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Computational RYB Color Model and its Applications

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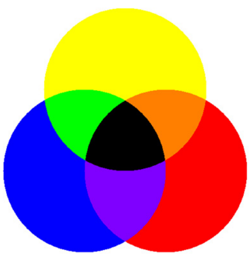
<Summary> The red-yellow-blue (RYB) color model is a subtractive model based on pigment color mixing and is widely used in art education. In the RYB color model, red, yellow, and blue are defined as the primary colors. In this study, we apply this model to computers by formulating a conversion between the red-green-blue (RGB) and RYB color spaces. In addition, we present a class of compositing methods in the RYB color space. Moreover, we prescribe the appropriate uses of these compositing methods in different situations. By using RYB color compositing, paint-like compositing can be easily achieved. We also verified the effectiveness of our proposed method by using several experiments and demonstrated its application on the basis of RYB color compositing.

Keywords: RYB, RGB, CMY(K), color model, color space, color compositing

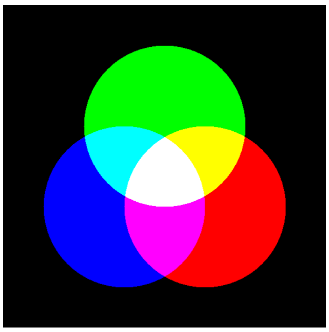
1. Introduction

Most people have had the experience of creating an arbitrary color by mixing different color pigments on a palette or a canvas. The red-yellow-blue (RYB) color model proposed by Johannes Itten[1] is still widely used in art education. This model is a subtractive color model in which red, yellow, and blue are defined as the three primary colors. **Figure 1**(a) presents an example of subtractive color mixing based on the RYB color model, whereas **Fig. 2**(a) shows Itten's RYB color wheel. As shown in Fig. 1(a), mixing red and yellow produces orange; mixing yellow and blue produces green; and mixing blue and red produces purple. When more colors are added, the resultant mixture becomes darker, based on subtracting color mixing.

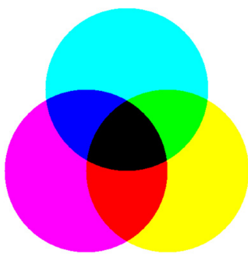
Color compositing is a commonly used operation in computer applications[2]. Because of the specifics of the human perception system and computer displays, most computer applications use the red-green-blue (RGB) color model[3]; however, this model is not comprehensible for many people who not trained in the RGB color model because of its use of additive color mixing. As shown in Fig. 1(b), RGB is an additive color model in which red, green, and blue are defined as the three primaries. Color compositing in the RGB color space fails to reproduce a paint-like appearance. The resulting colors are often different from those a viewer may have expected. This confusion also occurs in the cyan-magenta-yellow(-key) (CMY(K)) color space[3]. CMY(K) is a well-known subtractive color model commonly used in printing. As shown in Fig. 1(c), cyan, magenta, yellow, and the color of a key plate (typically black) are defined as the primary colors. As shown in Fig. 2(b), the CMY(K) model is essentially the complement of the RGB model; in other words, there is a close relationship between the CMY(K)



(a) RYB color model

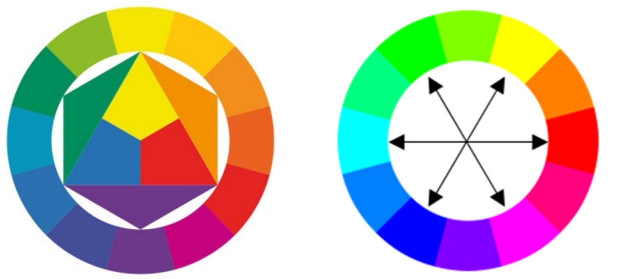


(b) RGB color model



(c) CMYK color model

Fig. 1 A primary color representation



(a) Itten's RYB color wheel

(b) RGB color wheel, with CMY(K) being the complement of RGB

Fig. 2 Color wheels

and RGB models in terms of compositing rules. Therefore, the CMY(K) model fails to reproduce a paint-like appearance, as does the RGB model.

Figure 3 presents an example of color mixing results in the RYB, RGB, and CMY(K) models. The values of the three primary colors ranging from 0 to 1 are shown under the color names. As shown in Fig. 3, yellow and blue make green in RYB, which is the same result as that yielded by the pigment compositing rules; however, yellow and blue make white in RGB. Moreover, yellow and blue make black in CMY(K). As stated earlier, the RGB and CMY(K) results do not produce paint-like results.

The RYB color model is an intuitive approach that can be used to mix colors that more closely resemble the expectations of those not trained in the RGB or CMY(K) models. However, the conversion equations between the RGB and RYB color spaces have yet to be proposed. If it is possible to convert between the RGB and RYB color spaces with a conversion equation, we anticipate that these equations would have applications in several fields, including computer application, computer graphics, visualization, art, design, and education.

In this paper, we formulate a mathematical bi-directional conversion between the RGB and RYB color spaces. We also show that simple compositing methods such as alpha blending[2] in the RYB color space are useful. Paint-like compositing can easily be realized by compositing the colors in the RYB color space. Moreover, we apply the RYB color model to several applications, which are color designations interfaces for users, such as the photo-retouching software [4], brush-stroke rendering for a digital painting system[5], or painterly rendering[6], and the visualization technique of multi-attribute data[7), 8)]. Experimental results have verified that the RYB color model is useful.

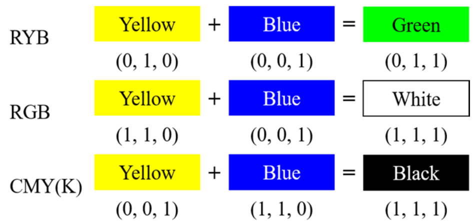


Fig. 3 Example of color mixing in RYB, RGB, and CMY(K) models

2. Related Work

Itten's RYB Color model[1] has been widely used in the analog world. To use the RYB color model in a computer, bi-directional RGB-RYB conversion is necessary. However, there are almost no studies on conversions between the RGB and RYB color spaces.

