The RBW Color Model

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ABSTRACT

This paper introduces a new color model, RBW, which can be used as an intuitive user-interface for selecting colors in computer graphics systems. It is based on the red-green, blue-yellow, and white-black color axes. These axes are similar to the axes in opponent color theory, but their semantics are different: in the RBW model, the white-black axis mixes white or black into the color rather than controlling the achromatic brightness. The RBW model has the advantages of opponent color models plus additional benefits: the color gamut has a simple cubical shape, color coordinates are assigned according to simple rules, and all basic colors are at gridpoints in the cube.

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1. Introduction

In many applications involving color display devices, it is important to provide a convenient user interface for the specification of colors. Colors can be described through a color model, which consists of a three-dimensional region and an associated coordinate system, in which each color corresponds to a point in the color model [1]. The coordinates of the point in the color model are used to specify the color. There are many color models, based on different arrangements of colors and different coordinate axes. [1-3].

This paper describes a new color model, called RBW, based on red-green, blue-yellow, and white-black coordinate axes. The RBW red-green and blue-yellow axes are similar to the axes in opponent color models, described later. However, the white-black axis in the RBW model behaves differently from the achromatic axis in opponent color models. This preserves the advantages of opponent color models, such as intuitive axes and ease of use, while yielding several new features. In particular, the color model is shaped as a cube, rather than an irregular region, simplifying the user interface. The color model also has all eleven basic colors positioned at gridpoints for easy selection, and these colors are positioned according to simple linguistic rules. The remainder of this paper describes the motivation for the RBW color model, explains the implementation of the model, discusses the model, and compares the model to prior color models.

2. Motivation

The RBW color model was motivated by Kay and McDaniel's discussion of the linguistic basis of color terms [4]. Linguistically, there are eleven basic color terms: red, orange, yellow, green, blue, violet, black, white, gray, brown, and pink [5]. Kay and McDaniel show that these color terms can be generated from the fundamental response categories of the human visual system: black, white, red, yellow, green, and blue. The five nonfundamental basic colors can be generated from combinations of the six fundamental categories: brown = black+yellow, purple = red+blue, pink = red+white, orange = red+yellow, and gray = white+black. (Kay and McDaniel note that the operation '+' refers to linguistic combination of categories and does not denote a single well-defined physical operation. The '+' operation has some similarities to subtractive color mixing and pigment mixing, but is not identical to these operations.)

The RBW color model extends Kay and McDaniel's linguistic discussion of basic color categories to form a color model. Kay and McDaniel consider the six fundamental categories to be fuzzy sets, where a color has a degree of membership in each category. In the RBW model, however, colors are represented by positions along axes, rather than by fuzzy set membership. The categories are arranged into three oppositions: black vs. white, red vs. green, and blue vs. yellow. Each pair of opposing categories labels a coordinate axis in the cube-shaped RBW color model. The first coordinate, r, indicates the position along the red-neutral-green axis. It has the value 1 for full red, -1 for full green, 0 for neutral, and intermediate values for colors that contain some red or green. The coordinate b indicates the position along the blue-neutral-yellow axis, with 1 indicating blue, and -1 yellow. The coordinate w indicates the position along the white-neutral-black axis, with 1 indicating white, and -1 black. Thus, coordinates in the RBW model are given as (r,b,w), with each coordinate component ranging from -1 to 1.

While Kay and McDaniel's combine color categories linguistically, the RBW model combines categories in terms of coordinates. For example, Kay and McDaniel form purple by combining the red and blue categories. In the RBW model, purple is formed by combining the red coordinate (1,0,0) and the blue coordinate (0,1,0) and thus has coordinate (1,1,0). Similarly, orange is formed from red (1,0,0) and yellow (0,-1,0) and has coordinate (1,-1,0). Pink is formed from red and white and has coordinate (1,0,1). Although Berlin and Kay form brown from the black and yellow categories, brown is more similar to dark orange, formed from red, yellow, and black, and thus has coordinate (1,-1,-1). The origin of the RBW coordinate system, (0,0,0), corresponds to medium gray. Nonbasic colors are generated similarly. For example, combining black and blue coordinates yields dark blue. Combining yellow and green yields chartreuse. Based on similar linguistic combinations of color categories, the colors at all 27 gridpoints of the RBW color model can be determined, as shown in Fig. 1.

