



Einführung in die Farbwissenschaft

Colorimetry

Colorimetry Content

- motivation
- standard illumination
- color matching experiments
- metamerism
- color spaces

What is our Goal?

- to be able to **quantify** color in a meaningful, expressive, consistent and reproducible way.
- problem: color is a **perceived quantity**, not a direct, physical observable

Color - A Visual Sensation

object → light stimulus → eye → nerve signal → brain

electromagnetic rays → color sensation

realm of direct observables | realm of psychology

Colorimetry

- **colorimetry** is the branch of color science concerned with **numerically specifying** the color of a physically defined visual stimulus in such manner that
 - ◆ stimuli with the same specification look alike under the same viewing conditions
 - ◆ stimuli that look alike have the same specification
 - ◆ the numbers used are continuous functions of the physical parameters

Colorimetry Properties

- colorimetry only considers the **visual discriminability** of physical beams of radiation
- in colorimetry „colors“ are equivalence classes of mutually **indiscriminable beams**
- colors in this sense cannot be said to be “red”, “green” or any other “color name”
- discriminability is decided before the brain - colorimetry is not psychology

CIE



- the **C**ommission **I**nternational de l' **E**clairage (CIE) was founded in 1913
- it succeeded the *Commission Internationale de Photometrie*
- is the recognized international standards body for questions of human perception and color
- the CIE colorimetric system is the standard from which all others are derived
- published the Basic Colorimetric Terms (BCT)

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6



CIE Basic Colorimetric Terms BCT: **Color**



- **Color in the psychophysical sense** is that characteristic of a visible radiant power by which an observer may distinguish differences between two structure-free fields of view of the same size and shape, such as may be caused by differences in the spectral composition of the radiant power concerned in the observation
- psychophysical color is specified by the tristimulus values of the radiant power entering the eye

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7



CIE BCT: **Color Stimulus**



- a **color stimulus** is radiant power of given magnitude and spectral composition, entering the eye and producing a sensation of color.

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CIE BCT: **Stimuli**



- a **monochromatic stimulus** is monochromatic radiant power of given magnitude and wavelength (or frequency), entering the eye and producing a sensation of light of color.
- an **achromatic stimulus** is the stimulus chosen because it usually yields a color perception which is devoid of hue under the desired viewing conditions.

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9



Omitted Problems



- dependence of the match on the observational conditions under which the match is made
- the possible effects of previous exposures to color stimuli on the eyes of the observer
- differences between observers

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10



Standard Light Sources & Illuminants



- most important light source: **natural daylight**
 - ◆ spectral characteristics quite variable
 - ◆ time, geographic location, weather
 - ◆ changes within a few minutes
 - ◆ 2000 K (morning) to >10000 K (late afternoon)
- therefore standard definitions:
 - ◆ **standard light source**
 - exists physically
 - ◆ **standard illuminant**
 - mathematical description of ideal light source

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11



Standard Illuminants

- CIE 1931
 - ◆ illuminant **A**: incandescent lamp
 - ◆ illuminant **B**: emulates sunlight
 - ◆ illuminant **C**: emulates average daylight
- CIE 1964
 - ◆ illuminants **D**
 - **D₆₅**: 6500 K
 - **D₇₅**: 7500 K
 - **D₅₅**: 5500 K
 - ... (**D_{xx}**: xx00 K)

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Standard Illuminant A

- formed by normed incandescent lamp
- color temperature 2856 K

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Standard Illuminant B

- emulates sunlight
- produced by two 1 cm liquid filters in front of A
- not enough UV, discontinued

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Standard Illuminant C

- emulates average daylight
- produced by two 1 cm liquid filters in front of A
- not enough UV, discontinued

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Standard Illuminant D₆₅

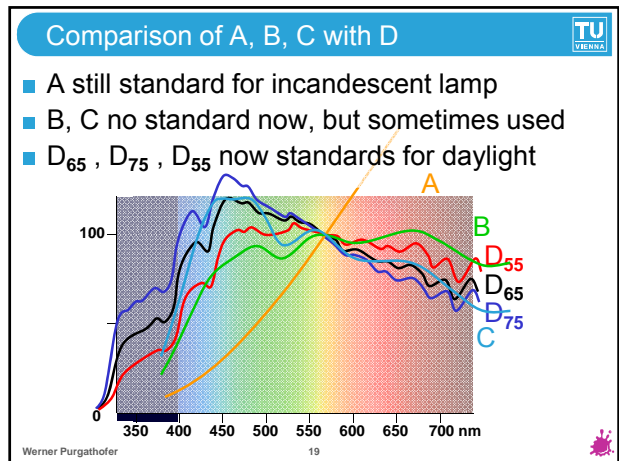
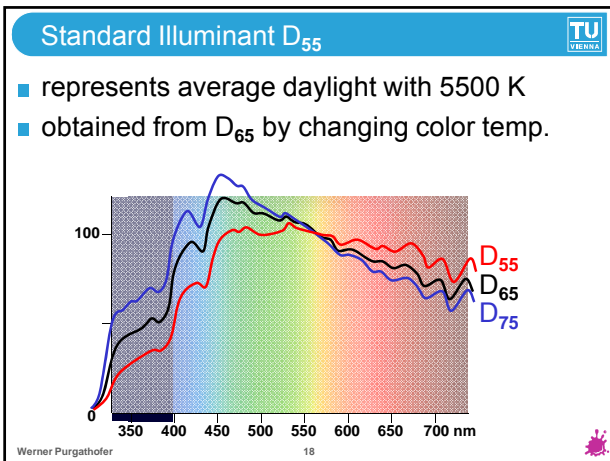
- represents average daylight with 6500 K
- based on many daylight measurements
- approx.: tungsten lamp + bluish glass filter

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Standard Illuminant D₇₅

- represents average daylight with 7500 K
- obtained from D₆₅ by changing color temp.

