Multimedia technologies - part 2

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Lecture content for part 2

- characteristics of the human visual system
- basic concepts of analog and digital video signal
- methods and standards for image and video compression

Literature:

Ze-Nian Li, Mark S. Drew, Jiangchuan Liu:

Fundamentals of Multimedia, Springer, 2014.

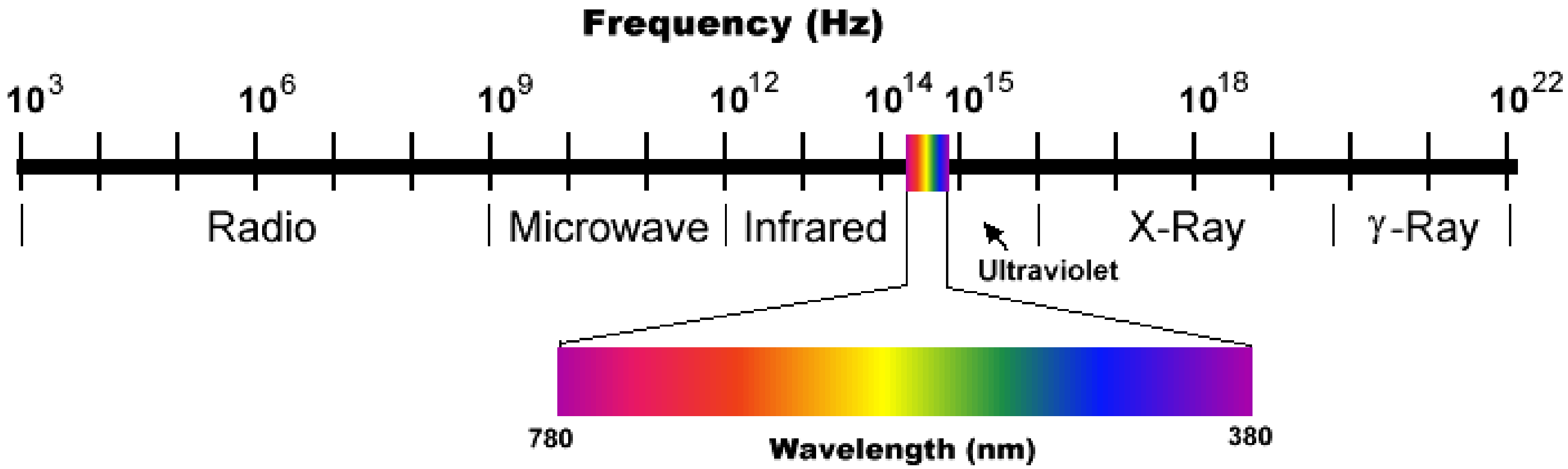
Laboratory exercises and homework

- laboratory exercises
  - two exercises - online (MS Teams)
  - exercises are performed on computers using appropriate software
  - the total number of points that can be achieved through laboratory exercises in this cycle is 5 (2 + 3)
  - homework will be given at the end of this lecture cycle
  - the total number of points that can be achieved through homework in this cycle is 5

Characteristics of the human visual system

Light

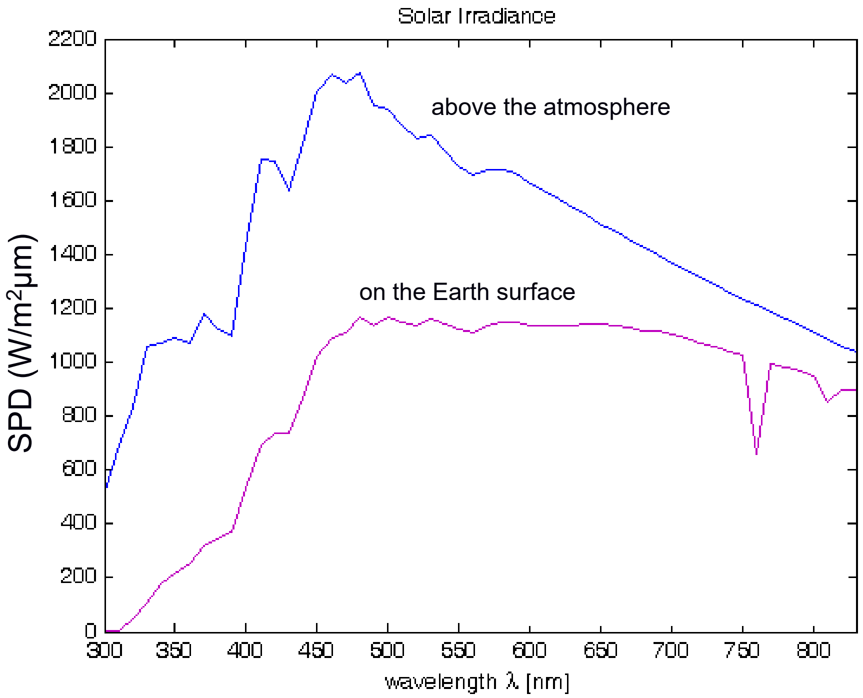
- the stimulus for vision
- visible light
  - electromagnetic (EM) radiation that can be detected by the human eye
  - wavelength range: 380 - 780 nm (frequency range between 10^{14} - 10^{15} Hz)



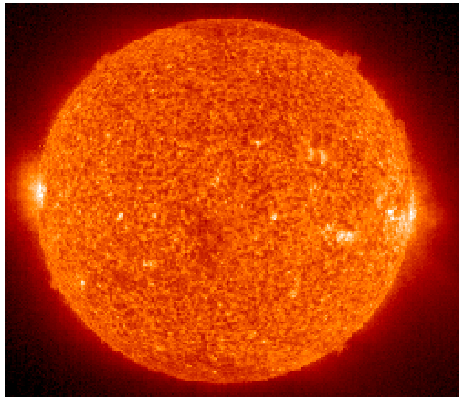
Light

- the physical quantities that determine the light source are:
  - wavelength (λ) expressed in nm
  - radiant flux or radiant power (P) expressed in W (watt)
- light sources
  - direct - create EM energy by radiation, combustion, luminescence
    - their characteristics are determined through the spectral power distribution (SPD)
    - SPD is the radiated power of light per unit wavelength
    - relative SPD is obtained by normalizing the SPD in relation to the radiated power at a wavelength of 560 nm
  - indirect - mediate in the transmission of stimuli (objects)
    - transmit, reflect or absorb light
    - the reflection properties of objects are determined by the reflectance function $\rho(\lambda)$
    - $\rho(\lambda)$ is the ratio of the power of light reflected from the surface of the object $P_r(\lambda)$ and the power of incident light $P_i(\lambda)$ in some range of wavelengths
    - incident power is the power radiated from a direct light source