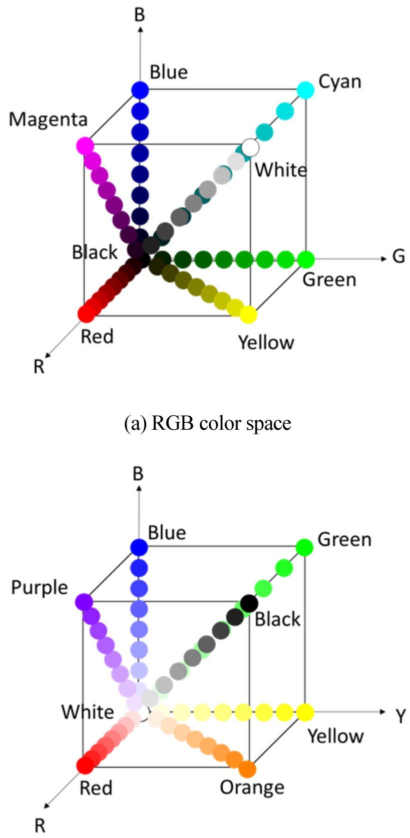
2.1 RYB to RGB conversion method

Gossett and Chen[7] proposed a paint-inspired RYB color model. To the best of our knowledge, their investigation is the only research on converting from the RYB model to the RGB model. They defined three paint pigment primaries and tri-linearly interpolated among them; however, this model offers an irreversible conversion because the interpolated color depends on the defined primary colors. Furthermore, Gossett and Chen[7] did not provide the details for converting from the RGB space to the RYB space. A mathematical equation was needed to convert between the RGB and RYB models.

2.2 Applications using the RYB color model

We describe studies on using the RYB color model. The RYB color model is used for visualizing multi-attribute data[7), 8)]. In visualization, the color can encode additional data attributes based on the human color perceptions. Constable and Zhang[9] used the RYB color wheel to perform hue-contrast analysis of paintings. Zhang et al.[10] proposed a method to transfer the visual style of paintings to photographic images by using the RYB color model. Sugita and Takahashi[11] proposed a non-photorealistic rendering method for generating pointillistic images based on the Seurat's color theory. In this method, the RYB color model was used to calculate complementary colors.

As mentioned above, it is likely that the RYB color model would have many applications and that its formulation would be useful.



(a) RGB color space

(b) RYB color space

Fig. 4 RGB and RYB color spaces

Table 1 Relationships between the values of each channel in RGB and RYB spaces for the eight colors at the corners of the RGB color cube

Name	Color	RGB values	RYB values
Red		(1, 0, 0)	(1, 0, 0)
Green		(0, 1, 0)	(0, 1, 1)
Blue		(0, 0, 1)	(0, 0, 1)
Yellow		(1, 1, 0)	(0, 1, 0)
Cyan		(0, 1, 1)	(0, 0.5, 1)
Magenta		(1, 0, 1)	(1, 0, 0.5)
Black		(0, 0, 0)	(1, 1, 1)
White		(1, 1, 1)	(0, 0, 0)

Table 2 Relationships between the values of each channel in RYB and RGB spaces for the eight colors at the corners of the RYB color cube

Name	Color	RYB values	RGB values
Red		(1, 0, 0)	(1, 0, 0)
Yellow		(0, 1, 0)	(1, 1, 0)
Blue		(0, 0, 1)	(0, 0, 1)
Orange		(1, 1, 0)	(1, 0.5, 0)
Green		(0, 1, 1)	(0, 1, 0)
Purple		(1, 0, 1)	(0.5, 0, 1)
White		(0, 0, 0)	(1, 1, 1)
Black		(1, 1, 1)	(0, 0, 0)

3. RYB Color Model

In the sections that follow, we describe the differences between the RGB and RYB color models.

3.1 RGB color model

An RGB color model is an additive color model[3]. Red, green, and blue are defined as the additive primaries in the RGB color space. The name of the model has been derived from the three primary colors, which combine to form one color. Red and green mix to form yellow; green and blue mix to form cyan; and blue and red mix to form magenta. As shown in **Fig. 4**(a), the RGB color space is defined as a cube with the axes representing red, green, and blue. The corners of the cube represent each of the eight colors, which are red, green, blue, cyan, magenta, yellow, white, and black.

3.2 RYB color model

An RYB color model is a subtractive color model[1]. Red, yellow, and blue are defined as the subtractive primaries in the RYB color model. Red and yellow mix to form orange; yellow and blue mix to form green; and blue and red mix to form purple. As shown in Fig. 4(b), the RYB color space is defined as a cube with the axes representing red, yellow, and blue. The corners of the cube represent each of the eight colors, which are red, yellow, blue, orange, green, purple, black, and white.

3.3 Relationships between the values in the RGB and RYB models

An RYB color model is based on some experiences of idealized paint mixing. In consideration of affinity with computers, we defined the RYB color model as follows: **Tables 1** and **2** show the relationships between the values in the RGB and RYB models handled in this paper. Table 1 shows the eight colors at the corners of the RGB color cube, and Table 2 shows the eight colors at the corners of the RYB color cube. Here the values of each of the RGB and RYB channels range from 0 to 1. In this paper, we present a conversion between the RGB and RYB color spaces. To do this, we introduce a mathematical equation to convert between the RGB and RYB models.

4. RGB-RYB Conversion

In the sections that follow, we derive bi-directional equations to convert between the RGB (R_{RGB}, G_{RGB}, B_{RGB}) and RYB (R_{RYB}, Y_{RYB}, B_{RYB}) color spaces. Note that $0 \leq R_{RGB}, G_{RGB}, B_{RGB}, R_{RYB}, Y_{RYB}, B_{RYB} \leq 1$.

The outline is the conversion from the RGB color space to the RYB color space in the section 4.1 is as follows: First, subtract the white component from the input RGB values (Eqs. (1) – (3)). Second, convert from the RGB color space to the RYB color space (Eqs. (5) – (7)). Additional details of the elicitation process of the RYB values from the RGB values are given in Appendix A. Third, normalize the RYB values (Eqs. (8) – (10)). Finally, add black component (Eqs. (12) – (14)). Both the process of subtracting white component firstly and adding black component finally are necessary to make a subtractive color model.

Conversion from the RYB color space to the RGB color space in the section 4.2 is also performed in the same procedure.