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Trichromatic Generalization

- = **key to colorimetry!**
 - ◆ based on physiology of eye → 3 cone types!
- over a wide range of conditions, many color stimuli can be matched in color completely by additive mixtures of **3 fixed primary stimuli** whose radiant powers were suitably adjusted
- these 3 primaries can be chosen (almost) arbitrarily – they just have to be mutually independent
- the 3 lights are usually chosen from the long, medium and short wavebands (RGB)

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Graßmann Laws (1853)



- (1) to specify a color **3 elements** are necessary and sufficient, e.g.:
 - ◆ hue, luminance, saturation
- (2) every color has a **complementary color**
 - ◆ when mixed it becomes a colorless gray
- (3) mix of 2 lights with same hue & saturation produces color with **identical hue & saturation**
- (4) **total luminance** of any mixture of light is the sum of each light's luminance

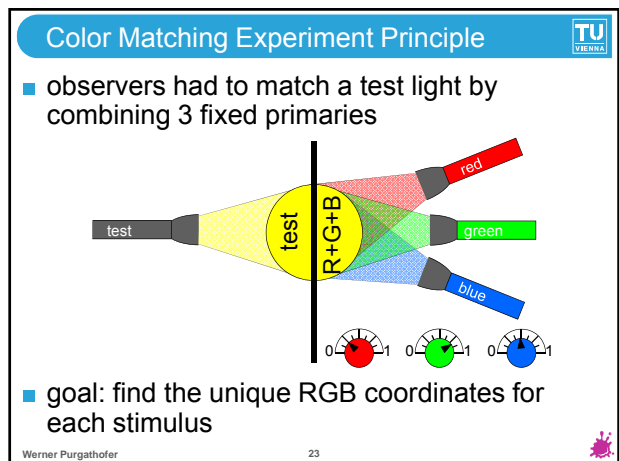
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Laws of Color Matching

- **Symmetry law:**
 - ◆ if A matches B, then B matches A
- **Transitivity:**
 - ◆ if (A m B) & (B m C), then A matches C
- **Proportionality:**
 - ◆ if A matches B, then x*A matches x*B
- **Additivity:**
 - ◆ if any 2 of (A m B), (C m D), ((A+C) m (B+D)) hold true, then so does (A+D) m (B+C)

(with + denoting additive color mixture)

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Tristimulus Values

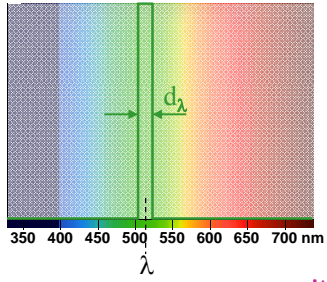
- the values R_Q , G_Q and B_Q of a stimulus Q that fulfill

$$Q = R_Q \cdot R + G_Q \cdot G + B_Q \cdot B$$
 are called the **tristimulus values** of Q
- in the case of a **monochromatic** stimulus Q_λ , the values R_λ , G_λ and B_λ are called the **spectral tristimulus values**

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Monochromatic Stimulus

- a monochromatic stimulus of wavelength λ is radiant power of only wavelength λ
- in practice it is radiant power in a wavelength interval d_λ centered at λ with the intensity P_λ
- d_λ is assumed to go towards zero



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Absolute Trichromatic Values

- after the idea of tristimulus values had been developed (which are dependent on the used lights), the next step was to attempt the definition of an **absolute reference system** for human color vision
 - for fixed reference values of R, G, B
 - extensive experiments to determine average human response to these stimuli

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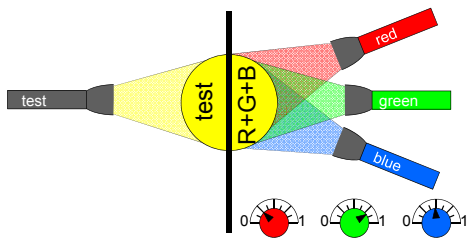
CIE Color Matching Experiments

- a sequence of experiments first conducted by the CIE from 1920-29 led to the **CIE 1931 XYZ color system**
- a particular set of R, G and B lights and viewing conditions was chosen
- experiments were conducted with observers that were given a 2° field of vision
- only monochromatic stimuli were matched**
- data is only valid for photopic vision (cones)

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Color Matching Experiment Principle

- observers had to match **monochromatic** test lights by combining 3 fixed primaries

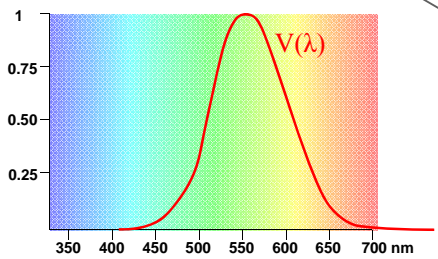


- goal: find the **unique** RGB coordinates for each stimulus

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Relative Photopic Luminous Efficiency

- luminous efficiency = luminance / radiance:
 - $\sigma(\lambda) = L(\lambda) / P(\lambda)$
 - $V(\lambda) = \sigma(\lambda) / \max(\sigma) = \sigma(\lambda) / 683$



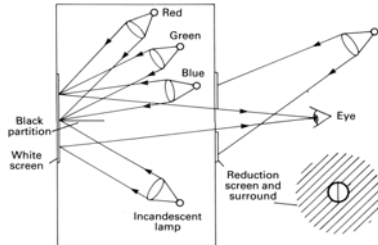
reminder

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Color Matching Experiments Details



- aperture diameter originally was 2° , later 10°
- RGB were fixed at
 $R = 700.0 \text{ nm}$, $G = 546.1 \text{ nm}$, $B = 435.8 \text{ nm}$
 (3 spectrum lines in mercury vapor)

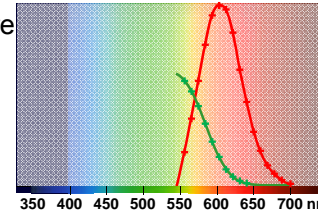


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Color Matching Procedure

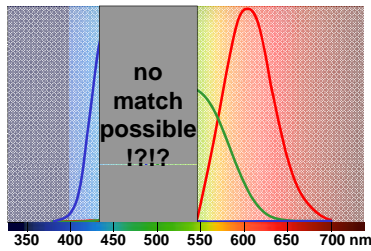


- (1) test field = 700 nm-red with radiance P_{ref}
 - ◆ observer adjusts luminance of R ($G=0, B=0$)
- (2) test light wavelength is decreased in constant steps (radiance P_{ref} stays the same)
 - ◆ observer adjusts R, G, B
- (3) repeat for entire visible range



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Color Matching Result !?