<<< Figure 1 should go about here >>

3. The implementation

This section gives algorithms for converting between RBW coordinates and HSV coordinates; the HSV coordinates can be converted to a displayable color model such as RGB by well-known algorithms. The HSV color model is used as an intermediate in the transformation because it is conceptually simpler to convert RBW to HSV than to convert RBW directly to RGB. The HSV color model [6], shown in Fig. 2, is hexcone shaped with a cylindrical coordinate system. The vertical value axis controls the value of the color, its departure from black. The saturation axis measures distance from the value axis, controlling the departure of the color from achromatic white or gray. The polar hue axis controls the hue of the color as a position on the color wheel.

<<< Figure 2 should go about here >>

Listing 1 gives an algorithm for converting a RBW coordinate to a HSV coordinate. The RBW to HSV transformation can be conceptually viewed as starting with the RBW cube, generating a hue coordinate around the black-white axis, converting the cube to a cylinder, and finally warping the cylinder with the transformation shown in Fig. 3, yielding the HSV cone. In detail, first, the hue H is determined from the ratio of the red-green and blue-yellow coordinates, which is computed in *f*, and from the quadrant of the color plane. Next, the cylindrical color variable c is computed as the horizontal distance from the white-black axis to the RBW coordinate, scaled to the range 0 to 1. The resulting intermediate point (H, w, c) lies in a unit cylinder. This cylinder is then converted to the HSV cone by mapping w and c to the saturation S and value V using the mapping illustrated in Fig. 3. The result in a HSV coordinate corresponding to the RBW coordinate. The algorithm in Listing 2 reverses the above process and converts a HSV coordinate to a RBW coordinate.

<<< Figure 3 should go about here >>

The final step in using RBW is conversion between HSV coordinates and the RGB (red, green, blue) coordinates used by video displays. This conversion to RGB coordinates is straightforward and is given in [1, 6]. For best performance, the final RGB coordinates should be gamma-corrected before display [1], so the perceived intensity is proportional to the RGB coordinates. Figure 4 shows five slices through the RBW color cube; each slice has a constant white-black coordinate. The axes in Fig. 4 are arranged as in Fig. 1.

<<< Figure 4 should go about here >>

4. Discussion

The RBW color model has similarities to color models based on opponent color theory. Opponent color models are based on research in human vision, which suggests that colors are processed in the brain into three components: an achromatic channel, a red-green opponent channel, and a yellow-blue opponent channel [3]. The achromatic channel indicates the luminance (or brightness) of the perceived color. The red-green channel indicates the difference between the perceived redness and greenness and the yellow-blue channel indicates the difference between the perceived yellowness and blueness. Together, the red-green and blue-yellow channels specify the chromatic content of the color. There are several justifications for basing a color model on opponent color theory [7-9]. Because it has a physiological basis, a color model based on opponent color theory may be easier to use. The opponent color model lets users modify color and luminance independently. The opponent color model allows easy selection of contrasting colors [7]. Schwarz et al found that an opponent color model worked well as a user interface for fast and accurate color selection [9].

The key difference between RBW and opponent color models is the semantics of the RBW white-black axis compared to the opponent color achromatic axis. In opponent color models, the achromatic axis controls the luminance of the color. For example, decreasing the achromatic axis coordinate would change red to dark red and then to black. In the RBW model, the white-black axis modifies both the lightness and the saturation of the color, generating different tones. For example, increasing the white-black component towards white would change red to pink, while decreasing it towards black would change red to dark red. The RBW white-black axis is also different from the HSV axes; Fig. 3 shows that changing the RBW white-black axis changes both the saturation and the value of the corresponding HSV color.

The RBW color model has several useful properties:

1. The color coordinates satisfy intuitive rules of color formation. For instance, pink is formed by combining the red and white coordinates, and orange is formed by combining red and yellow. This simplifies the user’s interaction with the model.

2. All eleven basic colors lie on grid points (coordinates of -1, 0, or 1), as shown in Fig. 2. As a result, it is especially easy to obtain the basic colors with the RBW model.

3. The color model maps the RGB cube of displayable colors into a cube. This simplifies user-interface design, since any coordinate in the RBW model

corresponds to a displayable color. As a result, three sliders can be used to control the three RBW components, and any set of slider positions will result in a unique and valid color.

4. The axes in the RBW model are similar to the axes in the opponent color theory. Since the opponent color axes have been found to allow fast color selection [9], color selection should be fast with the RBW axes too.

