Color Spaces and Their Conversions for Digital Earth[1]

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ABSTRACT The definitions, capabilities and limitations of various color spaces and the transformations between different color spaces are discussed, with emphases on color spaces of RGB system, XYZ system, LUV system, Lab system, and CMYK system and their conversions. This will be useful for digital earth researchers to select color spaces for color recording and reproduction systems, for the transmission of color signal (e.g.: TV transmission), for the processing of digital color images, for the sampling of digital color images, for printing of color images, and for display of color images. This can also be helpful to other design of color systems

KEY WORDS Color Spaces, Color Transforms, Color Image Processing, Digital Earth

1. Introduction

The Digital Earth allows the general public, both young and old, to easily see how the forces of the Earth - geological, biological, climatic, human civilization, etc. - affect our home planet. It also aids Earth scientists in identifying intricate correlation amongst these forces to better understand the Earth System. By using the latest in computer graphics, display, communication, store and virtual environ-ment technologies, the system of the digital earth will allows users to examine scientific information that is both measured and predicted. This informa-tion is often presented in different color spaces at different process and overlaid on top of a dramatic high-resolution model of the Earth. The increased use of color images has brought with it new challen-ges and problems. The capabilities and limitations of various color spaces and the transformations between different color spaces are discussed, with emphases on color spaces of RGB, CMYK, HSL, YUV, XYZ, Lu*v*, La*b* systems and their conversions. This will be useful for digital earth researchers to select color spaces for color recor-ding and reproduction systems, for the transmission of color signal, for the processing of digital color images, for the sampling of digital color images, for printing of color images, and for display of color images. This can also be helpful to other design of color systems.

2. Color and Color Space

2.1. Color

Color is the perceptual result of light in the visible region of the spectrum, having wavelengths in the region of 400 nm to 700 nm, incident upon the retina. Physical power (or radiance) is expressed in a spectral power distribution (SPD), often in 31 components each representing a 10 nm band.

Because there are exactly three types of color photoreceptor, three numerical components are necessary and sufficient to describe a color, providing that appropriate spectral weighting functions are used. This is the concern of the science of colorimetry. In 1931, the Commission Internationale de L'Éclairage (CIE) adopted standard curves for a hypothetical Standard Observer. These curves specify how an SPD can be transformed into a set of three numbers that specifies a color.

The CIE system is immediately and almost universally applicable to self-luminous sources and displays. However the colors produced by reflective systems such as photography, printing or paint is a function not only of the colorants but also of the SPD of the ambient illumination. If your application has a strong dependence upon the spectrum of the illuminant, you may have to resort to spectral mat-ching. As Sir Newton said, "Indeed rays, properly expressed, are not colored." SPDs exist in the phy-sical world, but color exists only in the eye and the brain.

2.2. Color Measure

Color is described normally by three attributes. Some terms have been defined by the CIE and are commonly used in measuring color are overviewed as follows.

（1） Brightness: the human sensation by which an area exhibits more or less light.

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（2） Hue: the human sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green and blue.

（3） Colorfulness: the human sensation according to which an area appears to exhibit more or less of its hue.

（4） Lightness: the sensation of an area's brightness relative to a reference white in the scene.

（5） Chroma: the colorfulness of an area relative to the brightness of a reference white.

（6） Saturation: the colorfulness of an area relative to its brightness.

2.3. Color Spaces

A color space is a method by which we can specify, create and visualize color. As humans, we may define a color by its attributes of brightness, hue and colorfulness. A computer may describe a color stimulus in terms of the excitations of red, green and blue phosphors on the CRT faceplate. A printing press describes a color stimulus in terms of the reflectance and absorbency of cyan, magenta, yellow and black inks on the paper. Such a color is usually specified by using three coordinates, or attributes, which represent its position within a specific color space. These coordinates do not tell us what the color looks like, only where the color is located within a particular color space.

Different color spaces are better for different applications, for example some equipment has limiting factors that dictate the size and type of color space that can be used.

Some color spaces are perceptually linear, i.e. a 10 unit change in stimulus will produce the same change in perception wherever it is applied. Many color spaces, particularly in computer graphics, are not linear in this way.