4.1 RGB to RYB conversion

To convert from the RGB space to the RYB space, we introduce two sets of variables, (r_{RGB}, g_{RGB}, b_{RGB}) and (r_{RYB}, y_{RYB}, g_{RYB}). The variables (r_{RGB}, g_{RGB}, b_{RGB}) are given by

$$r_{RGB} = R_{RGB} - I_w, \tag{1}$$
$$g_{RGB} = G_{RGB} - I_w, \tag{2}$$
$$b_{RGB} = B_{RGB} - I_w, \tag{3}$$

where I_w is the white component in the RGB color space and is given by

$$I_w = \min\{R_{RGB}, G_{RGB}, B_{RGB}\}, \tag{4}$$

where $\min\{\}$ is a function that calculates the minimum value of its arguments. The variables (r_{RYB}, y_{RYB}, b_{RYB}) are obtained from the variables (r_{RGB}, g_{RGB}, b_{RGB}) by using the following equations:

$$r_{RYB} = r_{RGB} - \min\{r_{RGB}, g_{RGB}\}, \tag{5}$$

$$y_{RYB} = \frac{\min\{r_{RGB}, g_{RGB}\} + g_{RGB}}{2}, \tag{6}$$

$$b_{RYB} = \frac{b_{RGB} + g_{RGB} - \min\{r_{RGB}, g_{RGB}\}}{2}. \tag{7}$$

Additional details of the elicitation process of (r_{RYB}, y_{RYB}, b_{RYB}) are given in Appendix A.

We normalize Eqs. (5) – (7) as

$$r_{RYB}' = \begin{cases} \dfrac{r_{RYB}}{n} & \text{if } n > 0 \\ r_{RYB} & \text{otherwise,} \end{cases} \tag{8}$$

$$y_{RYB}' = \begin{cases} \dfrac{y_{RYB}}{n} & \text{if } n > 0 \\ y_{RYB} & \text{otherwise,} \end{cases} \tag{9}$$

$$b_{RYB}' = \begin{cases} \dfrac{b_{RYB}}{n} & \text{if } n > 0 \\ b_{RYB} & \text{otherwise,} \end{cases} \tag{10}$$

where n is calculated as

$$n = \frac{\max\{r_{RYB}, y_{RYB}, b_{RYB}\}}{\max\{r_{RGB}, g_{RGB}, b_{RGB}\}}. \tag{11}$$

Here, $\max\{\}$ is a function that calculates the maximum value of its arguments.

Finally, by adding the black component I_b, the RYB values (R_{RYB}, Y_{RYB}, B_{RYB}) are obtained as follows:

$$R_{RYB} = r_{RYB}' + I_b, \tag{12}$$

$$Y_{RYB} = y_{RYB}' + I_b, \tag{13}$$

$$B_{RYB} = b_{RYB}' + I_b, \tag{14}$$

where I_b is given by

$$I_b = \min\{1 - R_{RGB}, 1 - G_{RGB}, 1 - B_{RGB}\}. \tag{15}$$

4.2 RYB to RGB conversion

We describe the conversion from the RYB space to the RGB space. First, the black component I_b is subtracted from each component (R_{RYB}, Y_{RYB}, B_{RYB}) in the RYB color space:

$$r_{RYB} = R_{RYB} - I_b, \tag{16}$$
$$y_{RYB} = Y_{RYB} - I_b, \tag{17}$$
$$b_{RYB} = B_{RYB} - I_b, \tag{18}$$

where I_b is calculated by

$$I_b = \min\{R_{RYB}, Y_{RYB}, B_{RYB}\}. \tag{19}$$

The variables (r_{RGB}, g_{RGB}, b_{RGB}) are obtained from (r_{RYB}, y_{RYB}, b_{RYB}) by using the following equations:

$$r_{RGB} = r_{RYB} + y_{RYB} - \min\{y_{RYB}, b_{RYB}\}, \tag{20}$$
$$g_{RGB} = y_{RYB} + \min\{y_{RYB}, b_{RYB}\}, \tag{21}$$
$$b_{RGB} = 2(b_{RYB} - \min\{y_{RYB}, b_{RYB}\}). \tag{22}$$

We normalize Eqs. (20) – (22) as

$$r_{RGB}' = \begin{cases} \dfrac{r_{RGB}}{n} & \text{if } n > 0 \\ r_{RGB} & \text{otherwise,} \end{cases} \tag{23}$$

$$g_{RGB}' = \begin{cases} \dfrac{g_{RGB}}{n} & \text{if } n > 0 \\ g_{RGB} & \text{otherwise,} \end{cases} \tag{24}$$

$$b_{RGB}' = \begin{cases} \dfrac{b_{RGB}}{n} & \text{if } n > 0 \\ b_{RGB} & \text{otherwise,} \end{cases} \tag{25}$$

where n is calculated as

$$n = \frac{\max\{r_{RGB}, g_{RGB}, b_{RGB}\}}{\max\{r_{RYB}, y_{RYB}, b_{RYB})\}}. \tag{26}$$

Finally, by adding the white component I_w, the RGB values (R_{rgb}, G_{rgb}, B_{rgb}) are obtained as follows:

$$R_{RGB} = r_{RGB}' + I_w, \tag{27}$$

$$G_{RGB} = g_{RGB}' + I_w, \tag{28}$$

$$B_{RGB} = b_{RGB}' + I_w, \tag{29}$$

where I_w is calculated by

$$I_w = \min\{1 - R_{RYB}, 1 - Y_{RYB}, 1 - B_{RYB}\}. \tag{30}$$

5. Color Compositing Methods

As mentioned in the previous section, our proposed equations make conversions between the RGB and RYB color spaces possible. Consequently, simple compositing methods in the RYB color space are available as with the RGB color space. In this section, we describe three methods for compositing colors, namely addition compositing, alpha compositing, and modified alpha compositing.

By addition compositing, we can obtain the same compositing results as those yielded by Itten's color compositing rules; however, in actual paintings, the color compositing behavior might vary depending on the reflectances and transparencies of scattering pigments. This means that either alpha compositing or modified alpha compositing is suitable for paint-like appearances.

When we overlay a foreground image on some background image, we must blend the foreground color C_{fore} and background color C_{back}. Here, C_{fore} and C_{back} both consist of three elements representing the red, yellow, and blue components of the RYB color space.

5.1 Addition compositing

The simplest method of compositing colors is to add the foreground and background colors. The new color C_{add} is calculated by

$$C_{add} = C_{fore} + C_{back}. \tag{31}$$

This method represents basic compositing. For example, when we add blue (0, 0, 1) to yellow (0, 1, 0) in RYB with addition compositing, the resulting color is green (0, 1, 1). This method yields the same results as does adding three component vectors in the RYB color space, as shown in Fig. 4 (b).

