Adding a White Subpixel

Adding a white subpixel to RGB color displays, in combination with subpixel rendering, can produce a display with a high effective pixel density and a significantly enhanced color gamut.

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The goal for most electronic color displays is to create images that mirror the “real world.” This is especially true for television displays, but it applies to all displays that show images. Natural images of the real world are typically made up of rich, saturated colors, which are hardly ever very bright, together with extremely bright unsaturated colors, such as reflections from smooth objects. Unfortunately, nature displays its colors by a subtractive color system, and virtually all electronic displays use additive color systems. Conventional design standards require the designers of these displays to make tradeoffs in brightness, color saturation, and power consumption.

These challenges can be overcome by adding a white subpixel to a conventional RGB display, which greatly increases the display’s ability to render natural images. Past attempts to implement RGBW have not been successful because of the notable penalties in color performance and cost associated with adding subpixels. But recently, a new approach using subpixel rendering – filtering the display in subpixel rather than entire pixel increments – along with RGBW, has offered a cost-effective way of achieving high-brightness wide-color-gamut displays without the same tradeoffs as conventional RGB (and RGBW) designs.


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Fig. 1: Natural images, such as this one, are likely to have dark highly saturated colors and bright unsaturated ones.

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The Colors of Natural Images
Except for relatively rare emissive light sources such as light-emitting diodes (LEDs) and lasers, high-brightness saturated colors are not found in real-world scenes. When relatively bright white light falls onto the pigmented objects encountered in daily experience, colors are formed because the objects selectively absorb parts of the spectrum and reflect other parts. Objects without saturated colors, such as those that are white or pastel colored, may reflect most of the light, thus being radiometrically and visually brighter than saturated-color objects.

Conversely, objects that form saturated colors absorb most of the light and reflect only a narrow band—or bands in the case of purple or magenta—of the full spectrum of light falling on them, reducing the brightness of saturated-color objects compared to unsaturated-color objects. This is especially true of saturated colors that are near the corners of the color triangle of red, green, and blue on the CIE standard chromaticity diagram since these colors are made up of light in very narrow wavelength bands.

Specular reflections from the surfaces of objects do not substantially alter the spectrum of light falling on those objects because these highlights are not color saturated, not even on objects that are highly color saturated in diffuse reflection. These highlights are the brightest portions of many natural scenes. The mirror-like reflection of an overhead light on a brightly colored billiard ball, for example, is white, not colored. Thus, by their very nature, real-world scenes may have bright unsaturated-color objects and darker saturated-color objects.

Figure 1 is a natural image with highly saturated colors, whose brightness and CIE color coordinates are plotted in Fig. 2. The brightest red, green, and blue colors are far darker than the white. The brightest of the strong colors is the yellow, and even this color is only half as bright as the white. This photograph is an extreme example, showing brightly colored objects; another typical photograph might not have such brightly colored areas.

It is possible to plot the typical distribution of colors vs. brightness found in large ensembles of natural images (Fig. 3). Saturated colors are relatively rare in natural images, but when they do occur, they are quite dark. Given the subtractive nature of color formation in natural scenes, colors that are both bright and saturated are almost non-existent.

The Challenge for Electronic Displays
Optimally, electronic displays would render natural scenes by creating very bright unsaturated colors and darker highly saturated

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**Fig. 2:** The luminance and CIE color coordinates of the pixels in Fig. 1 are plotted here.

**Fig. 3:** This distribution of CIE color coordinates vs. luminance is typical of that in large ensembles of natural images.
color rendering

<table>
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<th>Table 1. Impact of RGBW PenTile Pixel Format on Luminance</th>
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Note 1. Luminance calculated for constant backlight luminance.
Note 2. Calculations made for both narrow-gamut (high transmissivity) and wide-gamut (low transmissivity, high color saturation) matrix color filters.
Note 3. NTSC ratio is the ratio of a display's color gamut with the gamut specified for NTSC color television.

colors. But the brightness of unsaturated colors produced by the conventional three-primary-color system is limited because color can be created only by adding partially saturated-color primaries. If the saturated colors in natural images are mapped to the partially saturated RGB primaries, then the system is unable to map the bright unsaturated colors from the images. Conversely, if the brightest unsaturated colors in natural images are mapped to the brightest unsaturated RGB colors, then the RGB primaries are unnecessarily bright and insufficently saturated.