Some color spaces are intuitive to use, i.e. it is easy for the user to navigate within them and creating desired colors is relatively easy. Other spaces are confusing for the user with parameters with abstract relationships to the perceived color.

Finally, some color spaces are tied to a specific piece of equipment (i.e. are device dependent) while others are equally valid on whatever device they are used.

3. Common Color Spaces and Transforms

3.1. RGB Space

The RGB tricolor system was proposed by CIE in 1931, in which the R, G and B are respectively defined in Tab. 1.

Tab. 1. *RGB tricolor system*

Tricolor units	Luminous flux [Light Watt]	Wavelength [nm]	Symbol
1 Red Unit	1.1000	$\lambda = 700$	$[\mathbf{R}]$
1 Green Unit	4.5907	$\lambda = 546.1$	$[\mathbf{G}]$
1 Blue Unit	0.0601	$\lambda = 435.8$	$[\mathbf{B}]$

The RGB space is an additive color system based on trichromatic theory. Grassman's Laws of additive color mixture can be well described in the RGB space. Any color (source $\mathbf{F}$) can be matched by a linear combination of three other colors (primaries e.g. RGB), provided that none of those three can be matched by a combination of the other two. This is fundamental to colorimetry and is Grassman's first law of color mixture. So a color $\mathbf{F}$ can be matched by R units of red $(\mathbf{R})$, G units of green $(\mathbf{G})$ and B units of blue $(\mathbf{B})$. The units are can be measured in any form that quantifies light power.

$$\mathbf{F} = R[\mathbf{R}] + G[\mathbf{G}] + B[\mathbf{B}] \tag{1}$$

$$R + G + B = m \tag{2}$$

The normalized form is:

$$r = R/m, \quad g = G/m, \quad b = B/m \tag{3}$$

$$\mathbf{F} = R[\mathbf{R}] + G[\mathbf{G}] + B[\mathbf{B}] = m\{r[\mathbf{R}] + g[\mathbf{G}] + b[\mathbf{B}]\} \tag{4}$$

A mixture of any two colors (sources $\mathbf{F}_1$ and $\mathbf{F}_2$) can be matched by linearly adding together the mixtures of any three other colors that individually match the two source colors. This is Grassman's second law of color mixture. It can be extended to any number of source colors.

$$\mathbf{F}_3 = \mathbf{F}_1 + \mathbf{F}_2 = (R_1 + R_2)[\mathbf{R}] + (G_1 + G_2)[\mathbf{G}] + (B_1 + B_2)[\mathbf{B}] \tag{5}$$

Color matching persists at all luminance. This is Grassman's third law. It fails at very low light levels where rod cell vision (scoptopic) takes over from cone cell vision (photopic).

The equality sign should not be used to signify an identity, in colorimetry it means a color matching, the color on one side of the equality looks the same as the color on the other side. These laws govern all aspects of additive color work, but they apply only signals in the linear-light domain. They can be extended into subtractive color work.

Often found in systems that use a CRT to display images. RGB is easy to implement but nonlinear with visual perception. It is device dependent and specification of colors is semi-intuitive. RGB is very common, being used in virtually every computer system as well as television, video etc.

3.2. CIE XYZ Space (1931)

The CIE XYZ (1931) system is at the root of all colorimetry. It is defined such that all visible colors can be defined using only positive values, and, the Y value is luminance. Consequently, the colors of the XYZ primaries themselves are not visible. The chromaticity diagram is highly non-linear, in that a vector of unit magnitude representing the difference between two chromaticities is not uniformly visible. A color defined in this system is referred to as Yxy.

$$\mathbf{F} = X[\mathbf{X}] + Y[\mathbf{Y}] + Z[\mathbf{Z}] \tag{6}$$

$$\left.\begin{aligned} x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ z &= Z/(X+Y+Z) \end{aligned}\right\} \tag{7}$$

The third co-ordinate, z, can be redundant since $x+y+z=1$ for all colors.

（1） X, Y and Z all are positive values for any color.

（2） The luminance is dependent on only Y, and the light flux of $1[\mathbf{Y}]$ is 1 light-watt.

（3） When $X = Y = Z$, it is a white-light with equivalent-energy of the $R = G = B$ representation.