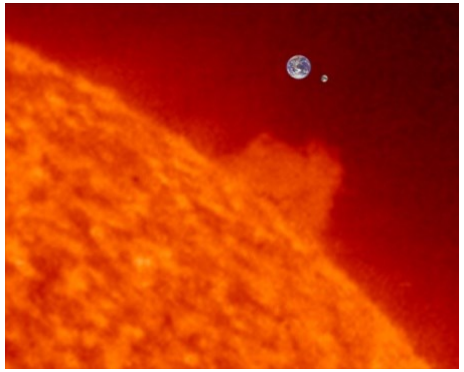
White light



Sun

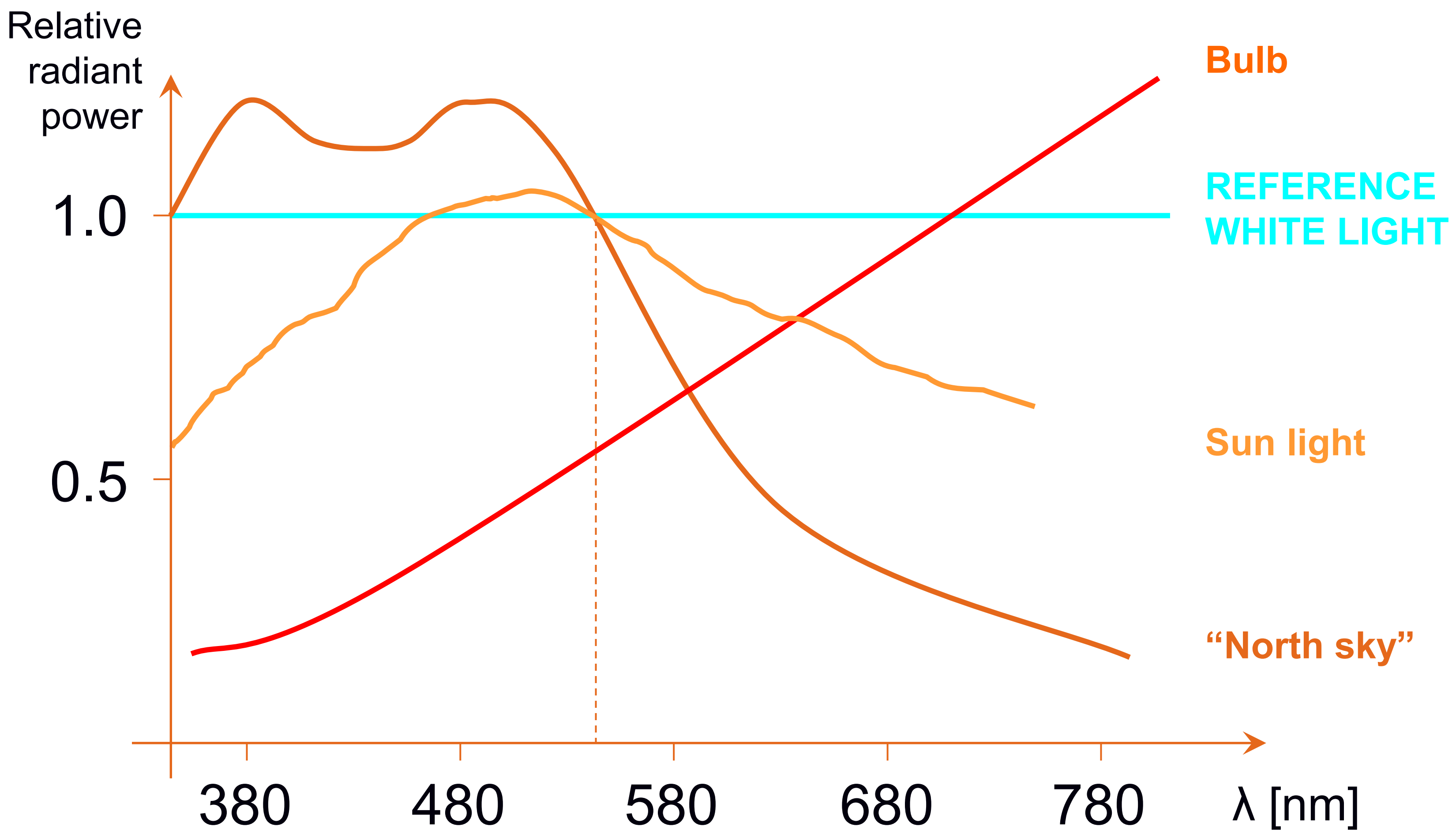


Sun, Earth, Moon



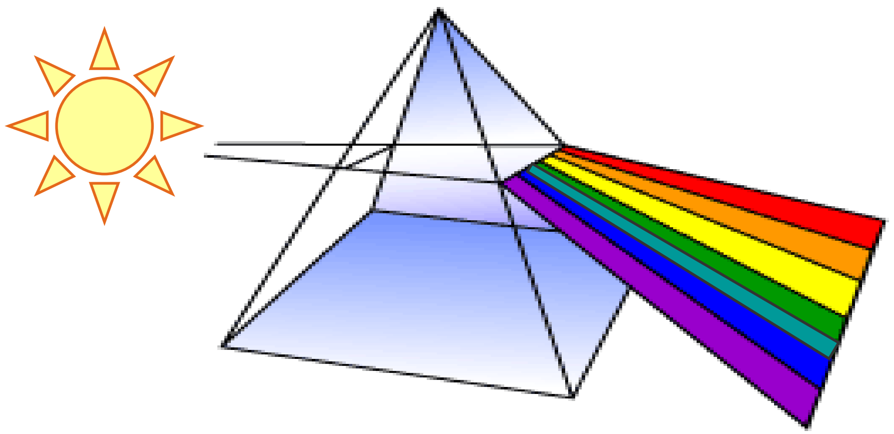
Note: SPD in this example is expressed as irradiance (radiated power per unit area of the irradiated object - W/m^2) per unit wavelength

White light


Relative radiant power
1.0
0.5
380
480
580
680
780
λ [nm]
Bulb
REFERENCE WHITE LIGHT
Sun light
"North sky"

White light

- upon passage through the prism, the white light is separated into its component colors
  - a spectrum of white light contains 7 dominant colors
  - the color of light is determined by the wavelength
- light radiation of a single wavelength in the visible spectrum, or by a relatively narrow band of wavelengths (~ 5-10 nm) results in the so-called **SPECTRAL COLORS** (monochromatic colors)
- **NON-SPECTRAL COLORS** are those that do not exist in the spectrum of white light, for example black, white, purple, brown



White light

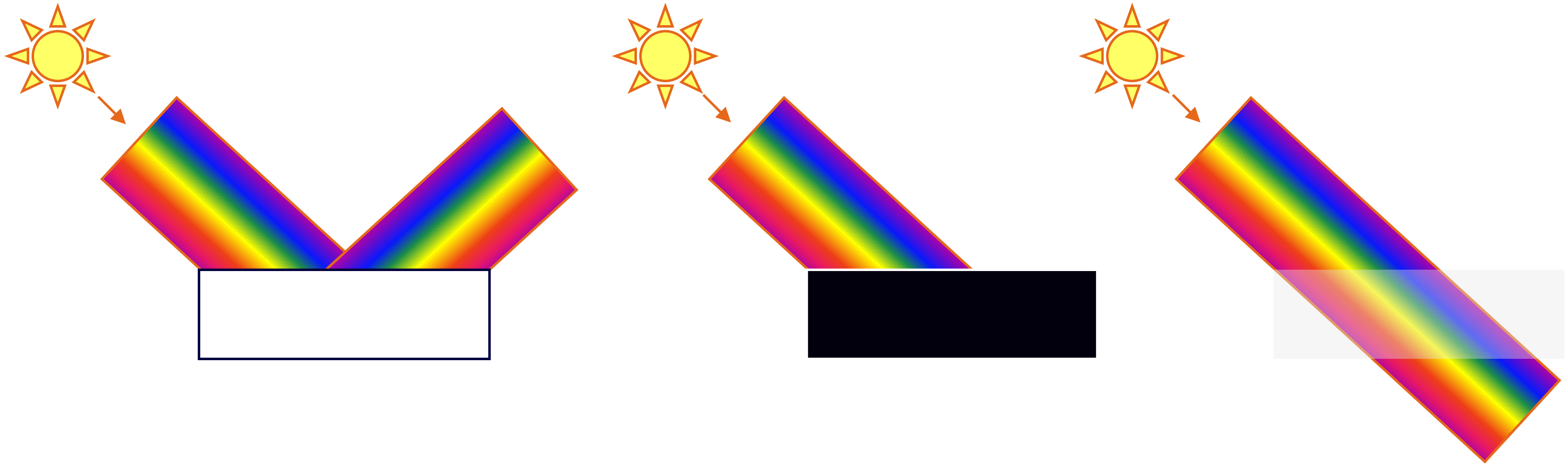
Wavelength (nm)	Color
380 - 430	violet
430 - 470	blue
470 - 500	cian
500 - 560	green
560 - 590	yelllow
590 - 605	orange
605 - 780	red

Objects

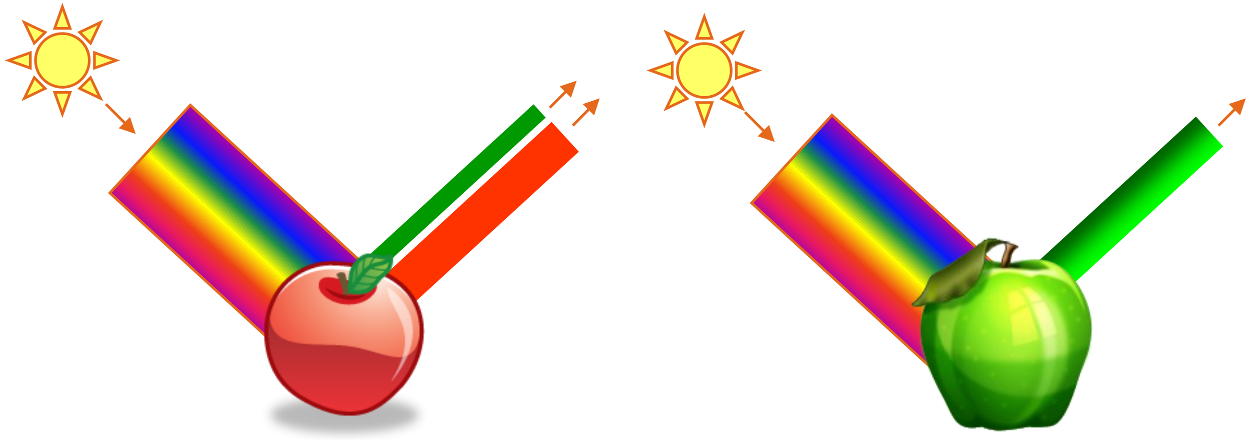
- division of objects
  - achromatic object
    - reflects, absorbs or transmits the same amount of light energy at all wavelengths
      - white object – reflects all wavelengths
      - black object – absorbs all wavelengths
      - transparent object - transmits all wavelengths
  - chromatic object
    - selectively extracts a single wavelength that is more reflected, absorbed, or transmitted than others
      - for example, red objects more reflects red light and absorbs light of other colors