- observers want to „subtract“ red light from the match side...!?

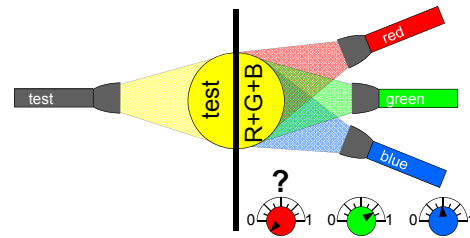
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32

Color Matching Experiment Problem



- for some colors observers want to reduce red light to negative values...!?
- but there is no negative light...!



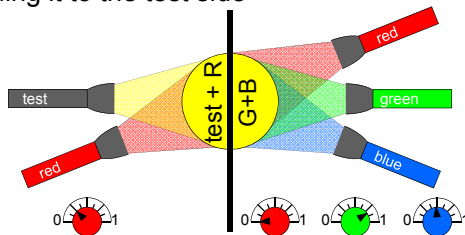
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33

“Negative” Light in a Color Matching Exp.



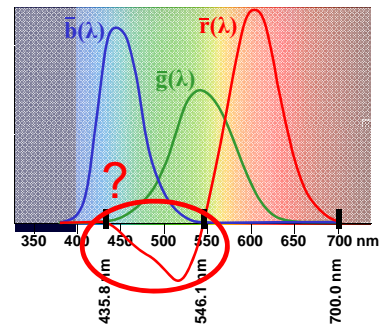
- if a match using only positive RGB values proved impossible, observers could simulate a **subtraction** of red from the match side by adding it to the test side



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34

CIE RGB Color Matching Functions



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35

CIE RGB Color Matching Functions



- aim of the color matching experiment: to obtain values for the

$$\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$$

color matching functions just mentioned

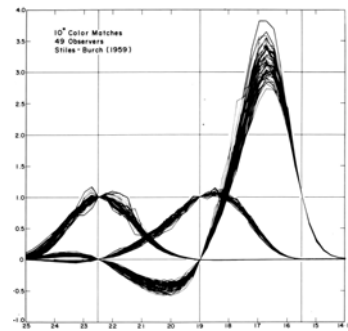
- these $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ functions have no underlying mathematical law – they are **empirical data** which has to be measured
- they also differ slightly for individuals and strongly for other viewing conditions

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36



CIE Color Matching Function Accuracy



curves are from the 10° matches, they differ from the 2° matches

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37



Equal Energy Stimulus



- obtained when all the monochromatic stimuli Q_λ contained in a spectrum Q have unit power
- denoted by E , and its components are also sometimes referred to as E_λ
- a color match for a given E_λ can always be obtained through

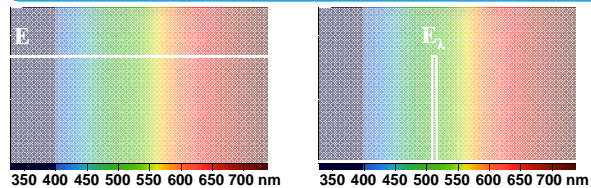
$$E_\lambda = \bar{r}(\lambda) \cdot R + \bar{g}(\lambda) \cdot G + \bar{b}(\lambda) \cdot B$$

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38



Equal Energy Stimulus

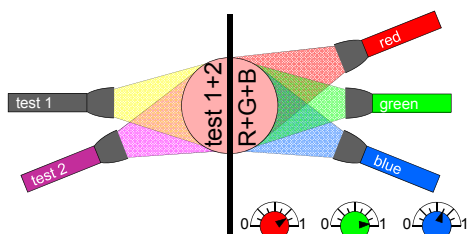


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Sum of Two Test-lights



- the sum of two test-lights is the same as the sum of the two tristimulus representations.

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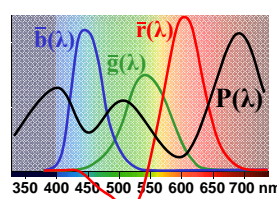
40



Tristimulus Values of Complex Stimuli



- a complex stimulus is a non-monochromatic wavelength distribution in the visible spectrum between λ_a and λ_b
- for a given power distribution $P(\lambda)$, the corresponding CIE RGB values are given by



$$R = \int_{\lambda_a}^{\lambda_b} P(\lambda) \bar{r}(\lambda) d\lambda$$

$$G = \int_{\lambda_a}^{\lambda_b} P(\lambda) \bar{g}(\lambda) d\lambda$$

$$B = \int_{\lambda_a}^{\lambda_b} P(\lambda) \bar{b}(\lambda) d\lambda$$

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41



Metamerism

- 2 complex stimuli $P_1(\lambda)$ and $P_2(\lambda)$ are *in color match* if all 3 following equations hold:

$$\int P_1(\lambda) \bar{r}(\lambda) d\lambda = \int P_2(\lambda) \bar{r}(\lambda) d\lambda \quad (R_1 = R_2)$$

$$\int P_1(\lambda) \bar{g}(\lambda) d\lambda = \int P_2(\lambda) \bar{g}(\lambda) d\lambda \quad (G_1 = G_2)$$

$$\int P_1(\lambda) \bar{b}(\lambda) d\lambda = \int P_2(\lambda) \bar{b}(\lambda) d\lambda \quad (B_1 = B_2)$$
- under certain constraints the two stimuli can have **completely different spectral distributions!**
- $P_1(\lambda), P_2(\lambda)$ = metameric stimuli, or *metamers*

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Metamerism

- contrary to what one might expect, this phenomenon occurs frequently in real life
- especially on (but not limited to) RGB monitors
- also one of the most interesting problems in the paint and pigment industry

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Printer Metamerism

- metamerism is generally not very problematic for *additive* output devices
- if the “wrong” pigments or dyes are chosen, → metamerism can significantly impair the ability of printers to produce good color output
- affects all types to some degree – matches are only possible for a given illuminant!