3.3. YUV, YIQ, YCbCr, YCC (Luminance - Chrominance)

These are the television transmission color spaces, sometimes known as transmission primaries. YIQ and YUV are analogue spaces for NTSC and PAL systems respectively while YC_bC_r is a digital standard.

These color spaces separate RGB into luminance and chrominance information and are useful in compression applications (both digital and analogue). These spaces are device dependent but are intended for use under strictly defined condi-tions within closed systems. They are also quite unintuitive, unless of course you are a TV engineer. Kodak uses a derivative of YCC in its PhotoCD system, PhotoYCC.

3.4. CIE YUV Space (1960)

This is a linear transformation of Yxy, in an attempt to produce a chromaticity diagrams in which a vector of unit magnitude (difference between two points representing two colors) is equally visible at all colors. Y is unchanged from XYZ or Yxy. Difference non-uniformity is reduced considerably, but not enough. A third co-ordinate, w, can also be defined but is redundant.

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.578 & 0.144 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad \text{(NTSC system)} \tag{8}$$

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.578 & 0.144 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad \text{(PAL system)} \tag{9}$$

$$\begin{bmatrix} Y \\ C_r \\ C_b \end{bmatrix} = \begin{bmatrix} 0.299 & 0.578 & 0.144 \\ 0.500 & -0.4187 & -0.0813 \\ -0.169 & -0.3313 & 0.500 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix} \tag{10}$$

3.5. CIE 1976 $L^*u^*v^*$ (CIELUV)

The L^*, u^*, v^* values corresponding to a stimulus with CIE XYZ tristimulus values X, Y, Z are defined as

$$\left.\begin{aligned} L^* &= 116 f\left(\tfrac{Y}{Y_n}\right) - 16 \\ u^* &= 13L^*(u' - u'_n) \\ v^* &= 13L^*(v' - v'_n) \end{aligned}\right\} \tag{11}$$

where

$$f(t) = \begin{cases} t^{1/3} & \text{if } t > 0.008856 \\ 7.787t + 16/116 & \text{if } t \le 0.00885 \end{cases} \tag{12}$$

$$\left.\begin{aligned} u' &= \frac{4X}{X+15Y+3Z}, & v' &= \frac{9Y}{X+15Y+3Z} \\ u'_n &= \frac{4X_n}{X_n+15Y_n+3Z_n}, & v'_n &= \frac{9Y_n}{X_n+15Y_n+3Z_n} \end{aligned}\right\} \tag{13}$$

and X_n, Y_n, Z_n are the tristimuli of the white strimulus. L^* serves as correlate of lightness. In the *u*v** plane, the radial distance ($\sqrt{(u^*)^2 + (v^*)^2}$) and angular position ($\arctan\left(\frac{u^*}{v^*}\right)$) serve as correlates of chroma and hue, respectively.

3.6. CIE $L^*a^*b^*$ (CIELAB)

The *L** coordinate of the CIELAB space is identical to the *L** coordinate for the CIELUV space, and the transforms for the a* and b* coordinates are given by

$$\left.\begin{aligned} a^* &= 500\left(f\left(\tfrac{X}{X_n}\right) - f\left(\tfrac{Y}{Y_n}\right)\right) \\ b^* &= 200\left(f\left(\tfrac{Y}{Y_n}\right) - f\left(\tfrac{Z}{Z_n}\right)\right) \end{aligned}\right\} \tag{14}$$

where $f(\cdot)$, X_n, Y and Z_n are as defined earlier. The *a** is red-green channel and *b** the yellow-blue channel. Once again, in the *a*b** plane, the radial distance ($\sqrt{(a^*)^2 + (b^*)^2}$) and angular position ($\arctan\left(\frac{a^*}{b^*}\right)$) serve as correlates of chroma and hue, respectively.

Again, *L** scales from 0 to 100. There are polar parameters that more closely match the visual experience of colors. Hue is an angle in four quadrants, and there is no saturation term in this system. When determining CIE*L*a*b** or CIE*L*u*v** values for CRT displayed colors it is usual to used the CRT's white point as the reference white.