5.2 Alpha compositing

Alpha compositing is often used in computer graphics applications for its simplicity and efficiency[2]. This composition method blends two colors while allowing for transparency effects. Here, α represents transparency. Note that the value of α ranges from 0 to 1. When $\alpha = 0$, the color is fully transparent, whereas when $\alpha = 1$, the color is fully opaque. The new color C_{alpha} is calculated as

$$C_{alpha} = \alpha C_{fore} + (1 - \alpha) C_{back}, \tag{32}$$

5.3 Modified alpha compositing

In some natural media, the compositing behavior might vary depending on the layer thickness. A thin foreground layer allows the colors of background pigments to show through, whereas a thick layer heavily obscures the background. In addition, high light absorbance can cause certain colors to result in dark composites if used in either the background or the foreground. For this reason, a modified alpha compositing method can be used to enhance either the background or the foreground color. The new color C_{ma} obtained via the modified alpha compositing method is calculated as

$$C_{ma} = C_{fore} + wC_{back}. \tag{33}$$

where w is a weight factor.

6. Experimental Results

To verify the effectiveness of the RYB model, we performed several experiments. The results that we obtained are described in the following sections.

6.1 Context of the RYB color model

To understand the entire context of the RYB color space, which was implemented by using the proposed conversion equation, we visualized the hue (H), saturation (S), and lightness (L) by using the HSL color space. The HSL color space is the common cylindrical-coordinate representation. For comparison, we also converted from the HSL to RGB

Procedure 1 Procedure of conversion from HSL to RYB

HSLtoRYB (c_{hsl})
$c_{ryb} \leftarrow$ HSLtoRGB (c_{hsl}) [HSL to RYB conversion by e.g., ColorMine];
$c_{rgb} \leftarrow$ RYBtoRGB (c_{ryb}) [RYB to RGB conversion by Eqs. (16)–(30)];
return c_{rgb};

color spaces. We used the ColorMine library[12] for converting from the HSL color space to the RYB color spaces. ColorMine is the open-source library, which has a collection of color converters. To convert from the HSL color space to RYB color space, we used the HSLtoRGB conversion function in a similar manner as the HSLtoRYB function. Note that the conversion from the RYB space to the RGB space is required for the display (HSL→RYB→RGB). The details are shown in **Proc. 1**. For the inverse conversion (from RYB to HSL color spaces), see the Appendix B.

Figure 5 and **Fig. 6** show the HSL representations of the RYB and RGB color models, respectively. Figure 5 and Fig. 6 are two-dimensional plots representing two parameters of the HSL color space. The hue ranges from 0° to 360°, whereas the saturation and lightness range from 0 to 1. Figure 5(a) and Fig. 6(a) are the hue-saturation spaces of RYB and RGB, respectively, when L = 0.5. Figure 5(b) and Fig. 6(b) are the saturation-lightness spaces when H = 0°. Figure 5(c) and Fig. 6(c) are the hue-lightness spaces when S = 0.5.

As shown in Fig. 6(a) and Fig. 6(c), we observed that the color sequences are the same as those in the RYB color wheel shown in Fig. 2(a); that is, the order of the colors is red, orange, yellow, green, blue, and purple.

As shown in Fig. 6(b) and Fig. 6(c), when the value of lightness approaches 1, it becomes brighter because RGB is an additive color model. Conversely, as shown in Fig. 5(b) and Fig. 5(c), when the lightness value approaches 1, it becomes darker, indicating that our proposed RYB color model successfully realized subtractive color mixing.

6.2 Color compositing results

Figure 1(a) was generated by addition compositing in the RYB color space, as described in section 5.1. The colors of the overlapped regions in Fig. 1(a) are calculated by using Eq. (31). As shown in Fig. 1(a), we observed that composited pairs of the primary colors, namely, red, yellow, and blue, produced the secondary colors orange, green, and purple.

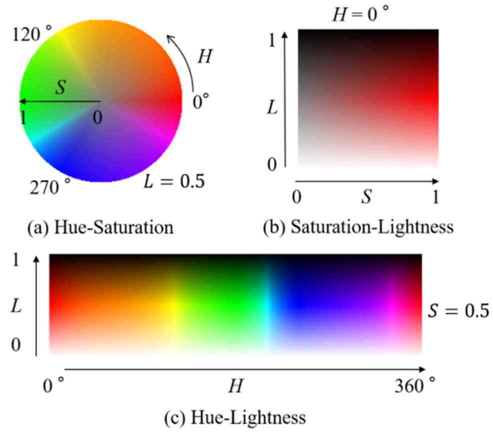


Fig. 5 The HSL representation of the RYB color space

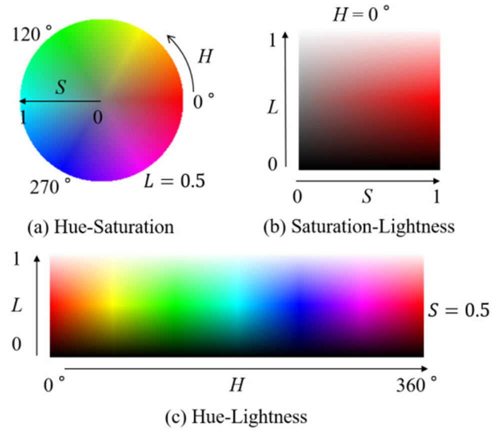


Fig. 6 The HSL representation of the RGB color space

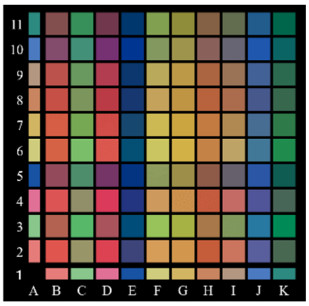
This result is in accordance with Itten's constructive color theory.

In the sections that follow, we describe the results of the color compositing methods alpha compositing and modified alpha compositing in the RYB color space.

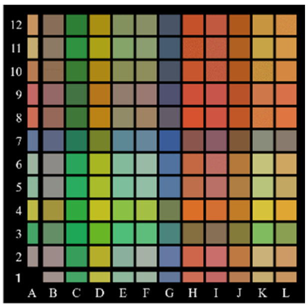
6.2.1 Comparison of color charts

We performed a visual comparison of the colors composited by the alpha and modified alpha compositing in the RYB color space and the actual pigment compositing by using a color chart. The color chart is used as a marker to observe how different pigments would appear when layered. Such color charts provide composition samples and serve as ground truths[13].