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Chromaticity Coordinates r, g, b

- every point in (+R,+G,+B)-space represents a valid combination of R-, G-, B-lamp intensities

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Tristimulus vs. Chromaticity

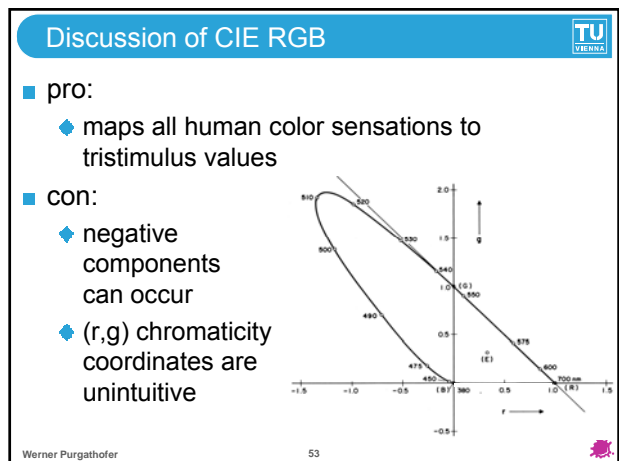
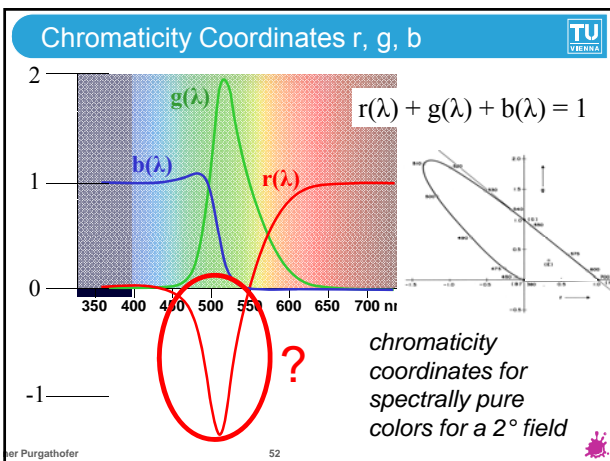
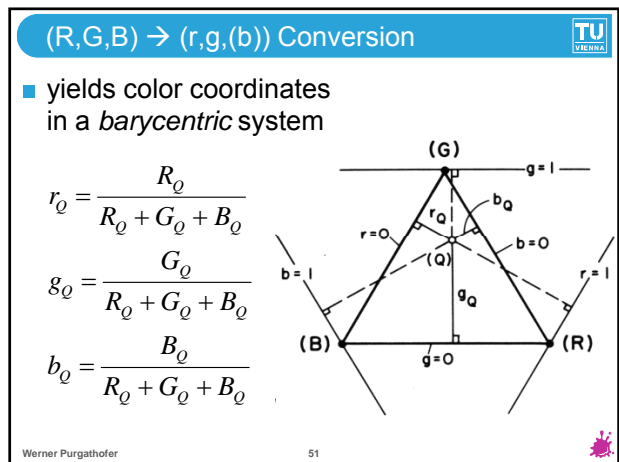
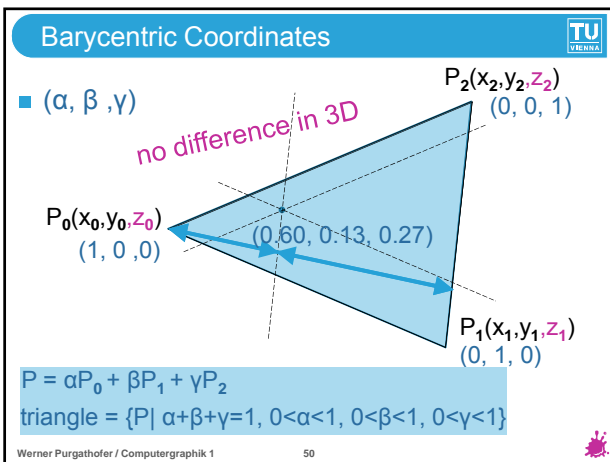
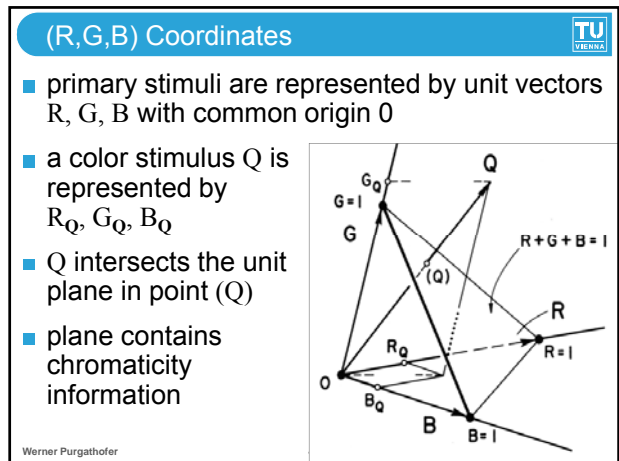
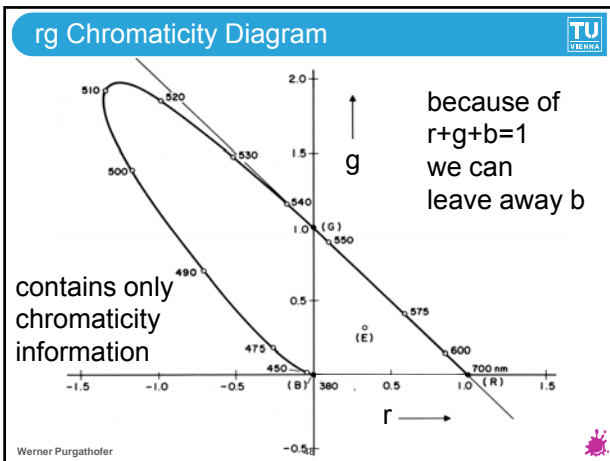
- tristimulus values are informative, but not convenient
- a two-dimensional representation of the color space would be desirable
- one possible solution is to use the intersection of a stimulus Q with the unit plane $R+G+B=1$
- shows “pure” chroma information
- intensity information is lost