Therefore, there is a tradeoff between the brightness of the unsaturated colors and the gamut of saturated colors produced by an RGB display. The more saturated the color primaries, the lower the unsaturated-color brightness, since white is made up of red plus green plus blue. This creates a luminance/saturation compression, in which the unsaturated colors are less bright and saturated colors are compressed or desaturated to fit within the limitations of the compromise system. Achieving both high brightness and wide color gamut requires higher-brightness backlights to compensate for the lower transmissivity of highly saturated color primaries. A color-formation system that adds an unsaturated "primary" such as white can better display natural images without making the same tradeoffs.

Clairvoyante's PenTile Matrix™ RGBW liquid-crystal-display (LCD) technology adds this additional white primary without increasing the subpixel count, which sounds impossible but which we will explain shortly. The white subpixels are much brighter than the red, green, and blue subpixels because the white is formed using a transparent filter that allows most of the light through, while the other three colors are formed by filtering out all but a narrow band of the spectrum. Since such color filters are not ideal bandpass filters, the transmissivity is less than 100% even in the desired bandpass wavelengths, which further darkens the subpixel. Since the white subpixel has higher light transmission, the RGBW system significantly increases the brightness of the panel when displaying the unsaturated colors characteristic of natural images, and consequently allows the use of more highly saturated-color primaries without significantly reducing the total display brightness.

In Clairvoyante's implementation, we combined the RGBW layout with the company's PenTile Matrix™ pixel-remapping and subpixel-rendering technology, which requires fewer subpixels for a given display resolution. This results in increased aperture ratio, which in itself enables increased saturated-color display.

Fig. 4: These subpixel structures are drawn to scale so that each shows the same modulation-transfer-function limit (MTFL), the highest number of black-and-white lines that may be simultaneously rendered without chromatic aliasing.

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brightness compared to an RGB-stripe configuration, especially at high pixel densities.

The impact of RGBW on luminance, which is the measurable quantity most closely associated with the sensation called "brightness," and color purity for a 2.4-in. VGA LCD with two different color-filter sets is shown in Table 1. The narrow-gamut color-filter set is representative of mobile-telephone or notebook displays, in which power consumption is more important than color purity. The wide-
gamut color-filter set is representative of television displays, in which wider color gamuts are more important than power efficiency. Note that for a 2.4-in. VGA LCD, the luminance can be increased by 80% even with higher-saturated color-filter sets. Individual color brightness is approximately the same, even though the colors are more saturated.

**RGBW Processing, Then and Now**

The optimized RGBW system more closely reproduces the real world's natural-image envelope and statistics than does RGB, providing higher brightness and deeper saturation. For black-and-white text, the increased white brightness and contrast of the RGBW system is also beneficial. But RGBW systems are not commonly used because inadequate gamut mapping algorithms wash out colors. In addition, adding a white subpixel increases the cost and lowers contrast, narrowing the color gamut by reducing color purity. The RGBW PenTile Matrix™ system addresses both issues by using a proprietary gamut mapping algorithm and subpixel rendering.

As has been true of the RGB striped color-pixel arrangement, a progression of algorithms has been used to address the inadequacies of RGBW, but each tended to solve one problem while causing another.

The first algorithms for RGBW usually treated the white subpixel as though it represented the luminance value of the image. A typical conversion from YUV to RGBW was

\[ R_w = Y - 1.371*V; \]
\[ G_w = Y - 0.698*V - 0.336*U; \]
\[ B_w = Y + 1.732*U; \]
\[ W = Y. \]

This severely desaturated all of the colors, especially the greens because the more saturated green colors were more heavily weighted in the Y component by the conversion from RGB to YUV. To overcome this shortcoming, more recent algorithms used were

\[ R_w = R; \]
\[ G_w = G; \]
\[ B_w = B; \]
\[ W = \min(RGB), \]

where \( \min(RGB) \) is the minimum of \( R, G, \) and \( B \).

This algorithm was an improvement in that fully saturated colors retained proper saturation. But moderately saturated colors were still severely desaturated because any addition of white always desaturates the color unless the values of the remaining primaries are
adjusted. More recent work has focused on "color correction" of the above algorithm using gamma correction, but this is both complicated and unsatisfactory. And the min(RGB) algorithm does not utilize the full gamut of brightness and saturation, nor does it take advantage of perceptually equal (metameric) combinations of RGBW for a given color and brightness. A new approach eliminates these problems without requiring compromises in other areas.