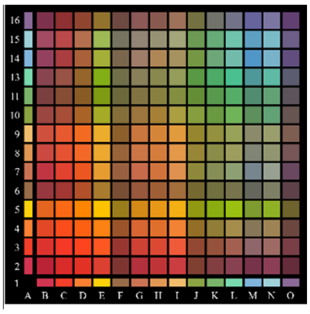
The color chart consists of n base colors and n^2 composited colors created by a pair of base colors. As shown in **Fig. 7**, the first row (row 1) and first column (column A) of each color chart indicate the base colors. The other colors are composites resulting from mixing the two corresponding base colors. For example, the color of row 4, column B (4B, in short) is created by mixing 4A and 1B.



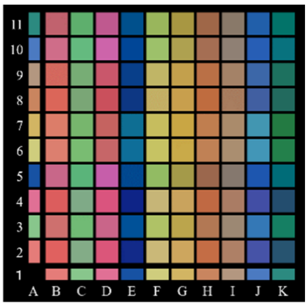
(a) Actual color chart of gouache



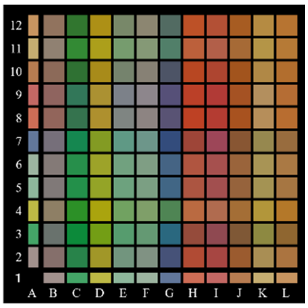
(b) Actual color chart of thin acrylic



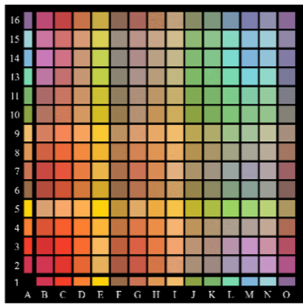
(c) Actual color chart of watercolor



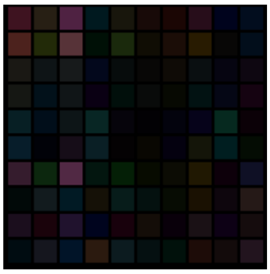
(d) Color chart by modified alpha compositing in the RYB color model ($w = 0.2$)



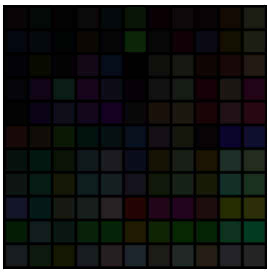
(e) Color chart by modified alpha compositing in the RYB color model ($w = 0.3$)



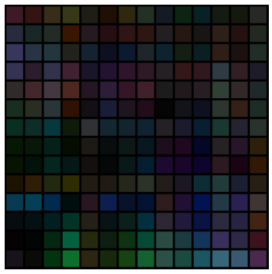
(f) Color chart by alpha compositing in the RYB color model ($\alpha = 0.6$)



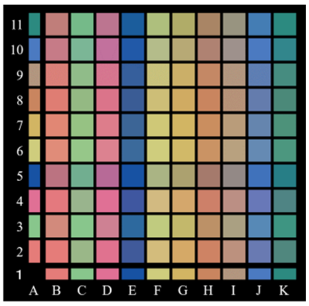
(g) Difference image between (a) and (d)



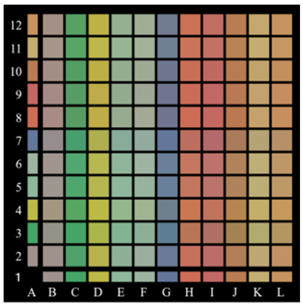
(h) Difference image between (b) and (e)



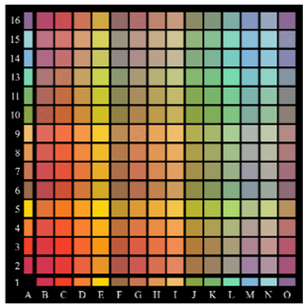
(i) Difference image between (c) and (f)



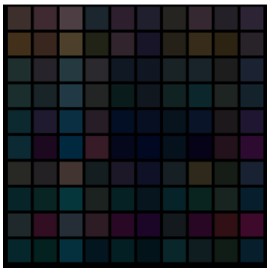
(j) Color chart by alpha compositing in the RGB color model ($\alpha = 0.8$)



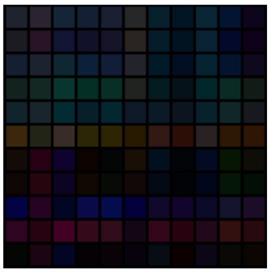
(k) Color chart by alpha compositing in the RGB color model ($\alpha = 0.85$)



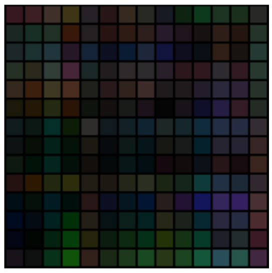
(l) Color chart by alpha compositing in the RGB color model ($\alpha = 0.6$)



(m) Difference image between (a) and (j)



(n) Difference image between (b) and (k)



(o) Difference image between (c) and (l)

Fig. 7 Comparison between actual color charts and our generated results

Figure 7 (a) – (c) are color charts processed from the actual color charts for different media that were obtained from the paper by Lu et al.[13]. Figure 7 (a) – (c) are the charts for gouache, thin acrylic, and watercolor, respectively. These charts were originally obtained from the Internet. To process the actual color charts from the Internet, Lu et al.[13] undid the gamma correction and extracted a single color from each grid cell by averaging the pixels around the cell center. The processing yielded one color for each grid cell.

Figure 7 (d) – (f) show composited charts based on the RYB color compositing method. Figures 7 (d) – (e) were generated by using the modified alpha compositing method, whereas Fig. 7(f) was generated by using alpha compositing. For example, we consider the case of calculating the color 3D in Fig. 7(d) from the colors 1D and 3A. First, we converted the color space of 1D and 3A from RGB to RYB by using Eqs. (1) – (15). Next, we composited the colors 1D and 3A by using Eq. (33) as C_{fore} = 1D, C_{back} = 3A, and $w = 0.2$, which is the color 3D. Finally, we converted the color space of 3D from RYB to RGB by using Eqs. (16) – (30) for the display.

Note that the details regarding whether to use alpha compositing or modified alpha compositing are discussed further in section 6.2.2.