Objects

- achromatic objects

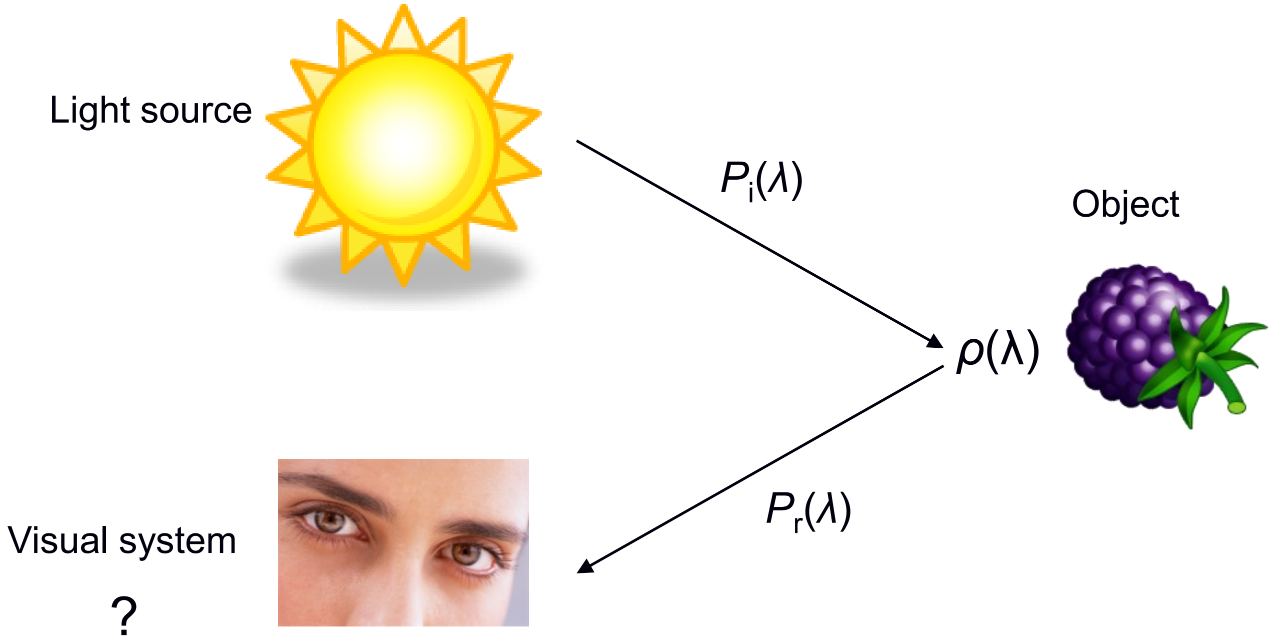


- chromatic objects



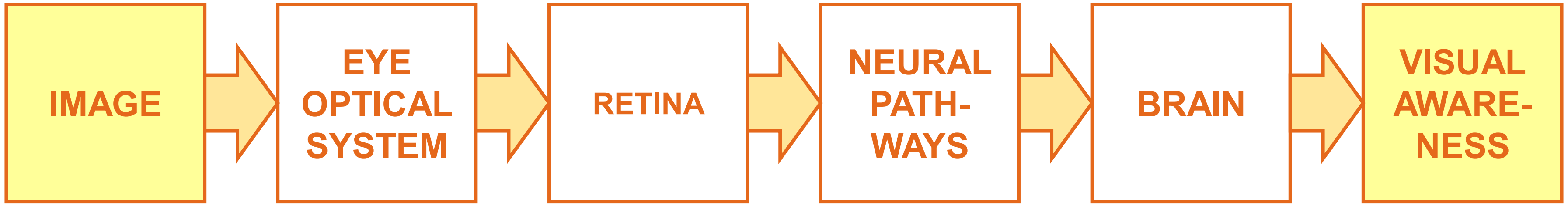
Sense of sight

- the light reflected from the object reaches the eye which contains photosensitive receptors
- the color perception of the observed object depends on the sensitivity of the receptors as a function of the wavelength
- the final image is created in the human brain

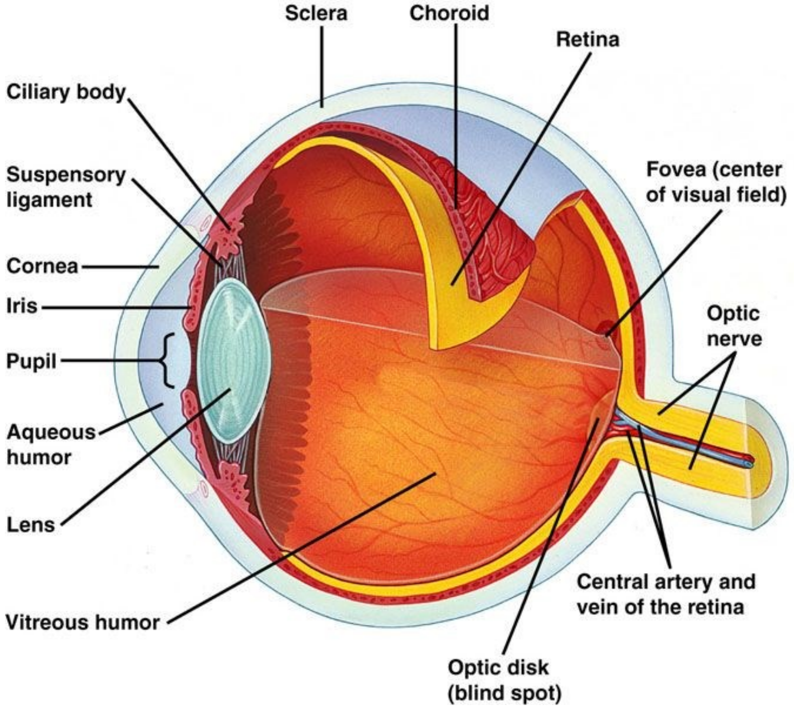


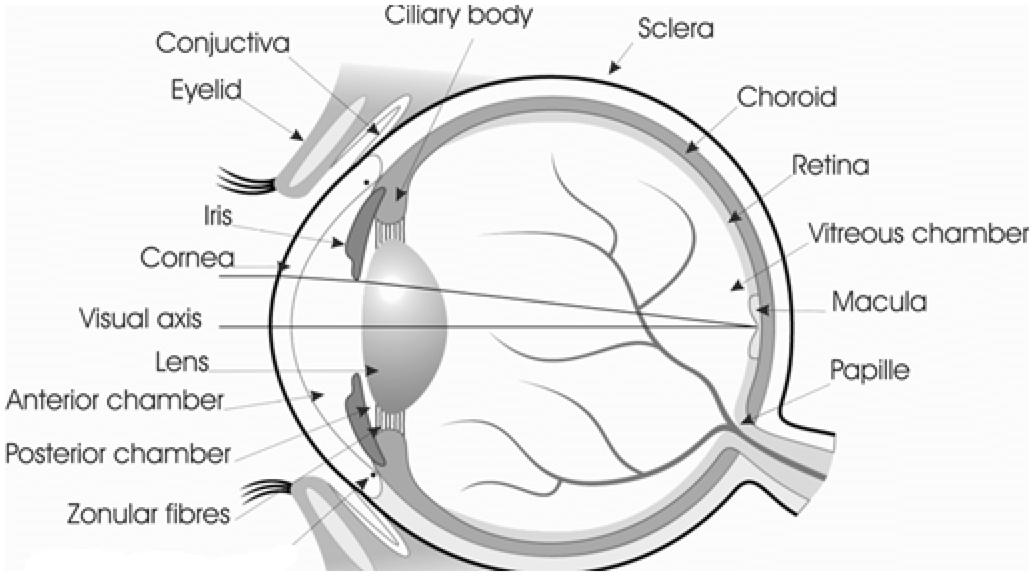
Visual perception

- elements of visual perception
  - light passes through the optical system of the eye which focuses it on the back of the eye where the retina is located
  - photosensitive receptors (rods and cones) in the retina convert light into electrical impulses
  - the retina is directly connected to the brain
  - electrical impulses created in the retina are transmitted by neural pathways to the brain where visual awareness is generated



