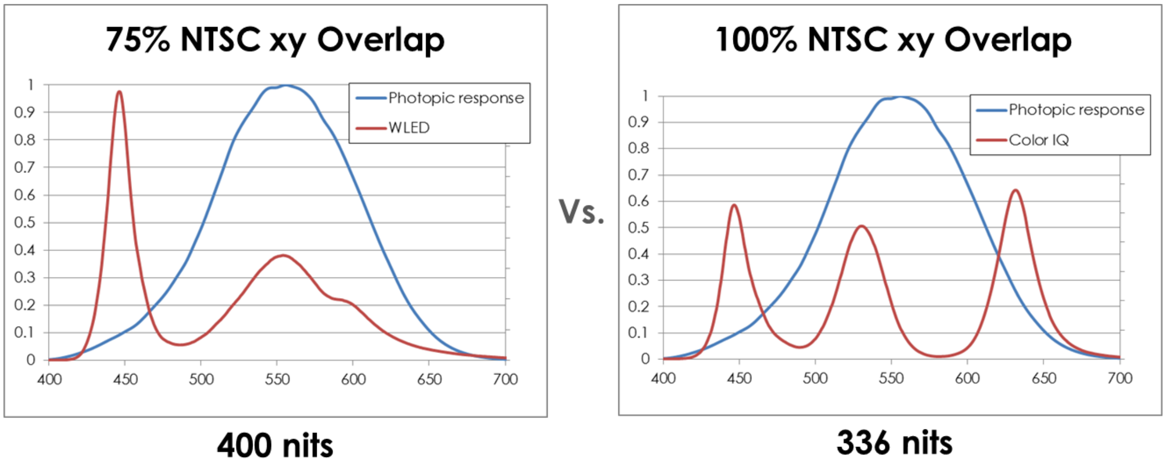
Brightness, Luminance, and the H-K Effect

By definition, brightness is the perception of light that is captured by the rods/cones in the human eye and processed by the brain. Because it is perceptual in nature, brightness is subjective and cannot be effectively measured, except comparatively. Luminance, on the other hand, is an objective measurement that has historically been measured in units known as "nits" (from the Latin *nitere*, meaning "to shine"). It should be noted that the terms brightness and luminance are not interchangeable.

Nits are calculated by measuring the light at the front of screen using a photometer, and then multiplying the resulting spectral distribution with the photopic response of the eye, peaked near $\lambda = 550$ nm. Therefore, the luminance of displays with different backlight technologies and different spectral distributions cannot be compared using nits alone. At best, nits act as a proxy for brightness comparisons only when the differences in the spectral distribution between displays are negligible. When comparing two systems, using a combination of the measured color gamut and the luminance together provides the best results.

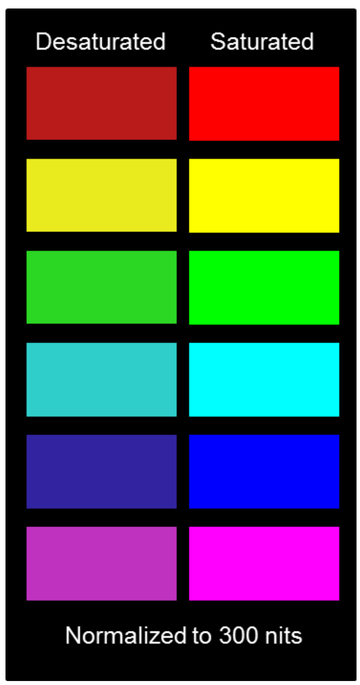
In the figure below, a conventional WLED backlight and a Cd-based QD backlight are plotted against the photopic response, where the spectra are normalized to output the same number of photons. The broad spectrum of the YAG phosphor used in conventional WLED backlights has more overlap with the photopic response than the narrow RGB primaries of the QD backlight, which contributes to a 19% higher luminance measurement. In this case, the WLED backlight is only capable of 75% NTSC overlap, while the QD backlight reaches 100% NTSC overlap. This example illustrates the fundamental tradeoff between luminance and color gamut.

[1] German Language power point presentation: http://www.ibi.de/files/Retourenmanagement-im-Online-Handel_-_Das-Beste-daraus-machen.pdf
[2] English Language reporting on this study: http://www.whiteboardmag.com/e-commerce-why-and-how-often-customers-sent-stuff-back-survey/



Comparison of conventional white LED (WLED) backlight at 400 nits relative to a Cd-based QD backlight. Assuming both spectral distributions output the same number of photons, the QD backlight with a higher color gamut (100% NTSC) will measure 336 nits (16% lower), but will appear brighter to the human eye due to the H-K effect.

An additional consideration when comparing the brightness of displays is the H-K effect, named after the researchers, Helmholtz and Kohlrausch, who first documented it. The H-K Effect is a psycho-visual phenomenon where more saturated colors appear brighter to the eye despite measuring the same number of nits. This phenomenon has been studied and quantified by matching the brightness of two blocks of identical hue values, varying only the amount of saturation between them. A simple demonstration of the H-K effect can be seen in the figure shown below:



Despite each set of color blocks measuring the same luminance level, the row of saturated color blocks appears brighter. In Cd-based QD displays with narrow RGB primaries, the H-K effect provides manufacturers and/or consumers the option to reduce the backlight power while still delivering a visually bright image. This reduction in the energy needed to achieve a suitably bright image can be significant.

Color utilization in content

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 greens of a tropical forest or golf course, to stunning blues the Caribbean Sea, 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 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 full color 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, it is not 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 colorful accuracy and excellent image quality.

Source material

With the widespread adoption of digital cameras for both photography and video, including movie and film production, the vast majority of content generated today has a significantly larger color gamut than even the Rec.2020 standard defines. Unfortunately, much of this valuable color information is being lost as content is mastered to lower color gamuts. This is part of the driving force behind both the Rec.2020, which defines the next generation of broadcast television, and the HDR10/Dolby Vision standard, which seeks to provide a higher quality, more consistent visual experience between the cinema, the television, and the computer or mobile device.

As both the standards and the displays evolve to support wider color gamuts, content providers are beginning to use this expanded color space to enhance their customer's viewing experience.

Lower color gamut solutions

When content encoded in a wider color gamut is displayed on a screen with a smaller, less-capable color space, the dynamic range is significantly reduced, resulting in loss of detail, banding, and other unpleasant—and unavoidable—side effects that reduce the overall picture quality significantly.

[Need to find a couple visuals to illustrate this]

Original content streamed in HDR

Both Amazon and Netflix are now streaming select portions of their programming in HDR, including the award-winning and highly-acclaimed original series: *Mozart in the Jungle* (Amazon), as well as *House of Cards, Breaking Bad,* and *Marco Polo* (Netflix). This streamed HDR content is higher-resolution (4K) and uses a wider color gamut to produce incredible picture quality. Because this content is streamed, rather than broadcast, it is the first 4K/HDR content available. Amazon has even expanded its distribution to the U.K., with plans to move beyond that and Netflix is expected to do the same.

Steven Tweedie, of the publication Business Insider, sums up the benefits of HDR this way:

> *"It's easiest to notice the difference HDR makes when you have a wide spectrum of colors in a scene.*
>
> *In "Marco Polo," there are scenes in which a colorist traditionally had to choose between either showing a dark shadow or ray of sunlight. With HDR, there's no such compromise — colorists are able to highlight the nuances of each, showing both dark shadows and bright light that doesn't appear washed out."*

In the same way as HD Television has found slow acceptance in some ways, it has become the norm when viewing sports events for examples. It is plausible that a similar development would follow an increase in screen quality.