Figure 7 (g) – (i) show difference images between actual color charts and composited charts based on the RYB color compositing methods. The difference images between two images are generated by the difference between each RGB channel of each pixel in each image.

For comparison, Fig. 7 (j) – (l) show the results with the RGB color space. Figure 7 (m) – (o) show difference images between actual color charts and composited charts based on the RGB color compositing methods.

Although some colors fail to reproduce a paint-like appearance, the RYB color compositing results are approximately the same as those from the actual compositing, whereas the RGB color compositing method fails to reproduce the paint-like appearance. The RYB color compositing methods have only one parameter, which is either α or w depending on the adopted compositing method. Therefore, although it can only be roughly adjusted, RYB color compositing is easy to use.

6.2.2 Reproducibility of the paint-like appearance

To evaluate the reproducibility of a paint-like appearance, we reported the color differences in the CIELab[3] color space between results of the RYB color compositing and the actual color compositing. We used actual color charts for different media, including gouache, thin acrylic, and watercolor, which were used as ground truths (i.e., Figs. 7(a) – (c)). We also used the ColorMine library[12] for converting from the RGB to CIELab color spaces.

The color chart consists of n base colors and n^2 composited colors created by a pair of base colors. The color difference ΔE_i in the CIELab color space between ith ($i \in n^2$) composited color of the actual color charts and color charts generated by using the RYB color model is given by

$$\Delta E_i = \sqrt{\left(\Delta L_i^*\right)^2 + \left(\Delta a_i^*\right)^2 + \left(\Delta b_i^*\right)^2}, \tag{34}$$

where ΔL_i*, Δa_i*, and Δb_i* are the differences in the L*, a*, and b* values. The average value ΔE_{avg} of the ΔE_i is given by

$$\Delta E_{avg} = \frac{1}{n^2}\sum_{i=1}^{n^2} \Delta E_i. \tag{35}$$

Table 3 Results of color differences between the color charts generated by using the RYB/RGB color model and the actual color charts

Media	Color Model	Addition	Alpha	Modified Alpha
Gouache	RGB	59.73	16.90 ($\alpha = 0.8$)	25.44 ($w = 0.2$)
	RYB	38.89	19.01 ($\alpha = 0.8$)	13.38 ($w = 0.2$)
Thin Acrylic	RGB	52.69	17.37 ($\alpha = 0.85$)	21.69 ($w = 0.2$)
	RYB	35.97	18.52 ($\alpha = 0.85$)	13.88 ($w = 0.3$)
Watercolor	RGB	55.00	16.33 ($\alpha = 0.6$)	32.62 ($w = 0.2$)
	RYB	26.29	18.08 ($\alpha = 0.6$)	19.81 ($w = 0.4$)

Table 3 shows the values of ΔE_{avg} for each of the three compositing methods, which are the addition, alpha, modified alpha compositing. We also calculated the color difference between the ground truth and RGB compositing results for comparison. We chose parameters α and w to yield the best results (with details provided in section 6.2.3).

As shown in Table 3, in addition compositing, we found that the RYB model performed much better than the RGB model for all media.

In alpha compositing, the RGB model performed slightly better than the RYB model for all media. The just-noticeable difference (JND) was between 1.0 and 2.3[14].

Differences less than the JND are not generally perceptible by casual viewers. Thus, in alpha compositing, there was no perceivable difference between the RGB and RYB results.

In modified alpha compositing, the RYB model performed better than the RGB model for all media. In particular, modified alpha compositing was suitable for highly scattering pigments, such as gouache or thin acrylic, in which the foreground colors appear strongly. Conversely, alpha compositing was suitable for lower scattering pigments, such as watercolors.

6.2.3 Influences of parameters

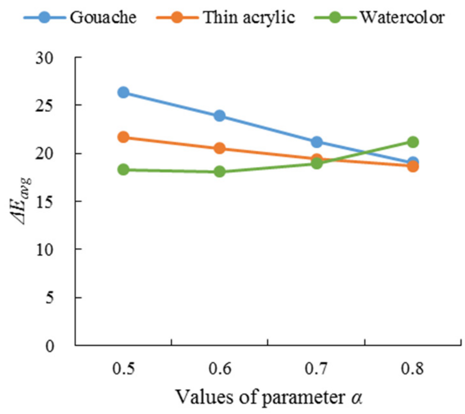
The alpha and modified alpha compositing methods both have a parameter, which is either α for the alpha compositing method or w for the modified alpha compositing method. We verified the optimal value of each of these parameters. **Figure 8**(a) shows the relationship between the ΔE_{avg} and parameter α for the alpha compositing method. We found that for low-scattering pigments (watercolor), α = 0.6 was suitable, whereas for high-scattering pigments (gouache and thin acrylic), α = 0.8 was suitable. Figure 8(b) shows the relationship between ΔE_{avg} and the parameter w of the modified alpha compositing method. We found that w = 0.4 was suitable for watercolors, whereas w = 0.2 or 0.3 was appropriate for gouache and thin acrylic.

6.3 Conversion error

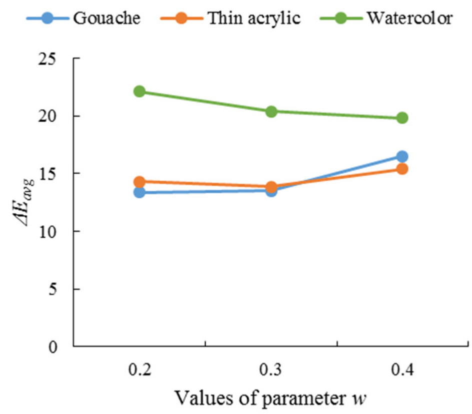
In this section, we analyzed the color space conversion error to verify the reversibility of the proposed conversion equation between the RGB and RYB color spaces. Here, we used the 8-bit RGB data ranging from 0 to 255. We also used the same number of bits of precision to convert the RGB data to RYB color space and to return to the RGB color space. The conversion error e_j ($j \in 256^3$) is calculated by

$$e_j = \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2}. \tag{36}$$

Here R_1, G_1, B_1 are the RGB values before conversion, and R_2, G_2, B_2 are the RGB values after conversion. The error e_j is calculated for all possible color combinations. Therefore, there are 256^3 cases in this experiment. **Table 4** shows the results of the minimum value, maximum value, mean, and standard deviation of the conversion error e_j.