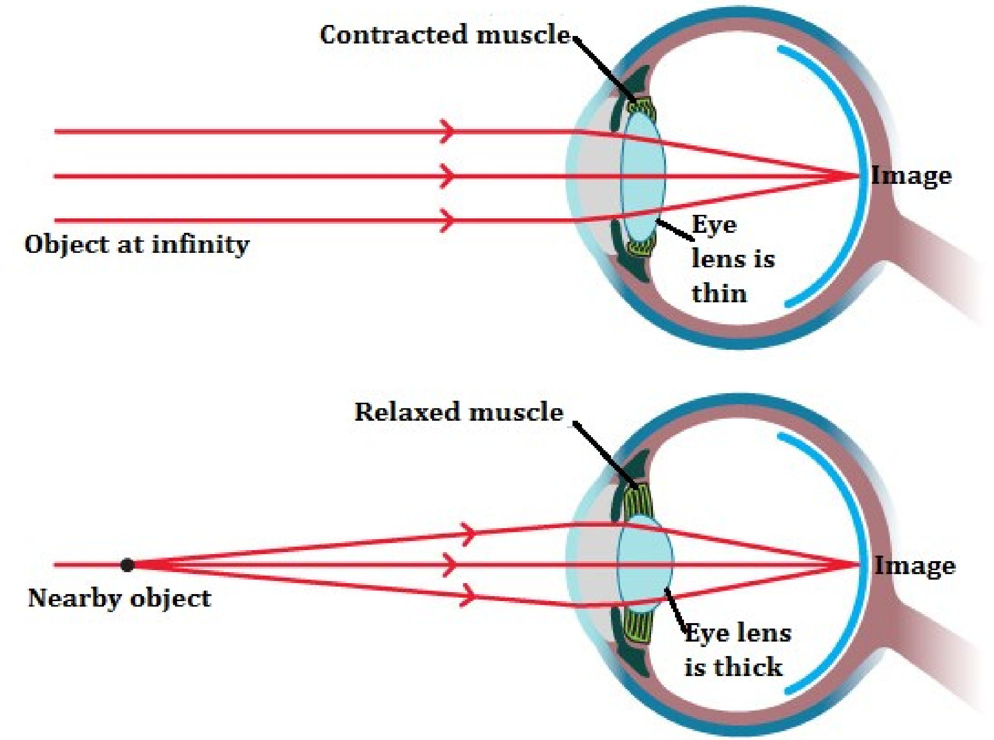
Eye anatomy


Sclera
Choroid
Retina
Ciliary body
Suspensory ligament
Cornea
Iris
Pupil
Aqueous humor
Lens
Vitreous humor
Fovea (center of visual field)
Optic nerve
Central artery and vein of the retina
Optic disk (blind spot)

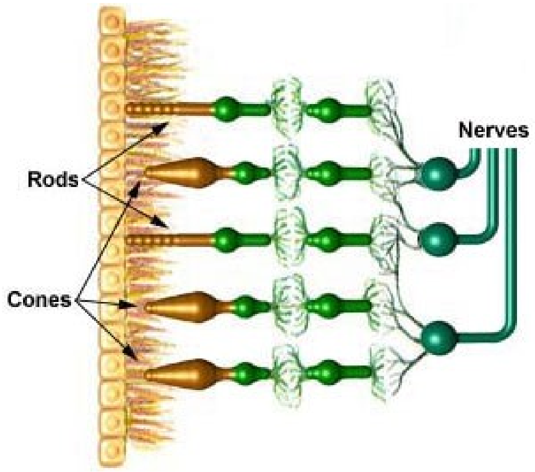

Ciliary body
Sclera
Conjuctiva
Eyelid
Choroid
Retina
Iris
Cornea
Vitreous chamber
Macula
Visual axis
Lens
Papille
Anterior chamber
Posterior chamber
Zonular fibres

Eye anatomy

- optical system of the eye
  - represented by a number of refractive mediums: cornea, moisture of the anterior and posterior chambers of the eye, lens, vitreous body
  - passing through all these refractive mediums, the rays of light focus on the retina
  - the lens has the accommodation ability
    - ability to adjust the distance of the object being viewed so that a sharp image of the observed object is always formed on the retina



Eye anatomy



- photoreceptors in retina
  - rods and cones
  - the rods are long and thin, the cones are shorter and thicker
  - contain photosensitive pigments
- cones and rods are not equally sensitive to the full range of wavelengths within the visible light spectrum
  - different types of monochromatic light excite either cones or rods
  - cones are most sensitive to wavelength of about 550 nm (yellow-green)
  - rods are most sensitive to wavelength of about 500 nm (green)
- color perception occurs when the light intensity (unit: cd) or luminance (cd/m^2) is high enough to activate the cones

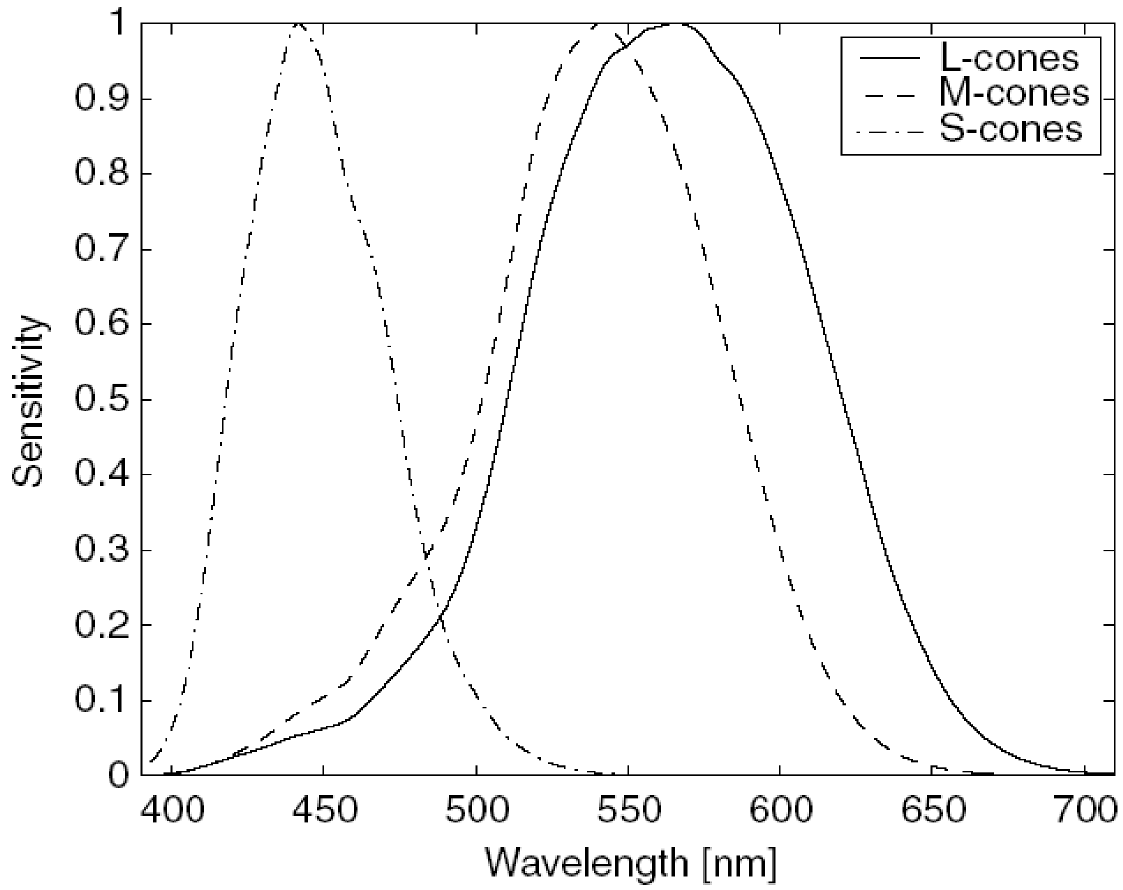
Eye anatomy

- rods
  - sensitive to light at low luminance levels below 1cd/m^2 ("night" viewing or scotopic vision)
  - sensitive only to changes in luminance and not sensitive to changes in color
  - light stimuli that excite only rods are perceived as different shades of gray
- cones
  - contribute to the sensation and differentiation of colors
  - become active at higher luminance levels
  - at luminance levels between 1cd/m^2 and 100 cd/m^2 both rods and cones are active (photopic vision)
  - at luminance levels above 100 cd/m^2 the rods become saturated and only the cones are active