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Chromaticity Coordinates r, g, b

- all points in RGB-space can be mapped to the unit plane $R+G+B=1$ → *chromaticity diagram*

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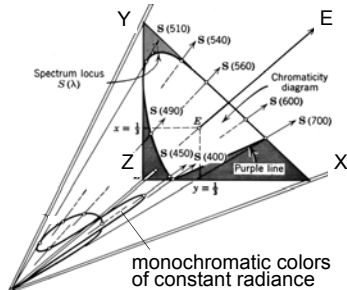
CIE XYZ



- to solve these problems, a tristimulus system derived from RGB and **based on imaginary primaries** referred to as XYZ was defined in 1931

- X, Y, Z are virtual primaries outside the diagram

- only positive (x,y,z) values inside diagram!



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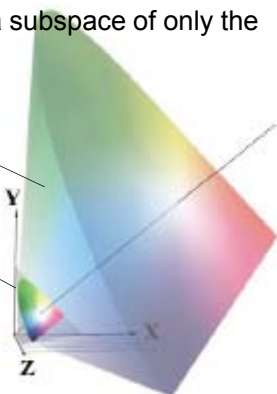
CIE XYZ Space



- valid color values form a subspace of only the first octant

- monochromatic colors are on the bounding surface of the subspace

- the projection to the unit plane $x+y+z=1$ defines the chromaticity diagram



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Transformation CIE RGB → XYZ (1931)



- projective transformation specifically designed so that $Y = V$ (luminous efficiency function V)

$$\begin{aligned} X &= 2.77 \cdot R + 1.75 \cdot G + 1.13 \cdot B \\ Y &= 1.00 \cdot R + 4.59 \cdot G + 0.06 \cdot B \\ Z &= 0.00 \cdot R + 0.06 \cdot G + 5.59 \cdot B \end{aligned}$$

- XYZ → CIE RGB: uses inverse matrix
- XYZ → any RGB matrix: is device dependent

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56

Transformation CIE RGB → XYZ



- projective transformation specifically designed so that $Y = V$ (luminous efficiency function V)

$$\begin{aligned} X &= R \cdot 0.4124 + G \cdot 0.3576 + B \cdot 0.1805 \\ Y &= R \cdot 0.2126 + G \cdot 0.7152 + B \cdot 0.0722 \\ Z &= R \cdot 0.0193 + G \cdot 0.1192 + B \cdot 0.9505 \end{aligned}$$

- XYZ → CIE RGB: uses inverse matrix
- XYZ → any RGB matrix: is device dependent

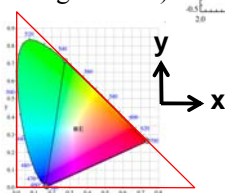
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57

Transformation CIE rg(b) → xy(z)



$$\begin{aligned} x &= \frac{(2.77r + 1.75g + 1.13b)}{(3.77r + 6.40g + 6.78b)} \\ y &= \frac{(1.00r + 4.59g + 0.06b)}{(3.77r + 6.40g + 6.78b)} \\ z &= \frac{(0.00r + 0.06g + 5.59b)}{(3.77r + 6.40g + 6.78b)} \end{aligned}$$



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RGB Matrix Example: sRGB



- sRGB: standardized set of RGB phosphors which in turn define a RGB color space

$$\begin{aligned} r_{sRGB} &= 3.240X - 0.969Y + 0.55Z \\ g_{sRGB} &= -1.537X + 1.875Y - 0.204Z \\ b_{sRGB} &= -0.498X + 0.041Y + 1.057Z \end{aligned}$$

- negative (r,g,b) values are possible → gamut mapping can be necessary!

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59

CIE RGB vs. XYZ

Stimulus	R, G, B System (Chromaticity Coordinates)			X, Y, Z System (Chromaticity Coordinates)		
	r	g	b	x	y	z
(R) 700.0 nm	1	0	0	0.73467	0.26533	0.00000
(G) 546.1 nm	0	1	0	0.27376	0.71741	0.00883
(B) 435.8 nm	0	0	1	0.16658	0.00886	0.82456
Illuminant E	↓	↓	↓	↓	↓	↓
Illuminant A	0.55255	0.32126	0.12619	0.44757	0.40745	0.14498
Illuminant B	0.36230	0.34305	0.29465	0.34842	0.35161	0.29997
Illuminant C	0.28226	0.33326	0.38448	0.31006	0.31616	0.37378

XYZ values can be obtained from xyz and V by

$$X = \frac{x}{y} V, \quad Y = V, \quad Z = \frac{z}{y} V$$

RGB vs. XYZ #1

- negative component disappears
- y(λ) is the achromatic luminance sensitivity

RGB vs. XYZ #2

- E remains constant
- all colors are now in the positive quadrant
- Y = achromatic – no color information is lost!

CIE 1964 Color Matching Functions

- 10° observer
- qualitatively similar to 2°-observer
- minor differences

CIE 1964 10° Chromaticity Diagram

- which of the 2 standard observers is used depends on the problem at hand!