Clairvoyante's proprietary RGB-to-RGBW gamut mapping algorithm treats the white subpixel as another color primary. Starting from color-theory basics, it is possible to construct matrices to convert RGBW values to CIE XYZ and then back into other color systems. These matrices have been invaluable tools for verifying that the gamut mapping algorithm maintains the hue and saturation of all colors.

The mapping from RGBW to CIE XYZ (or to RGB) is determinate. A single combination of the primaries in RGBW produces a unique color in CIE XYZ. However, in the conversion from, for example, RGB to RGBW, the mapping is one to many and non-determinate. A single RGB combination can be correctly represented as any one of many RGBW combinations (or metamers). This non-determinate conversion is both a challenge and an opportunity for the gamut mapping algorithm to be optimized for best image quality. The Clairvoyante gamut mapping algorithm has a function that selects the best RGBW metamer for the image being subpixel-rendered.

**RGBW Subpixel Architectures**

There are a number of possible subpixel architectures for RGBW, each with advantages and disadvantages (Fig. 4). The architectures in the figure represent a 6 x 4-pixel area of a display screen. These figures lead to a simplified figure of merit for subpixel efficiency, in which the number of pixels is expressed by the modulation-transfer-function limit (MTFL) in each axis divided by the number of subpixels per pixel, expressed as a percentage. As a reference, the conventional RGB-stripe architecture has a figure-of-merit value of 33%.

**RGBW Quad.** One of the most widely used RGBW arrangements in the past was the quad pattern, in which four subpixels were repeated in a square pattern (Fig. 4, left). The quad pattern was treated as a single square pixel. It was more expensive and had lower contrast than the conventional RGB-stripe LCD. Although subpixel rendering could be applied, it was not ideal since in this pattern subpixel rendering required two lines of subpixels in any axis to draw a single white line. Since it took four subpixels to equal one pixel, the figure-of-merit value was 25%.

**RGBW Eight-Subpixel Repeat Cell.** A more efficient design for subpixel rendering is characterized by a repeat cell of eight subpixels with a 1:2 aspect ratio (Fig. 4, center). This layout has less subpixel edge boundary, which gives rise to liquid-crystal disclinations, and thus has higher contrast than an RGBW quad — and even an RGB-stripe LCD. This layout, like the quad above, is 25% white, so it can provide approximately 75-100% higher luminance than an RGB-stripe panel with the same resolution. Note that each color is on a square grid at 45°, a good property for subpixel rendering. This layout requires only one row of subpixels to draw a single white line, while it still requires two subpixel columns. The figure-of-merit value is thus 50%.

**RGBW Six-Subpixel Repeat Cell.** The most efficient design replaces half of the blue subpixels with white, an ideal layout for very high-resolution [more than 330 dots per inch (dpi)] mobile telephones and media players (Fig. 4, right). This closely matches the characteristics of human vision, which has less
resolution in blue. However, this layout must be used with a high-color-temperature backlight to ensure that enough blue light is available to keep the panel at a desired white-point color when all of the subpixels are turned up to full value. Since the white area is only 17%, the luminance increase is approximately 50% (or more). The aspect ratio of the subpixels is 2:3, and this arrangement offers the highest contrast and color purity of the three RGBW designs. The figure of merit for this layout is 66%.

These designs have been implemented in hardware. BOE-HYDIS Technology Co., Ltd., has fabricated a 1.8-in. quarter-VGA LCD panel using the RGBW eight-subpixel repeat-cell architecture and Clairvoyant's gamut mapping algorithm (Fig. 5). Samsung Electronics has built a 400-dpi VGA LCD panel using the RGBW six-subpixel repeat cell architecture and Samsung's proprietary, colorimetrically correct gamut mapping algorithm (Fig. 6).

Conclusion
The RGB-stripe system requires a compromise in power and brightness to render the very bright unsaturated colors and darker highly saturated colors that most often occur in natural images. Adding a white subpixel resolves many of the problems panels have in properly rendering the natural images they are required to display. When the layout is further optimized with gamut mapping algorithms and subpixel-rendering techniques, both wide color gamut and high brightness can be achieved without increasing system complexity, power, or cost. ■