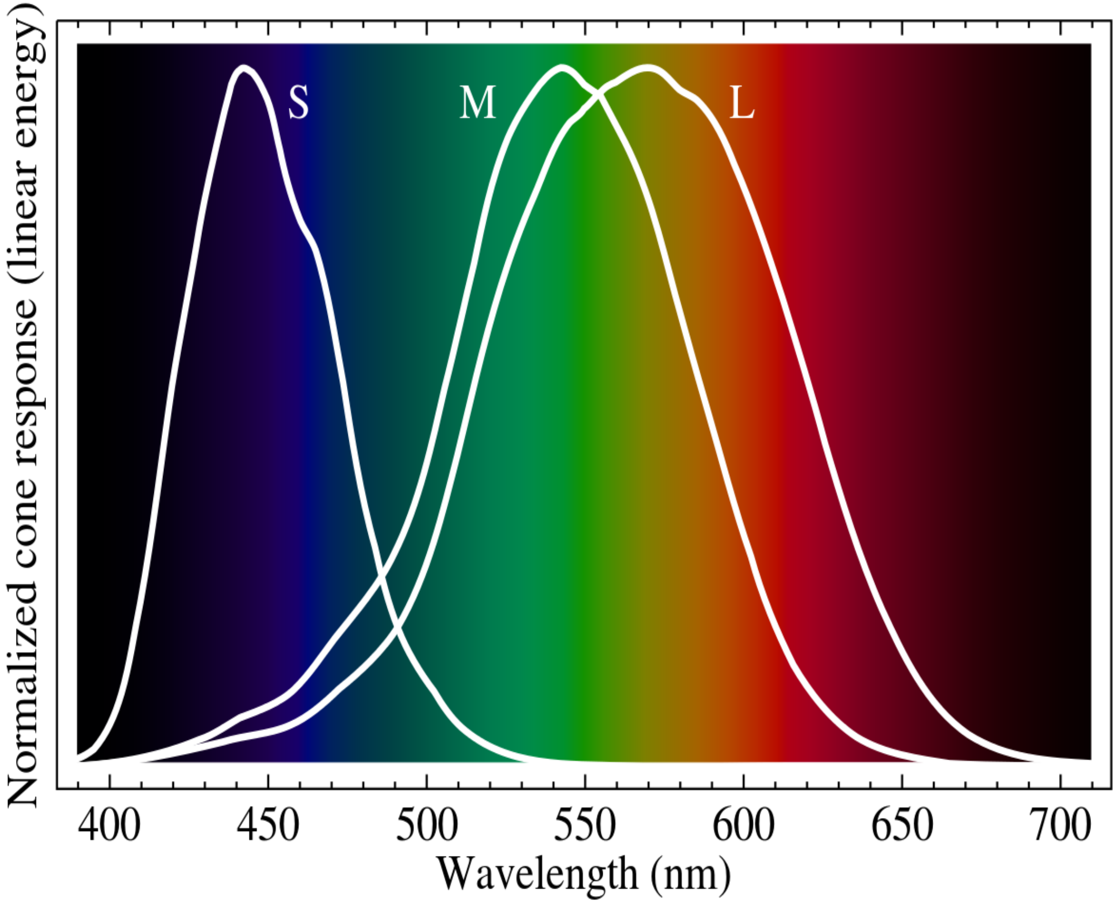
Eye anatomy

- the retina of each eye contains approximately
  - 100 million rods
  - 5 - 7 million cones
- the human visual system is more sensitive to changes in luminance than to changes in color
- the cones are labeled according to the ordering of the wavelengths of the peaks of their spectral sensitivities
  - blue cones (S-cones)
  - green cones (M-cones)
  - red cones (L-cones)
  - peak sensitivities occur around 440 nm, 540 nm, and 570 nm
  - the majority of cones are green and red sensitive
  - less than 10% of cones are blue sensitive

Eye anatomy



L-cones
M-cones
S-cones
Sensitivity
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
400
450
500
550
600
650
700
Wavelength [nm]

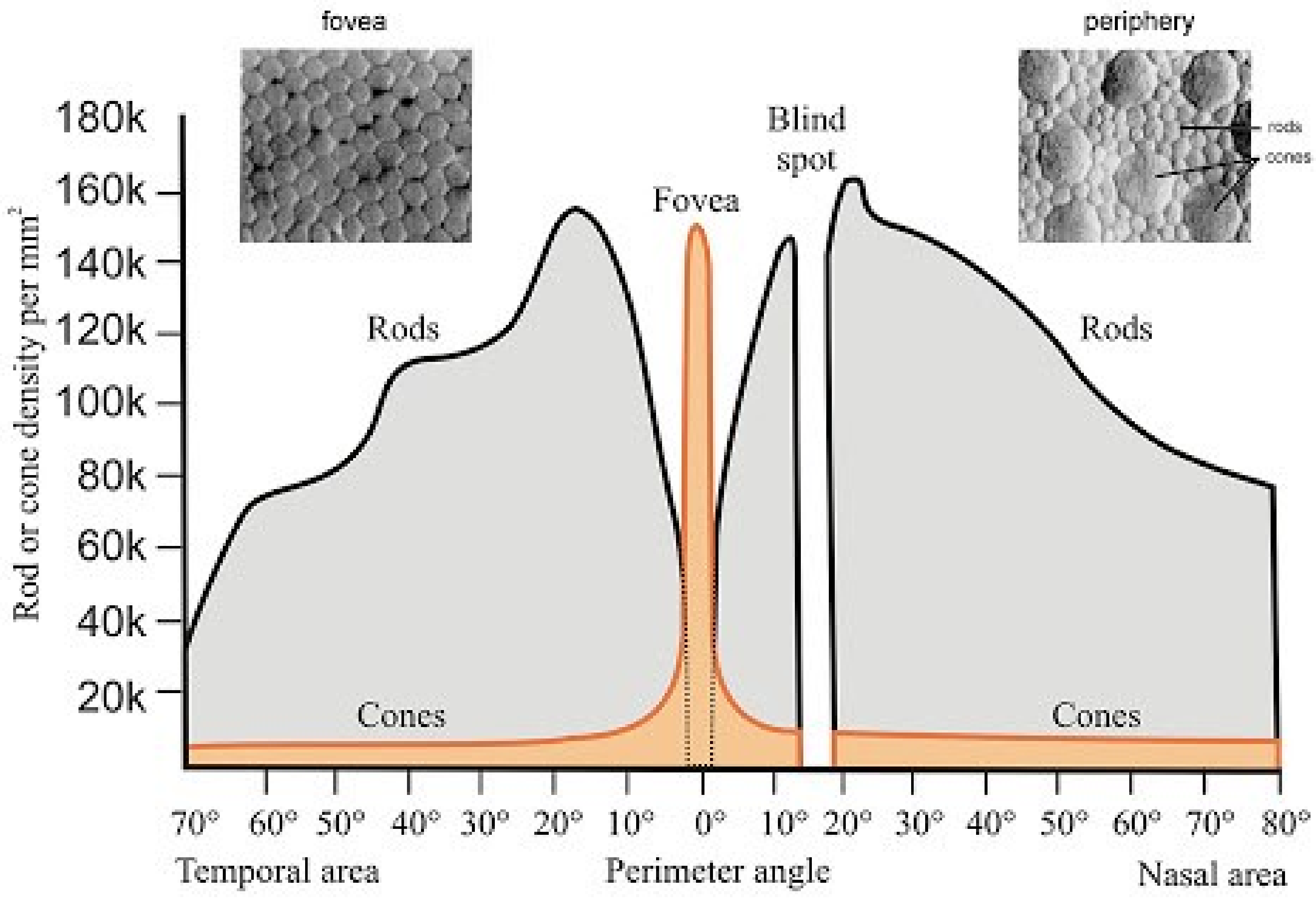


S
M
L
Normalized cone response (linear energy)
400
450
500
550
600
650
700
Wavelength (nm)