3.7. CMY(K) (Cyan Magenta Yellow (Black))

This is a subtractive based color space and is mainly used in printing and hard copy output. The fourth, black, component is included to improve both the density range and the available color gamut (by removing the need for the CMY inks to produce a good neutral black it is possible to used inks that have better color reproductive capabilities). CMY(K) is fairly easy to implement but proper transfer from RGB to CMY(K) is very difficult (simple transforms are, to put it bluntly, simple). CMY(K) is device dependent, nonlinear with visual perception and reasonably unintuitive.

4. Transforms between Color Spaces

4.1. RGB and XYZ Spaces

RGB to XYZ:

$$\begin{bmatrix}[\mathbf{X}]\\ [\mathbf{Y}]\\ [\mathbf{Z}]\end{bmatrix} = [A]\begin{bmatrix}[\mathbf{R}]\\ [\mathbf{G}]\\ [\mathbf{B}]\end{bmatrix} \quad \text{or} \quad \begin{bmatrix}[\mathbf{X}]\\ [\mathbf{Y}]\\ [\mathbf{Z}]\end{bmatrix} = [A^{\mathrm{T}}]^{-1}\begin{bmatrix}[\mathbf{R}]\\ [\mathbf{G}]\\ [\mathbf{B}]\end{bmatrix} \qquad (15)$$

where

$$[A] = \begin{bmatrix} 0.4185 & -0.0912 & 0.0009\\ -0.1587 & 0.2524 & -0.0025\\ -0.0828 & 0.0157 & 0.1786 \end{bmatrix}$$

$$[A^{\mathrm{T}}]^{-1} = \begin{bmatrix} 2.7689 & 1.7517 & 1.1302\\ 1.0000 & 4.5909 & 0.0601\\ 0.0000 & 0.0565 & 5.5943 \end{bmatrix}$$

The transform from RGB to CIE XYZ only works for display devices. It will not enable you to deter-mine the CIE co-ordinates of, say, a color patch on a photograph scanned with your favorite scanner.

XYZ to RGB:

$$\begin{bmatrix}[\mathbf{R}]\\ [\mathbf{G}]\\ [\mathbf{B}]\end{bmatrix} = [A]^{-1}\begin{bmatrix}[\mathbf{X}]\\ [\mathbf{Y}]\\ [\mathbf{Z}]\end{bmatrix} \quad \text{or} \quad \begin{bmatrix}[\mathbf{R}]\\ [\mathbf{G}]\\ [\mathbf{B}]\end{bmatrix} = [A^{\mathrm{T}}]\begin{bmatrix}[\mathbf{X}]\\ [\mathbf{Y}]\\ [\mathbf{Z}]\end{bmatrix} \qquad (16)$$

where

$$[A^{\mathrm{T}}] = \begin{bmatrix} 0.4185 & -0.1587 & -0.0828\\ -0.0912 & 0.2524 & 0.0157\\ 0.0009 & -0.0025 & 0.1786 \end{bmatrix}$$

$$[A]^{-1} = \begin{bmatrix} 2.7689 & 1.0000 & 0.0000\\ 1.7517 & 4.5909 & 0.0565\\ 1.1302 & 0.0601 & 5.5943 \end{bmatrix}$$

4.2. RGB and YUV Spaces

Considering of the human vision effect and non-linearities of CRT and $L_R = 0.299,\ L_G = 0.587,\ L_B = 0.114,$ $K_U = 0.493,$ $K_r = 0.887$, we have following transforms.

RGB to YUV:

$$\begin{bmatrix}Y\\ U\\ V\end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114\\ -0.147 & -0.289 & 0.436\\ -0.615 & -0.514 & -0.101 \end{bmatrix}\begin{bmatrix}R\\ G\\ B\end{bmatrix} \qquad (17)$$

YUV to RGB:

$$\begin{bmatrix}R\\ G\\ B\end{bmatrix} = \begin{bmatrix} 1.00908 & 0.00362 & 1.1345\\ 1.00908 & -0.39800 & -0.58577\\ 1.00908 & 2.2084 & -0.00535 \end{bmatrix}\begin{bmatrix}Y\\ U\\ V\end{bmatrix} \qquad (18)$$