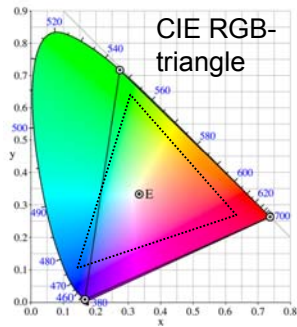
Chromaticity Diagram Properties

- intensity information is not represented
- all colors that can be realized by an additive mixture of 2 stimuli lie on a straight line between these 2 points
- all real chromaticities plot in a finite domain bounded by the spectrum locus and the purple line

CIE RGB color gamut



- all colors inside the triangle can be described with positive RGB values
- R, G, B lie on the border and span a very large triangle
- gamuts of RGB-monitors are smaller



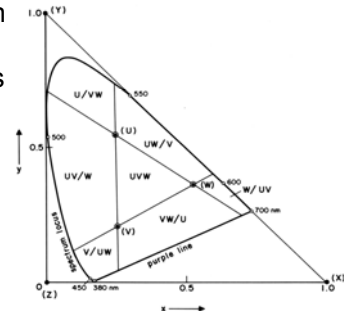
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66

Tristimulus Color Mixing



- tristimulus mixing possible with any UVW
- separation of x,y-space into areas that can be described by particular mixtures of UVW
- left of dash = adding light
- right of dash = subtracting light

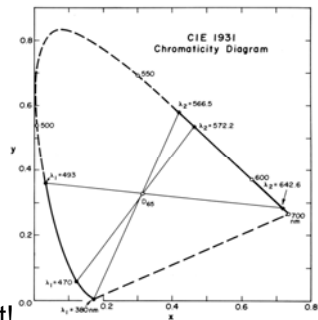


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Complementary Colors



- monochromatic complementary stimuli are only possible for colors that are not opposite the magenta line
- also dependent on the given white point!



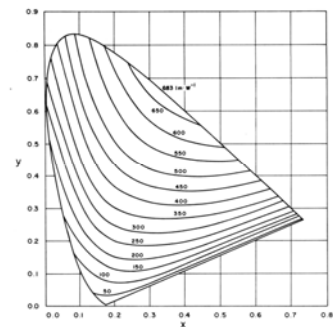
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68

Maximum Luminous Efficiency



- shape of iso-lines directly dependent on luminous efficiency function $V(\lambda)$
- highest luminous efficiency in the yellow-green area
- lowest in the blue region



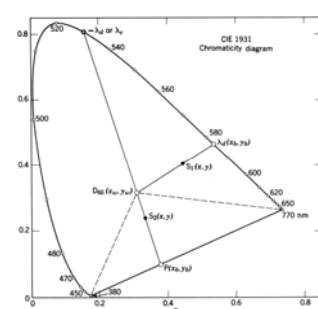
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69

Dominant Wavelength



- the dominant wavelength λ_d is the wavelength of a monochromatic stimulus that when mixed with the achromatic stimulus can match a given stimulus
- loosely corresponds to hue



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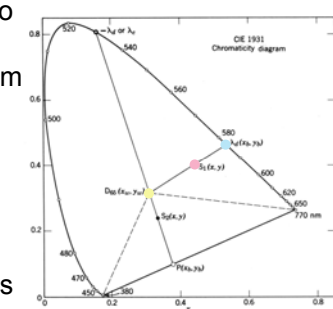
70

Excitation Purity



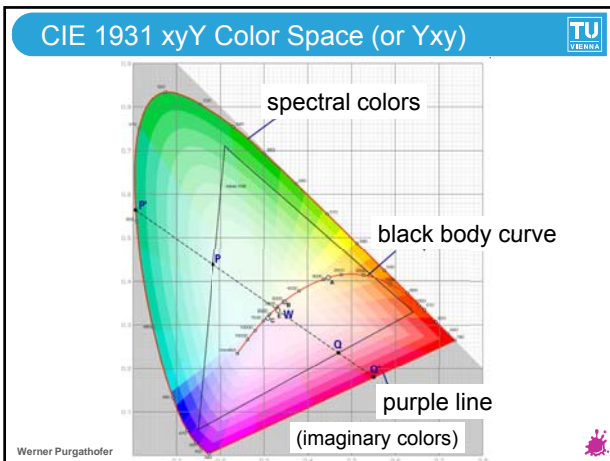
- exactly defined ratio of distances in the chromaticity diagram
- y values can be used alternatively
- loosely corresponds to saturation