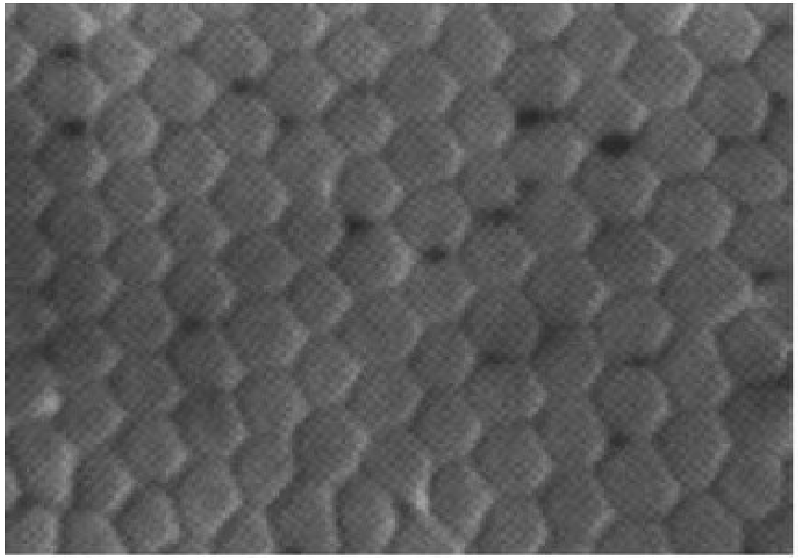
Eye anatomy

- the density of the cones and rods changes over the retina
  - at the center of the retina is a small depression from 2.5 to 3 mm in diameter known as the yellow spot or macula
    - macula has the highest concentration of cones
  - in the center of the macula is a fovea (diameter 0.3 mm, occupies 2^{o} angle of view) which contains <u>only cones</u>
    - the cones in the fovea have hexagonal shape and diameter of 1-3 μm
    - the size of the cones outside the fovea increases (diameter 5-10 μm) and the space between them is filled with rods
  - rods dominate outside the fovea (the diameter of the rods is 1-5 μm)
  - the blind spot is the place where the optic nerve connects to the eye
    - there are no photoreceptor cells to detect light in this area
- the size and arrangement of the photoreceptors determine the maximum spatial resolution of the human visual system

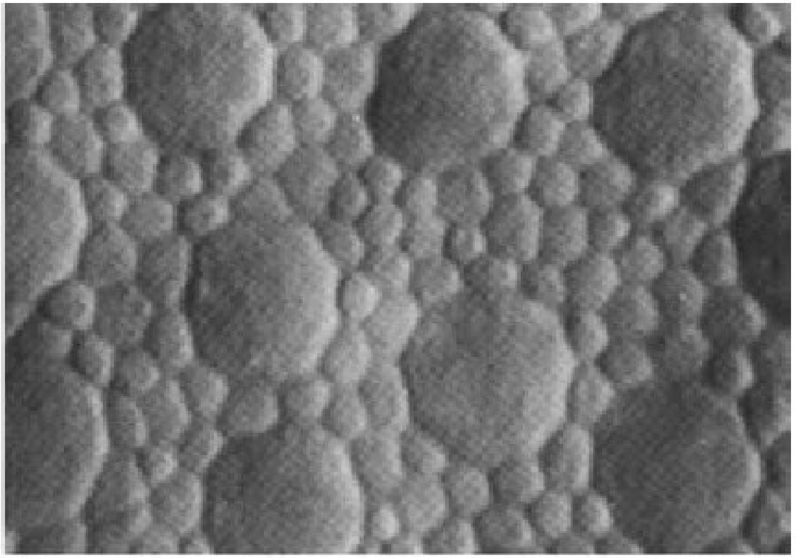
Eye anatomy


fovea
periphery
rods
cones
180k
160k
140k
120k
100k
80k
60k
40k
20k
Rod or cone density per mm²
Blind spot
Fovea
Rods
Rods
Cones
Cones
70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80°
Temporal area
Perimeter angle
Nasal area