5. The mapping between the RBW color model and RGB is bijective. (An example of a non-bijective color model is the HSV model, which is degenerate when V=0 or S=0. Although the RBW conversion algorithm uses HSV as an intermediate, the conversion algorithm ensures that the non-bijectivity of HSV does not affect the mapping between RBW and RGB.) Because the RBW mapping is bijective any color has a unique representation in the RBW color model. This simplifies comparing colors for equality.

Because of these five properties, the RBW color model provides a convenient user interface for selecting colors.

5. Comparison with Previous Color Models

There are several published color models based on the opponent color axes [7-10]. However, none of these previous models satisfy Properties 1, 2, or 3 above, which the RBW model satisfies. Schwarz et al describe an color model formed by applying opponent color theory to CIE color coordinates [9]. This model has an irregular shape and requires trigonometric computation. The Xerox YES model [10] and Naiman's ARgYb (Achromatic, Red-green, Blue-yellow) color model [7] are linear transformation of the RGB color cube to opponent color axes. They are mathematically simple, but also have irregular shapes. Ware and Cowan describe two RGYB (Red-Green, Yellow-Blue) color models [8] that use color axes rotated 45 degrees from the opponent color red-green and blue-yellow axes. These models are mathematically simple and cube-shaped.

However, in the first RGYB variant, some points correspond to colors that cannot be displayed. The second variant lacks some colors, such as saturated magenta.

Various color models have been designed to provide a simple computer user interface [6, 11]. The most popular is Smith's HSV (hue, saturation, value) color model [6], which was designed for ease of use and is based on the artistic qualities of hue, tint, shade, and tone. The Tektronix HLS (hue, lightness, saturation) color model [1] is similar to HSV, but is shaped as a double hexcone, with the lightness axis replacing the value axis of HSV. The HSV and HLS color models are considered more intuitive to use than RGB, but user performance with HSV has been found to be slow [9]. The HSV and HLS color models don't satisfy any of the five useful properties of the RBW color model listed above. Berk, Brownstone, and Kaufmann used a linguistic approach to color specification with their color notation system that allows specification of colors through combinations of English color words according to a simple syntax (e.g. "light grayish red-orange") [12]. While Berk et al. found their system was fast and accurate, it is not a full color model as it only describes 627 colors.

In the commercial world, color specification often uses color sample systems, which provide a collection of physical color samples and identifiers [13]. These color samples are normally organized according to a coordinate system, for example the Munsell system [14], the Natural Color System [15], and the Ostwald Color System [16]. Other color sample systems, such as the Dictionary of Color [17], don't provide a coordinate system, but instead assign common names to each color.

The RBW color model has some similarities to the Ostwald and NCS color systems. The Ostwald color system is formed around the same six fundamental color sensations as RBW: white, black, blue, yellow, red, and green, arranged into oppositions [18]. However, the Ostwald color system is arranged into a double cone, with peaks at white and black. The Swedish NCS [15] is also based on these six basic colors arranged into a double cone. Although these color systems are based on the same six colors as RBW, they have a different shape from the RBW model and they express their coordinates in terms of hue and tone. Thus, their color axes are more similar to the HLS color axes than to the opponent color axes.

One disadvantage of the RBW color model is that it is not perceptually uniform. Perceptually uniform color models attempt to correlate distances in the coordinate system with perceived differences in color [19], so colors that are perceived as being the same distance apart visually should be separated by approximately the same Euclidean distance in the color model. These color models have several uses, such as generating color scales with uniform perceptual differences between entries [20], storing images with uniform color resolution [21], and ensuring that displayed colors are suitably distinct. Examples of perceptually uniform color models include CIE LUV and CIE LAB [3], the Optical Society of America (OSA) uniform color scale [22], the Tektronix HVC model [23], and the Munsell system [14].

6. Conclusions

The RBW color model provides an intuitive user interface for specifying colors. The RBW color model has a red-green axis, a blue-yellow axis, and a white-black axis. The red-green and blue-yellow axes are similar to the opponent color axes. However, unlike the achromatic opponent color axis which modifies the luminance, the RBW white-black axis adds blackness or whiteness to the color, changing the value and saturation of the color. The RBW color model has several advantages over other color models: the color model is a cube rather than an irregular shape, colors are formed by intuitive linguistically-based rules, and basic colors are easily selectable at gridpoints of the cube.