$$p_e = \frac{x - x_w}{x_b - x_w}$$

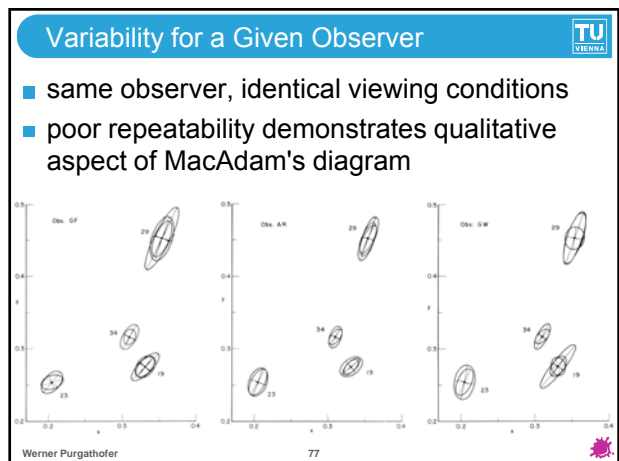
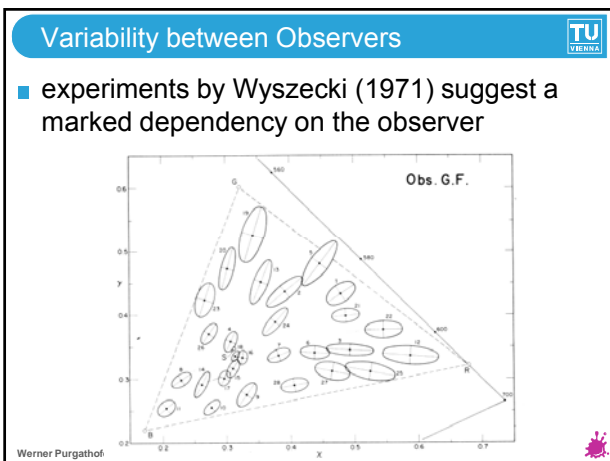
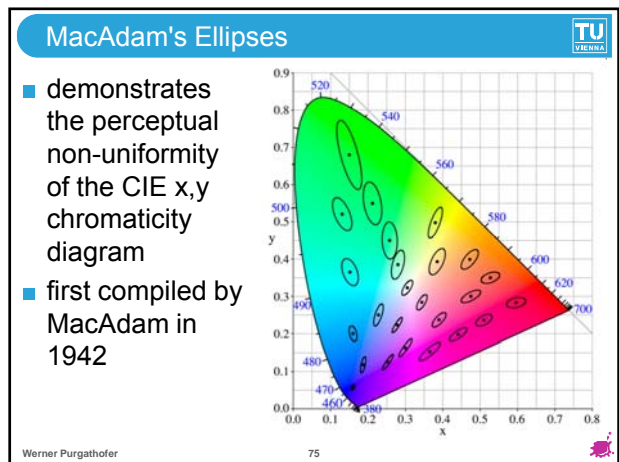
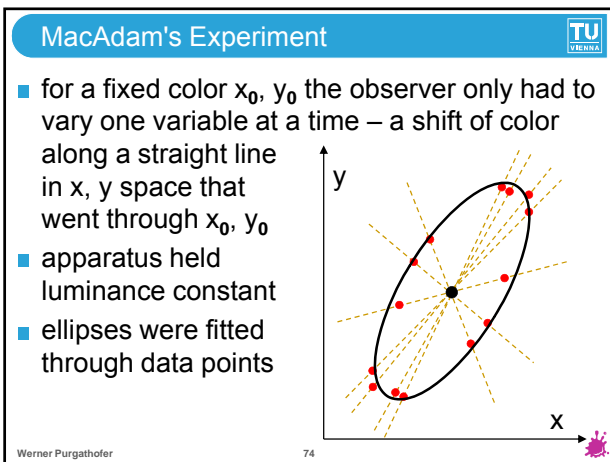


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71



- ### CIE Perceptual Issues
- desirable feature of a chromaticity diagram: geometric distance between chromaticities corresponds to perceptual difference (difference measure)
 - the just noticeably different chromaticities should be situated in a circle around a given point x, y
 - use of difference measures: color picking, design choice evaluation
- Werner Purgathofer



CIE Uniform Color Spaces



- chromaticity diagrams only show *proportions* of tristimulus values
- for comparisons of stimuli: luminance has to be taken into account
- goal: a device-independent color space in which the Euclidian distance between stimuli (incl. Y) is proportional to their difference
- 1976 the CIE proposed 2 such color spaces:
 - ◆ CIE L*u*v* (CIELUV)
 - ◆ CIE L*a*b* (CIELAB)

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78

CIE 1976 L*u*v*



- derived from earlier u', v' color space
- rectangular coordinates
- u'_n, v'_n are coordinates of reference white
- Y_n is set to 100
- originally mainly used for additive color systems, e.g. for monitors

$$L^* = 116 \sqrt[3]{\frac{Y}{Y_n}} - 16$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

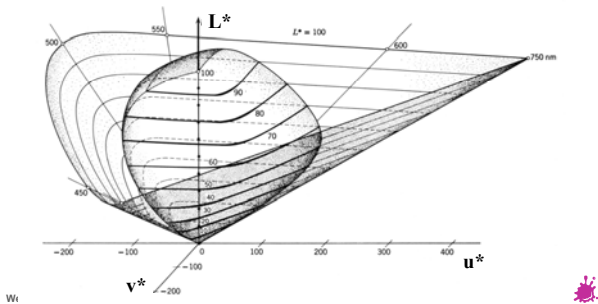
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79

CIE L*u*v* Visualization

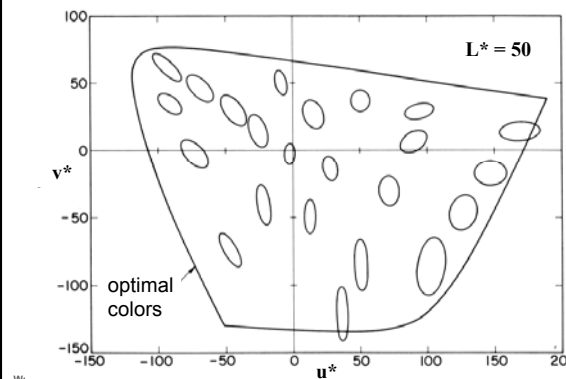


- outer surface: monochromatic colors
- inner surface: D65 / optimal object colors



W1

CIE 1976 u*v* Ellipses



W1

L*u*v* Color Difference



- Euclidian distance between sample points
- $$E_{uv}^* = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}$$
- also known as total color difference
 - for constant lightness L* the u*, v* plane is a transformed x, y chroma diagram
 - straight lines in the x, y diagram are also straight in the u*, v* diagram (color mixing!)