(a) Alpha compositing



(b) Modified alpha compositing

Fig. 8 Relationship between parameter and average ΔE_{avg} for (a) alpha compositing and (b) modified alpha compositing

Table 4 Results of conversion error

Minimum value	Maximum value	Mean	Standard deviation
0	4.1231	0.6271	0.7929

The results show that it is possible to convert the proposed conversion equation with an error less than 1 on average.

6.4 Applications of the RYB color model

In the sections that follow, we present the examples of applications of the RYB color model.

6.4.1 Color designation interface

Color designations for users, such as the photo-retouching software Adobe photoshop[4] or the office suit Microsoft office[15], are often done by using a dialog box. Colors are designated by setting the values of three channels of the RGB color model. Color designation by the RGB color model can be confusing for those who are not trained in the RGB color model.

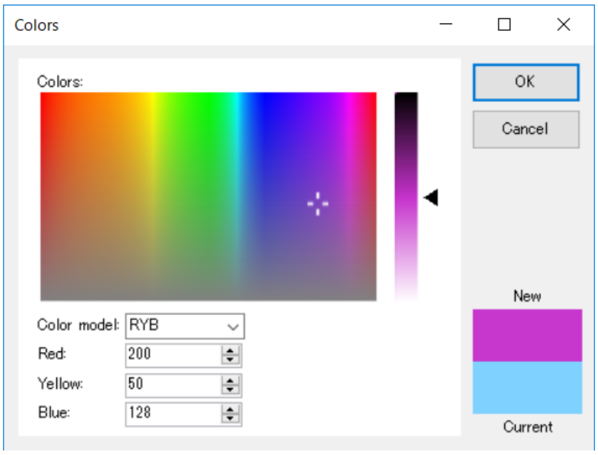
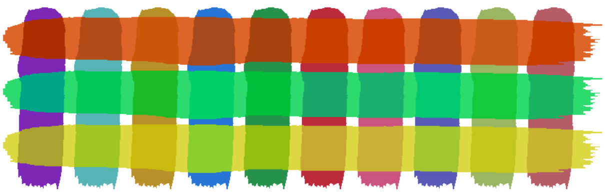


Fig. 9 Example of color-setting dialog box by using the RYB color model

(a) Alpha compositing ($\alpha = 0.6$)



(b) Modified alpha compositing ($w = 0.25$)

Fig. 10 Example of the stroke rendering with different compositing methods

Figure 9 shows the example of the color-setting dialog box by using the RYB color model. The color settings with the RYB color model can be used intuitively for the users who are familiar with the color mixing of pigments.

6.4.2 Stroke rendering

For brush-stroke rendering [6], we adopted the RYB color model to composite the colors in the regions in which strokes overlapped.

Figure 10 shows the results of the stroke rendering with the RYB color compositing method. Figure 10(a) shows the results of alpha compositing with $\alpha = 0.6$ in the RYB color space, whereas Fig. 10(b) shows the results of modified alpha compositing with $w = 0.25$. In both these cases, we used ten tandem strokes as the background layer and three horizontal strokes as the foreground layer. We observed here that the foreground colors appeared more strongly in the modified alpha compositing results than in the alpha compositing results.

By compositing the colors in the RYB color space, we could easily produce paint-like compositing. Therefore, RYB color compositing methods can be adopted for numerous applications, including digital painting[5] systems or non-photorealistic rendering (NPR) methods for painterly rendering[6].

6.4.3 Visualization

The RYB color compositing strategy can provide a more intuitive effect than RGB compositing for information visualization[7, 8].

Figure 11 shows the example of the visualization of multi-variate data by using the RYB color model. Figure 11 is the map of the United States of America. Three traits are visualized by using different colors, which are red, yellow/green, and blue in this map. States that have multiple traits are represented by composite colors.

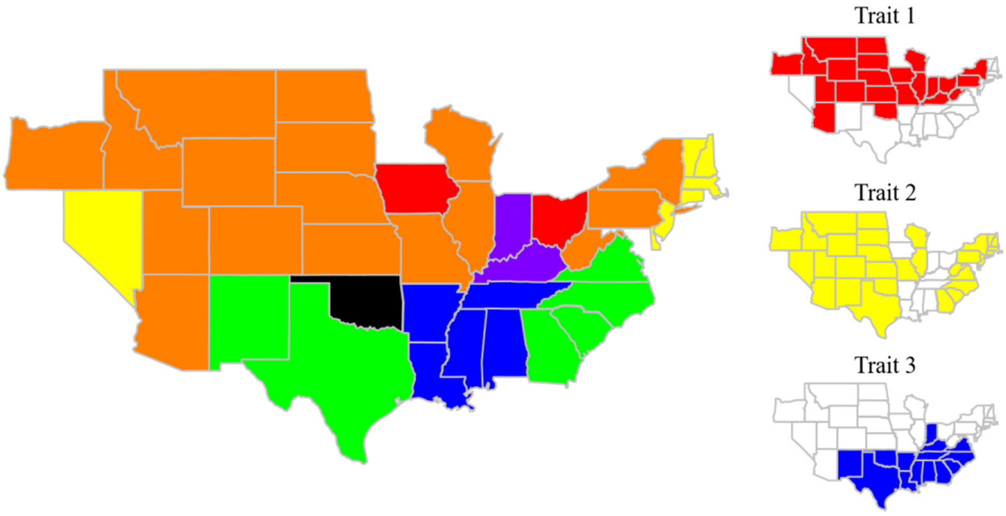
Figure 11(a) is an example of representation using the RYB color compositing method, and Figure 11(b) is an example of representation using the RGB color compositing method.

As shown in Fig. 11(b) for the RGB map, the state of Oklahoma is represented by white. In this case, Oklahoma State contains all three traits. However, the observer receives the impression that the Oklahoma State is blank. As shown in Fig. 11(a) for the RYB map, the Oklahoma State is represented by black. The RYB map is able to show better than the RGB map that the Oklahoma State has all three traits.