7. Acknowledgements

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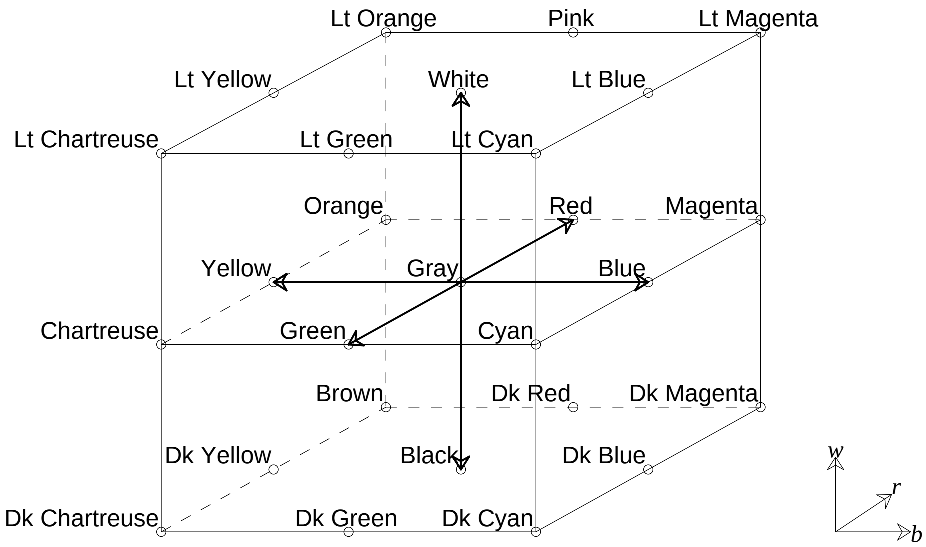
Lt Orange
Pink
Lt Magenta
Lt Yellow
White
Lt Blue
Lt Chartreuse
Lt Green
Lt Cyan
Orange
Red
Magenta
Yellow
Gray
Blue
Chartreuse
Green
Cyan
Brown
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Dk Yellow
Black
Dk Blue
Dk Chartreuse
Dk Green
Dk Cyan
w
r
b

Figure 1.

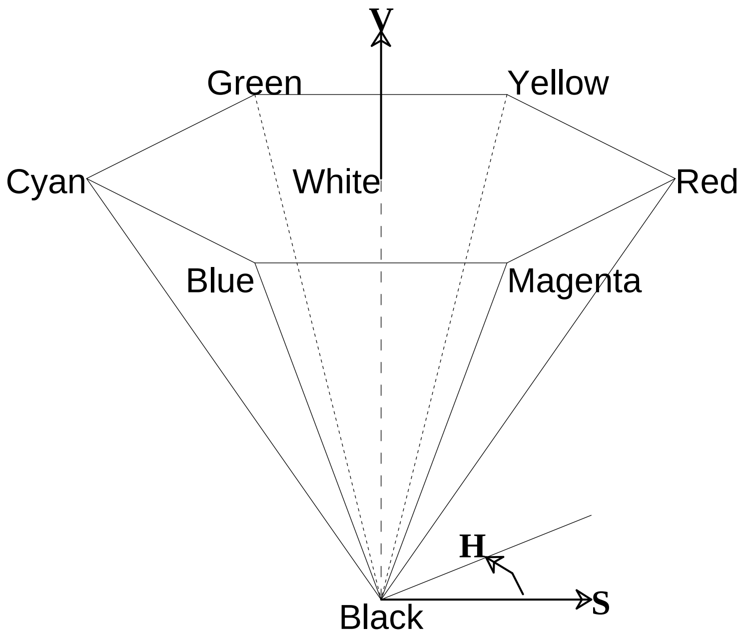

Figure 2.