4.3. RGB and YIQ Spaces

RGB to YIQ:

$$\begin{bmatrix}Y\\ I\\ Q\end{bmatrix} = \begin{bmatrix} 0.299 & 0.578 & 0.144\\ 0.596 & -0.275 & -0.321\\ 0.212 & -0.523 & 0.311 \end{bmatrix}\begin{bmatrix}R\\ G\\ B\end{bmatrix} \qquad (19)$$

YIQ to RGB:

$$\begin{bmatrix}R\\ G\\ B\end{bmatrix} = \begin{bmatrix} 1.00908 & 0.95322 & 0.61398\\ 1.00908 & -0.274048 & -0.65275\\ 1.00908 & -1.11064 & 1.69919 \end{bmatrix}\begin{bmatrix}Y\\ I\\ Q\end{bmatrix} \qquad (20)$$

4.4. RGB and YCrCb Spaces

RGB to YCrCb:

$$\begin{bmatrix}Y\\ C_r\\ C_b\end{bmatrix} = \begin{bmatrix} 0.299 & 0.578 & 0.144\\ 0.500 & -0.4187 & -0.0813\\ -0.1687 & -0.3313 & 0.500 \end{bmatrix}\begin{bmatrix}R\\ G\\ B\end{bmatrix} + \begin{bmatrix}0\\ 128\\ 128\end{bmatrix} \qquad (21)$$

YCrCb to RGB:

$$\begin{bmatrix}R\\ G\\ B\end{bmatrix} = \begin{bmatrix} 1.00908 & 1.395 & -0.003162\\ 1.00908 & -0.720589 & -0.34724\\ 1.00908 & -0.0066199 & 1.76885 \end{bmatrix}\begin{bmatrix}Y\\ C_r\\ C_b\end{bmatrix} \qquad (22)$$

*4.5. XYZ and CIE La*b* Spaces*

XYZ to La*b*:

$$\left.\begin{aligned} L &= 25Y^{\frac{1}{3}}-16 \\ a^* &= 109.5X^{\frac{1}{3}}-107.7Y^{\frac{1}{3}} \\ b^* &= 43.0Y^{\frac{1}{3}}-41.92Z^{\frac{1}{3}} \end{aligned}\right\} \tag{23}$$

La*b* to XYZ:

$$\left.\begin{aligned} X &= [(a+107.7)((L+16)/25)/10 \quad 9.5]^3 \\ Y &= [(L+16)/25]^3 \\ Z &= [\frac{43.0(\mathrm{L}+16)/25-6}{41.92}]^3 \end{aligned}\right\} \tag{24}$$

4.6. XYZ and CIEYUV Spaces

XYZ to YUV:

$$u = 2x(6y-x+1.5) \tag{25}$$

$$v = 3y(6y-x+1.5) \tag{26}$$

YUV to XYZ:

$$x = 4.5u/(3u-12v+6) \tag{27}$$

$$y = 3v/(3u-12v+6) \tag{28}$$

4.7.XYZ and CIE YU’V’ Spaces

XYZ to YU’V’:

$$u' = u = 2x(6y-x+1.5) \tag{30}$$

$$v' = 1.5v = 4.5y(6y-x+1.5) \tag{31}$$

YU’V’ to XYZ:

$$x = 4.5u'/(3u'-8v'+6) \tag{32}$$

$$y = 2v'/(3u'-8v'+6) \tag{33}$$

4.8.RGB and CMYK Spaces

Assuming the value range of R，G，B is 0-MAX, we have

$$\begin{cases} C = \mathrm{MAX}-R \\ M = \mathrm{MAX}-G \\ Y = \mathrm{MAX}-B \end{cases} \tag{34}$$

When C=M=Y=MAX, let K=MAX, thus

$$\begin{cases} R = \mathrm{MAX}-C \\ G = \mathrm{MAX}-M \\ B = \mathrm{MAX}-Y \end{cases} \tag{35}$$

RGB to CMY:

$$\begin{cases} C = 1-R \\ M = 1-G \\ Y = 1-B \end{cases} \tag{36}$$

CMY to RGB:

$$\begin{cases} R = 1-C \\ G = 1-M \\ B = 1-Y \end{cases} \tag{37}$$

CMY to CMYK:

$$\begin{cases} K = \min(C,M,Y) \\ C = (C-K)/(1-K) \\ M = (M-K)/(1-K) \\ Y = (Y-K)/(1-K) \end{cases} \tag{38}$$