Eye anatomy

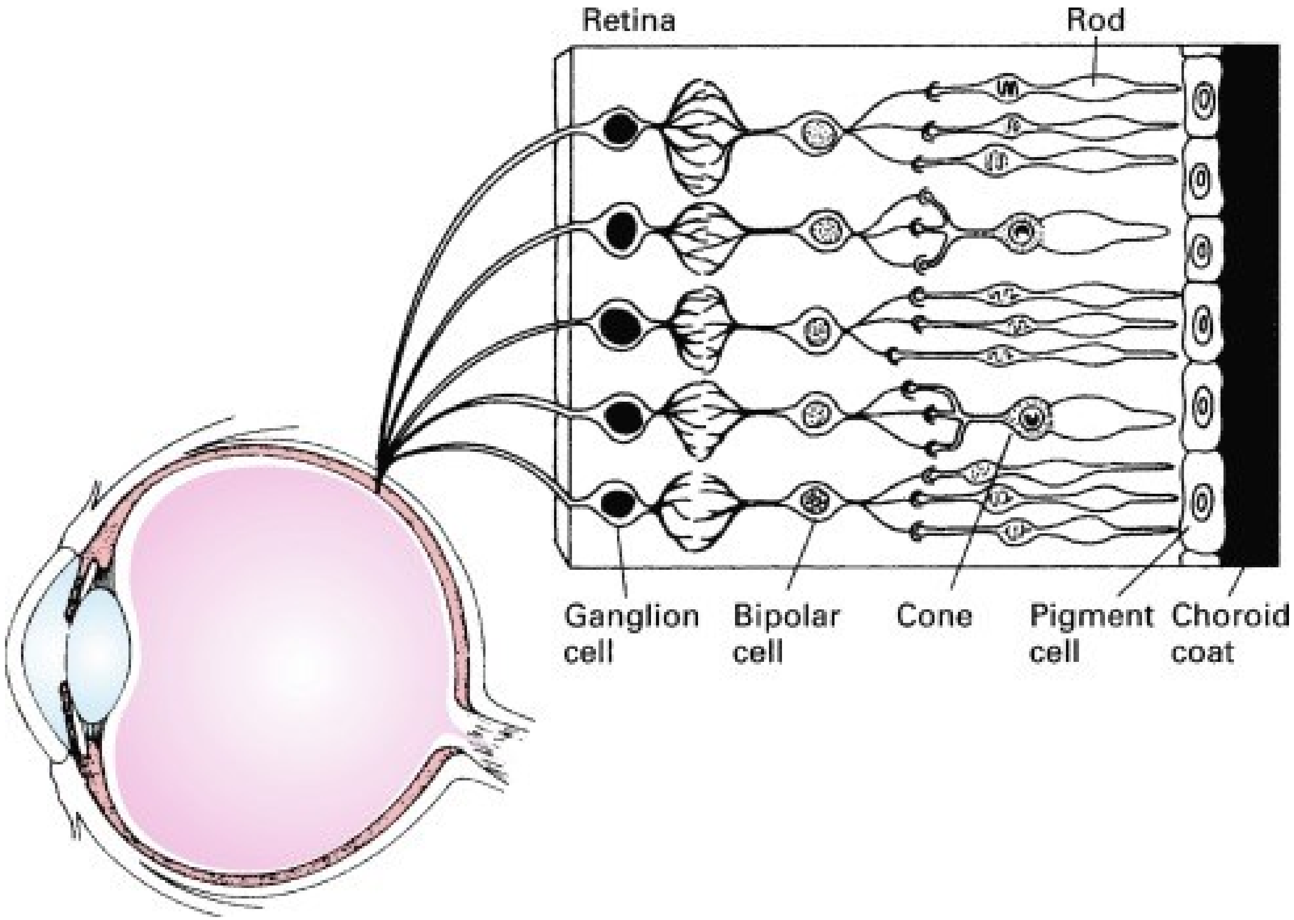


(a) Fovea



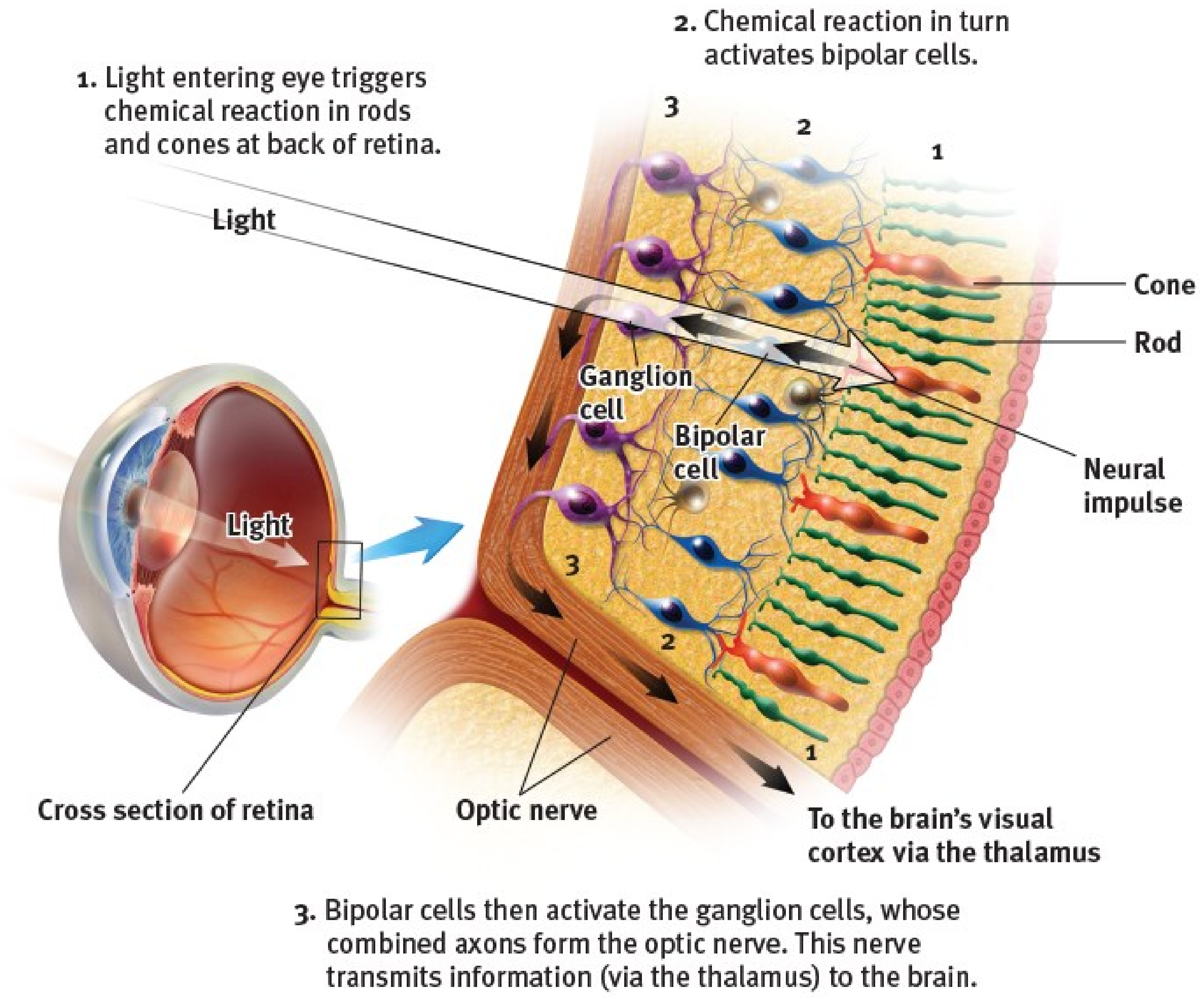
(b) Periphery

Eye anatomy



Retina
Rod
Ganglion cell
Bipolar cell
Cone
Pigment cell
Choroid coat

Eye anatomy


1. Light entering eye triggers chemical reaction in rods and cones at back of retina.
2. Chemical reaction in turn activates bipolar cells.
3
2
1
Light
Cone
Rod
Ganglion cell
Bipolar cell
Neural impulse
Light
3
2
1
Cross section of retina
Optic nerve
To the brain's visual cortex via the thalamus
3. Bipolar cells then activate the ganglion cells, whose combined axons form the optic nerve. This nerve transmits information (via the thalamus) to the brain.

Eye anatomy

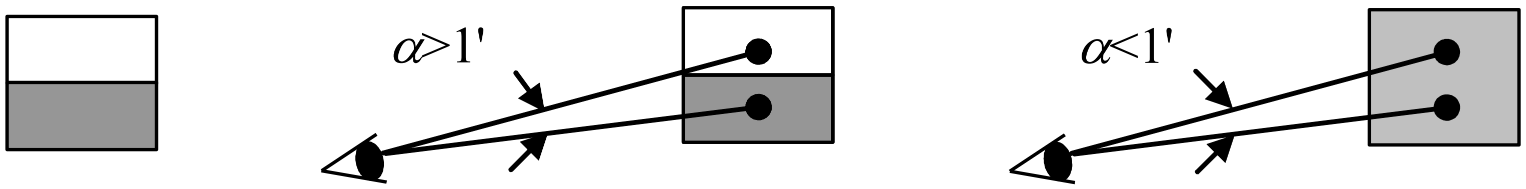
- the pigment cells build the outer layer of the retina where the ends of the rods and cones lie
  - absorbs light that is not absorbed in photoreceptors
- ganglion and bipolar cells participate in the transmission of electrical signals from cones and rods to the brain
  - the optic nerve is a set of extensions of ganglion cells that lead to the brain
  - there are approximately 800 000 nerve fibers within the optic nerve
  - as the total number of rods and cones is over 100 million, each photoreceptor does not have its own path to the higher center

Visual acuity

- the human eye has a limitation in the ability to discern small details in an image determined by visual acuity
  - visual acuity is ability of the eye to discriminate two adjacent points as separate
  - it is determined by visual angle
  - the minimum angle at which two points are just perceived as separate is the minimum angle of resolution
  - for the eye to make this discrimination, the minimum separation of the two points should be one arc minute (1’ = 1/60th of a degree)

Visual acuity

- minimum angle of resolution (*minimum separable*)
  - the angle at which two points are just perceived as separate
  - the human eye can see separately two adjacent image details (points or lines) if the angle α at which the eye sees them is equal to or greater than 1 arc minute
  - if the angle at which the eye perceives the two details of the image is less than 1 arc minute, the eye cannot discern the two details as separate details and perceives them as a single area

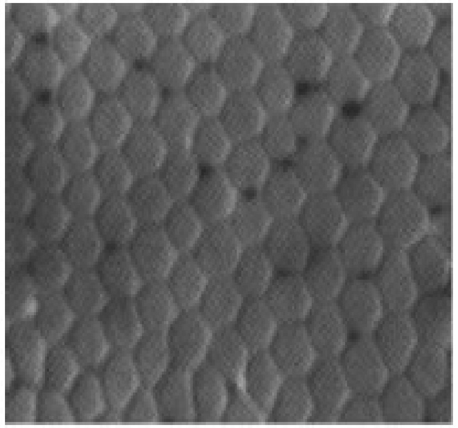


Visual acuity

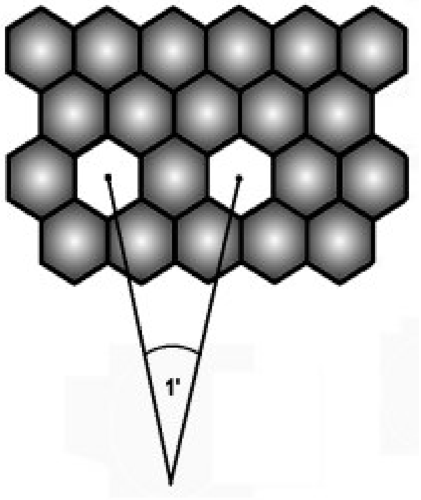
- minimum angle of resolution is determined by the size of the cones in fovea
  - cones creates mosaic in retina
  - to perceive two points as separate each point must excite at least one cone between which one unexcited cone should remain
  - visual acuity is significantly affected by viewing distance and illuminations
    - changing the distance changes the angle at which the eye perceives two adjacent details in the image
    - at high luminant levels all cones are active
    - at low luminance levels only the most sensitive cones are active, which tends to reduce visual acuity

Visual acuity

Cones in fovea

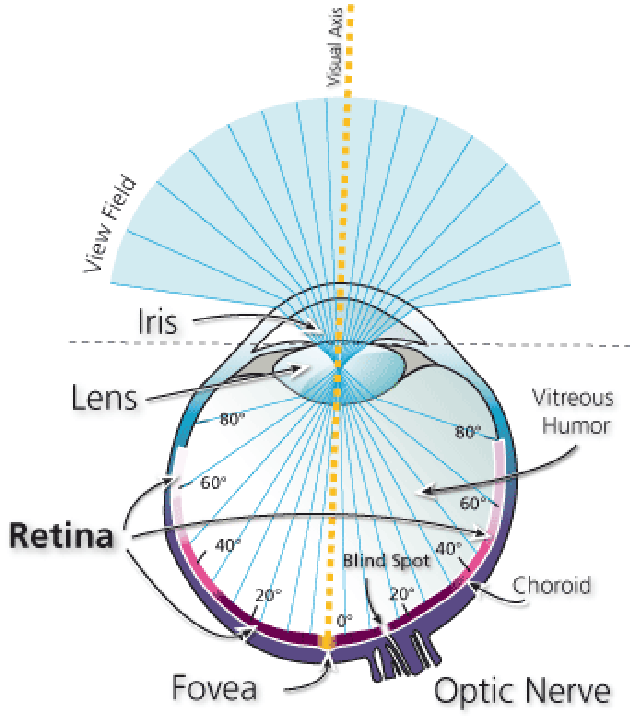


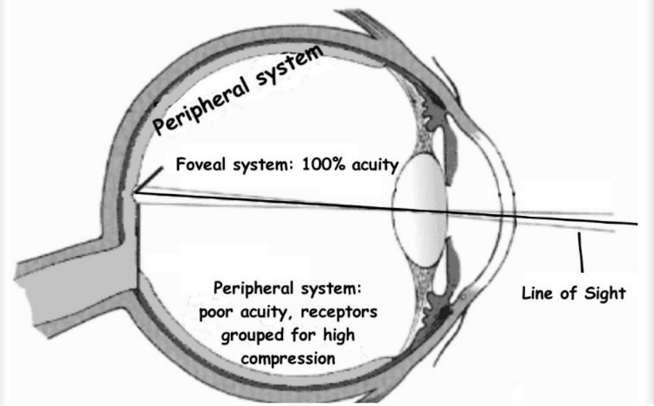
Minimum angle of resolution



Central and peripheral vision

- the number and size of cones and rods changes over the surface of the retina
  - when we focus on a particular point or area, the visual system samples that area with the highest spatial resolution, while as we move away from the center of gaze, the resolution decreases rapidly
- foveal (central) vision
  - high-resolution vision near the point of fixation to which the observer directs his gaze
  - detail perception, object identification, color perception
- peripheral vision
  - low-resolution vision outside the point of fixation (away from the center of gaze)
  - shapes perception, shades of gray perception, movement detection





Peripheral system for general holistic impression of the situation.
Foveal system for high quality details.