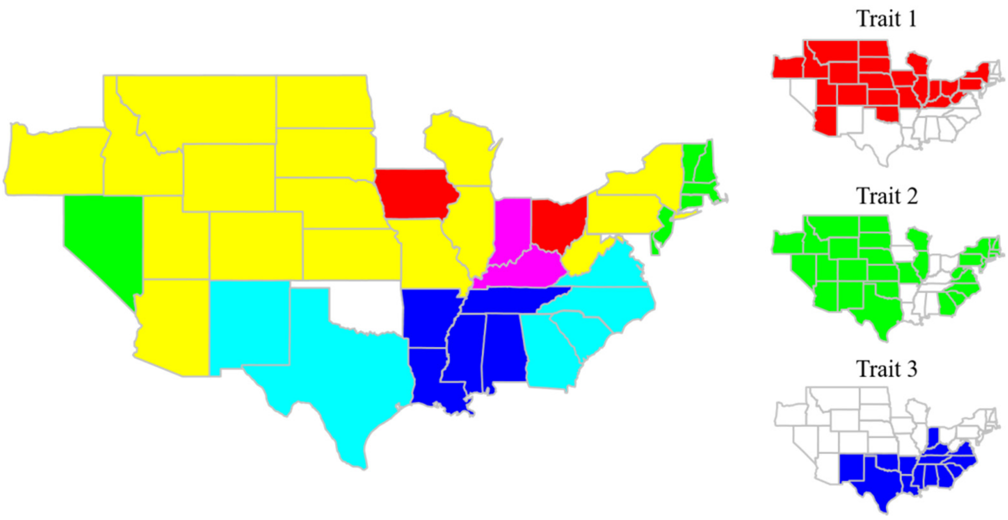
Figure 12 shows another example. This example is generated by using alpha compositing in the RYB color space. In this example, the texture generated by the Perlin noise[16] is overlaid on the map for the paint-like effect. Using our RYB compositing strategy, a user can obtain various compositing results by switching the compositing method and parameter.

7. Conclusion

In this paper, we presented the computational RYB color model and compositing methods. We formulated a conversion between the RGB and RYB color spaces. We also proposed and compared a class of compositing methods in the RYB color space. We applied the RYB color model to several applications, such as color designations interface, brush-stroke rendering, and the visualization technique of multi-attribute data.



(a) Use of RYB color compositing on the US map



(b) Use of RGB color compositing on the US map

Fig. 11 Example of visualization of multi-variate data with color compositing strategy

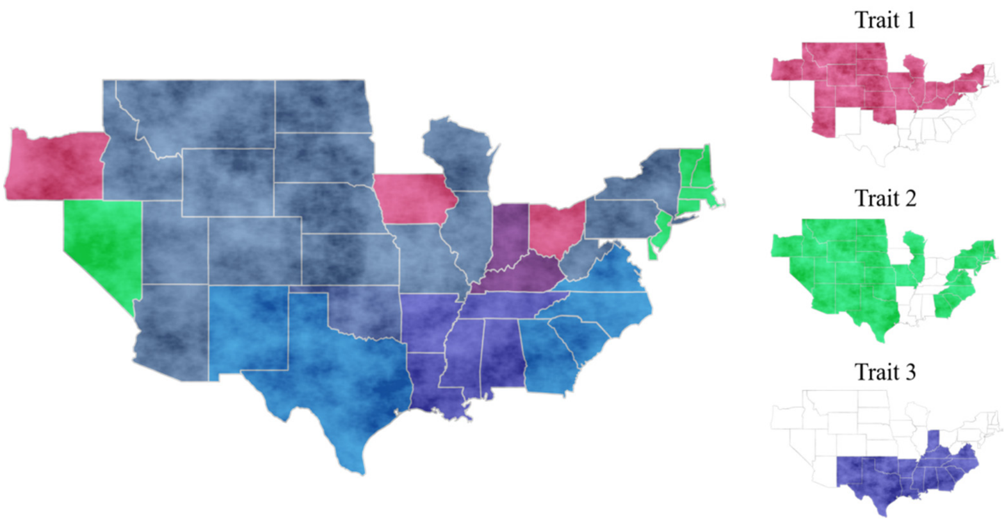


Fig. 12 Use of alpha compositing in the RYB color space on the map

It was found that the RYB color compositing method can indeed produce a paint-like appearance quite easily. Using the RYB color model, we can achieve comprehensible color compositing for casual users by subtractive color mixing, which is not possible with the RGB color compositing method.

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Appendix A

We supplement the derivation of Eqs. (5) – (7) in section 4.1, which relate to converting the color space defined by the three axes red, green, and blue shown in Fig. 4(a) into the color space defined by the three axes of red, yellow, and blue in Fig. 4(b).

The definition of yellow in the RGB color space was given by Walther[17), 18)]. Yellow is perceived as the overlap of red and green in equal parts; therefore, the amount of yellow contained in the RGB color space is given by

$$y_{RGB} = \min\{r_{RGB}, g_{RGB}\}. \tag{A.1}$$

In the RYB color space, the amount of yellow is handled by the yellow axis; therefore, yellow is subtracted from red and green in the RGB color space as follows:

$$r_{RYB} = r_{RGB} - y_{RGB}, \tag{A.2}$$

$$g'_{RGB} = g_{RGB} - y_{RGB}. \tag{A.3}$$

Substituting Eq. (A.1) into Eq. (A.2) yields Eq. (5) of section 4.1.

When combining blue and green, halve the values of blue and green to preserve the range of the maximum value as follows:

$$b'_{RGB} = \frac{b_{RGB}}{2}, \tag{A.4}$$

$$g''_{RGB} = \frac{g'_{RGB}}{2}. \tag{A.5}$$

Because green is represented as the combination of blue and yellow in the RYB color space, we distribute the remaining green to yellow and blue as follows:

$$y_{RYB} = y_{RGB} + g''_{RGB}, \tag{A.6}$$

$$b_{RYB} = b'_{RGB} + g''_{RGB}. \tag{A.7}$$

Substituting Eq. (A.1) and Eq. (A.5) into Eq. (A.6) yields Eq. (6); and substituting Eq. (A.4) and Eq. (A.5) into Eq. (A.7) yields Eq. (7) in section 4.1.

Equations (20) – (22) in section 4.2 can be derived from the same idea for the RYB to RGB conversion.

Appendix B

Procedure B.1 shows the procedure of conversion from the RYB to HSL color space. Note that we need to convert from RYB to RGB once (RYB→RGB→HSL).

Procedure B.1 Procedure of conversion from RYB to HSL

RYBtoHSL (c_{ryb})
C_{rgb} ← RYBtoRGB (c_{ryb}) [RYB to RGB conversion by Eqs. (16)–(30)];
C_{hsl} ← RGBtoHSL (c_{rgb}) [RGB to HSL conversion by e.g., ColorMine];
return c_{hsl};

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