CMYK to CMY:

$$\begin{cases} C = \min(1, C(1-K)+K) \\ M = \min(1, M(1-K)+K) \\ Y = \min(1, Y(1-K)+K) \end{cases} \tag{39}$$

These cheap and nasty transforms may be fine for printing a bar chart or for spot color on a newsletter but for even semi-critical applications the color reproduction is very poor. A more accurate method is to calculate the displayed CIE tristimulus values from your RGB image pixel values and use these as target values for a similar conversion back through the CMY(K) devices chromaticity values and transfer function to the appropriate CMY(K) values. If you want good color reproduction this is the kind of complexity you will need to go to.

5. Discussions

The color and common used color spaces are overviewed with a number of examples. The chara-cteristics, transforms relationships and potential applications to digital earth are given in Tab. 2.

Color management system interfaces in the future are likely to include the ability to accom-modate commercial proprietary color specification systems. They are likely to provide their color specification systems in shrink-wrapped form to plug into color managers. In this way, users will have guaranteed color accuracy among applicatio-ns in digital earth and peripherals.

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Tab. 2. *Color spaces---Characteristics and Applications*

	Main Characteristics	Applications to Digital Earth and etc.
RGB	● Additive color system, R: red, G: green, B: blue ● Based on trichromatic theory, only for display devices ● Easy to implement ● Non-linear ● Device dependent, unintuitive ● May negative values	● CRT displays, common used in television cameras, computer graphics etc. ● Proportions of excitation of red, green and blue emitting phosphors produce colors when visually fused
CMY(K)	● Subtractive color, Cyan, M: Magenta, Y: Yellow, K: Black ● Fairly easy to implement ● Difficult to transfer properly from RGB (often use simple transforms) ● Device dependent ● Printers often include black ink ● Non-linear ● Unintuitive	● Color printing ● Color photography ● Painting art ● Improve the color gamut ● Improving blacks, saving money and speeding drying (less ink to dry)
HSL HSI HSV HCI HVC TSD	● This represents a wealth of similar color spaces HSL: Hue Saturation Lightness HSI (intensity) HSV (value) HCI (chroma / colorfulness) HVC, TSD (hue saturation and darkness) ● Most of these color spaces are linear transforms from RGB ● Device dependent, non-linear but very intuitive	● Image processing Separation of the luminance com-ponent has advantages in image processing and other applications. (NB.: complete isolation of the separate components requires space optimized for devices.)
YUV **YIQ** **YCbCr** **YCC**	● YIQ and YUV are analogue for NTSC and PAL ● YCbCr is for digital ● They separate luminance from chrominance (lightness from color) ● They are device dependent ● Unintuitive, unless you are a TV engineer ● Kodaks PhotoCD system uses a type of YCC color space, PhotoYCC, a device calibrated color space.	● Television transmission ● Color image transmission ● Image compression and image processing ● Image storing
CIEXYZ	● The root of all colorimetry, referred to as Yxy. ● X, Y and Z all are positive values for any color ● Y value is luminance, the light flux of $1\mathbf{[Y]}$ is 1 light-watt. ● $\mathbf{[X],[Y],[Z]}$ primaries themselves are not visible ● The chromaticity diagram is highly non-linear ● not uniformly visible ● $X = Y = Z$ is corresponding to $R = G = B$ with equal energy light	● As a standard color space, it was often used to define other color spaces, such as La*b*, Lu*v* etc. ● Exchange of color image data between different devices ● Deterring color matches ● Calibration for different devices
CIELUV **CIELAB**	● CIE color spaces. L=Y is perceived lightness ● Nearly linear with visual perception ● Based on human vision, ● Device independent ● Quite unintuitive ● Two-dimensional chromaticity chart, useful for showing additive color mixtures, but CIELAB has no associated two-dimensional chromaticity diagram and no correlate of saturation.	● Calibration for different devices, such as color printer, digital cameras ● Exchange of color image data between different devices ● Color management ● Image processing ● Comparing stimuli under similar conditions of adaptation