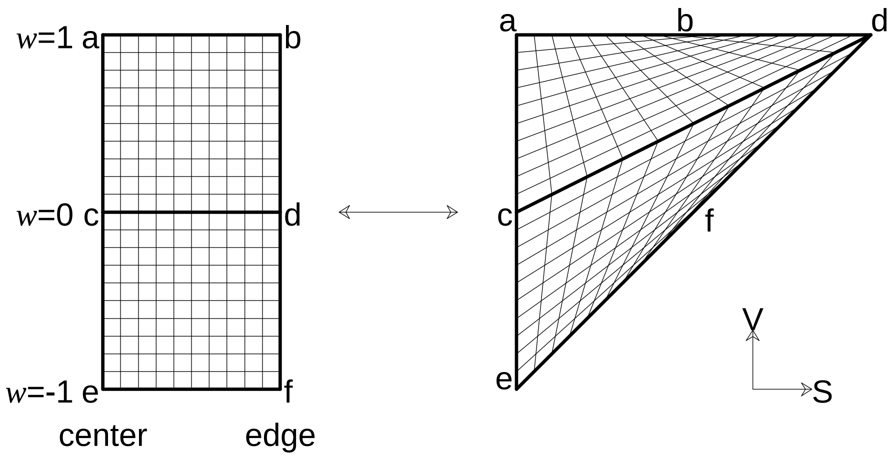

Figure 3.

```
function RBWtoHSV(r,b,w)
  r,b,w = red, blue, white coordinates: [-1,1]
  h = hue coordinate: [0,360) or undefined, 0=red
  s,v = saturation, value coordinates: [0,1]
  f = hue fraction (distance from hue diagonals): [-1,1]
  c = color fraction (distance from white-black axis): [0,1]

  Determine the hue from the r and b coordinates.
  if (r=0 and b=0)                        Achromatic case.
    h = undefined                         "undefined" is a special HSV value.
  else                                    Chromatic case.
    if (abs(b)>abs(r))
      f = 1-abs(r/b)
    else
      f = abs(b/r)-1
    endif
    if (r>=0 and b<=0)                    red - yellow
      h = .5+f/2
    else if (r<=0 and b<=0)               yellow - green
      h = 1.5-f/2
    else if (r<=0 and b>=0)               green - blue
      h = 3+f
    else if (r>0 and b>=0)                blue - red
      h = 5-f
    endif
    h = h*60                              Convert hue to degrees.
  endif

  Map the w coordinate and c into value and saturation.
  The base mapping is the unit square to unit triangle
  mapping: (x,y) -> (x+y-xy, x-xy/2).
  c = max(abs(r),abs(b))
  if (w>=0)
    v = (w+1+c*(1-w))/2
    t = c*(2-w)/2                         t is an intermediate value.
  else
    v = (w+1+c)/2
    t = c*(2+w)/2
  endif
  if (v=0)                                Avoid division by zero.
    s = 0
  else
    s = t/v                               Scale saturation to [0,1].
  endif
  return (h,s,v)
end
```

Listing 1

```
function HSVtoRBW(h,s,v)
  Undo the mapping from w and c into value and saturation.
  if (v*(2-s)>1)
    a = 1.5-v+v*s                        a is an intermediate value.
    w = 1
  else
    a = .5+v
    w = -1
  endif
  t = sqrt(a*a-2*v*s)                    t is an intermediate value.
  c = a-t
  w = w*(2-a-t)

  Determine r and b from the hue and c.
  if (c=0)
    r = 0                                Achromatic case
    b = 0
  else
    h = h/60                             Convert h from degrees to [0,6).
    if (h<=1)                            red - yellow
      f = 2*h-1
      r = c
      b = -c
    else if (h<=2)                       yellow - green
      f = 3-2*h
      r = -c
      b = -c
    else if (h<=4)                       green - blue
      f = h-3
      r = -c
      b = c
    else if (h<=6)                       blue - red
      f = 5-h
      r = c
      b = c
    endif
    if (f>=0)
      r = (1-f)*r
    else
      b = (1+f)*b
    endif
  endif
  return (r,b,w)
end
```

Listing 2

Figure captions:

Fig. 1. The RBW color model. Each coordinate ranges from -1 to 1. The origin is at ‘‘gray’’. (‘‘Lt’’ indicates ‘‘light’’, ‘‘Dk’’ indicates ‘‘dark’’.)

Fig. 2. The HSV color model. The hue axis measures the angle around the value axis. The saturation axis measures the distance from the value axis.

Fig. 3. The mapping from the RBW model to S and V in the HSV model. In the red plane, the labels correspond to a = white, b = pink, c = gray, d = red, e = black, f = dark red.

Fig. 4. Five slices through the RBW color model. The white-black coordinate is constant in each slice.

Listing 1. This code converts RBW coordinates to HSV coordinates. Italics indicate comments.

Listing 2. This code converts HSV coordinates to RBW coordinates.