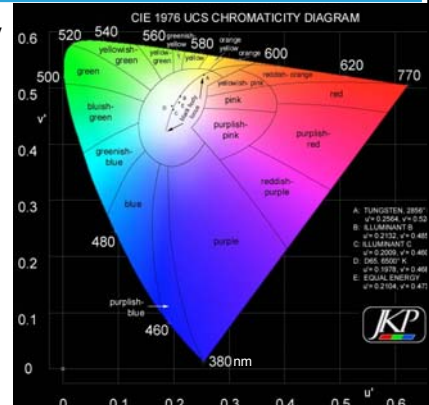
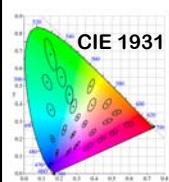
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82

CIE 1976 UCS Diagram



- chromaticity diagram for the 1976 L*u*v* space



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CIE 1976 L*a*b*



- based on Hunter's earlier Lab color space
- no associated chromaticity diagram due to cube root in a* and b*
- originally devised for use in the paint industry
- values of a*, b* are associated with complementary colors and hence intuitive

$$L^* = 116 \sqrt[3]{\frac{Y}{Y_n}} - 16$$

$$a^* = 500 \left[\sqrt[3]{\frac{X}{X_n}} - \sqrt[3]{\frac{Y}{Y_n}} \right]$$

$$b^* = 200 \left[\sqrt[3]{\frac{Y}{Y_n}} - \sqrt[3]{\frac{Z}{Z_n}} \right]$$



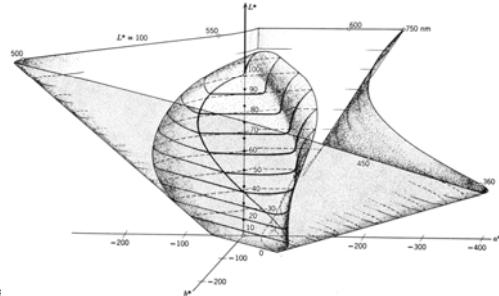
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84

CIE L*a*b* Visualization



- outer surface: monochromatic colors
- inner surface: D65 / optimal object colors

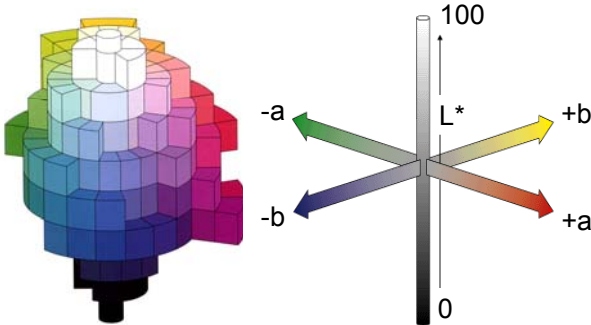


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CIE L*a*b*



- a* and b* axes correspond to red/green and blue/yellow opponent color stimuli



L*a*b* Total Color Difference



- Euclidian distance between sample points

$$E_{uv}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

- formula similar to L*u*v* distance metric
- also known as the 1976 (L*a*b*) color difference formula
- sometimes abbreviated as CIELAB
- well suited for most viewing conditions

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87

Chroma



- for L*a*b* and L*u*v* the chroma value C* of a stimulus can be determined through

$$C_{uv}^* = \sqrt{(u^*)^2 + (v^*)^2}$$

$$C_{ab}^* = \sqrt{(a^*)^2 + (b^*)^2}$$

respectively



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88

Saturation



- only in the case of L*u*v* the quantity s*_{uv} can be defined as a correlate of saturation:

$$s_{uv}^* = \frac{C_{uv}^*}{L^*}$$

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89

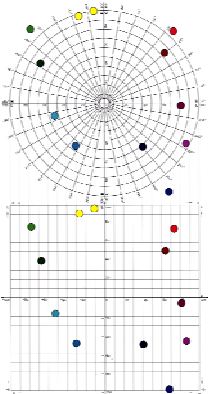
Hue Angle

■ for $L^*a^*b^*$ and $L^*u^*v^*$ the hue angle of a stimulus can be determined through

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right)$$

$$h_{uv} = \arctan\left(\frac{v^*}{u^*}\right)$$

respectively



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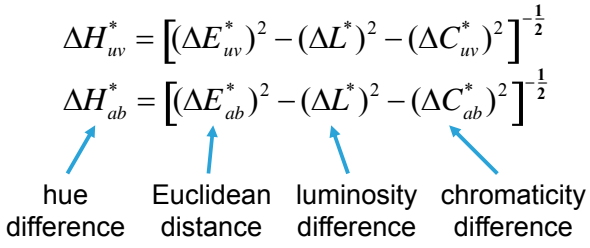
Hue Differences

■ for $L^*u^*v^*$ and $L^*a^*b^*$ the hue difference H of a pair of stimuli can be determined through

$$\Delta H_{uv}^* = \left[(\Delta E_{uv}^*)^2 - (\Delta L^*)^2 - (\Delta C_{uv}^*)^2 \right]^{-\frac{1}{2}}$$

$$\Delta H_{ab}^* = \left[(\Delta E_{ab}^*)^2 - (\Delta L^*)^2 - (\Delta C_{ab}^*)^2 \right]^{-\frac{1}{2}}$$

hue difference Euclidean distance luminosity difference chromaticity difference



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Total Color Difference

■ the **total color difference** E^* can also be defined as consisting of 3 components:

- ◆ luminosity difference ΔL^*
- ◆ chromaticity difference ΔC^*
- ◆ hue difference ΔH^*

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CIELUV vs. CIELAB Summary

- both are very similar color spaces
- the existence of 2 similar color spaces has historical and practical reasons
 - ◆ $L^*u^*v^*$ with its uniform chroma diagram is used for luminous colors
 - ◆ $L^*a^*b^*$ with its intuitive opponent coordinates is more suited for object colors
- there is no perfect color space suited for all tasks

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Color Space vs. Color Model

- **color space**
 - ◆ absolute definition of color values
 - ◆ unambiguous values for a color
 - ◆ examples: XYZ, CIE- $L^*u^*v^*$, CIE- $L^*a^*b^*$, ...
- **color model**
 - ◆ concept how to classify colors
 - ◆ values depend on reference colors
 - ◆ examples: RGB, HLS, CMYK, YCbCr, ...

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