Central and peripheral vision

- the right image shows a simulation of vision mode when the focus of the observer's attention is on the lower part of the image

Visual perception process

- psychophysical and psychological rules of the of visual sensing are specific to each person
  - much of what we have learned about how vision works has come from <u>psychophysical experiments</u>
    - researchers present people with a visual display and ask them whether or not they can see a stimulus or resolve one visible stimulus from another
    - the results of experiments are averaged and describe hypothetical standard observer
- <u>standard observer</u>
  - a hypothetical typical human visual system that is described in terms of equations relating its quantitative visual responses to measurable physical statistics of light stimuli
  - the equations that define the standard observer are based on averages of laboratory measurements of the visual responses of real human subjects to specific light stimuli under controlled viewing conditions

Visual perception process

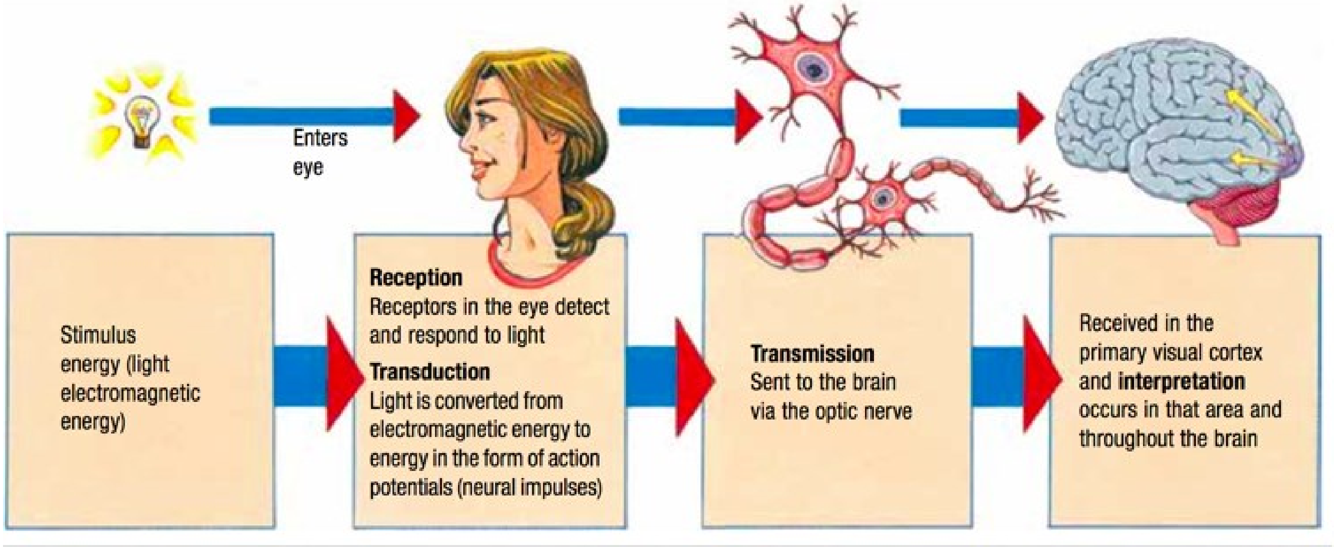
- visual sensing and perception is based on

  ① physical characterstics of light stimuli

  ② physiological laws
    - electrochemical activity in nerves

  ③ psychophysical laws
    - relationship between physical characterstics and subjective experience

  ④ psychological laws
    - awareness of what is seen

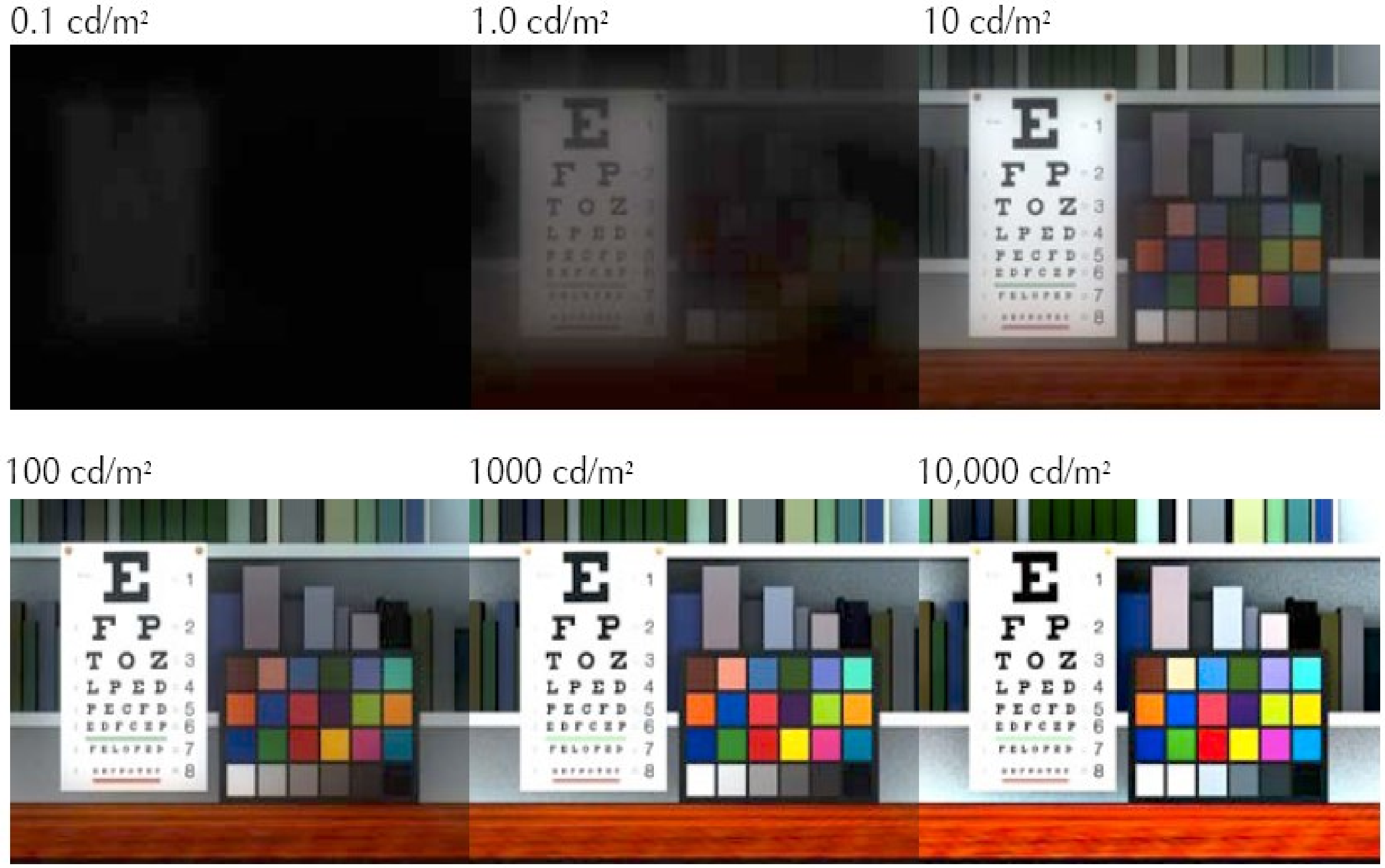


Visual perception process

- object identification under normal viewing conditions is performed using SHAPE and COLOR
  - depend on the characteristics of the light illuminating the object
    - in daylight the colors are transmitted in the diversity of shades
    - in the dark the eye distinguishes shapes but does not distinguish colors
  - color is not a property of the physical world, but a psychic experience triggered by a physical cause
    - that depends on physiological processes in the body and various psychological factors
    - in technology and real life, we talk about the color of light and the color of objects, although it is the RESPONSE that arises in human consciousness
      - the same object is experienced in different colors depending on the lighting that falls on it
      - light of the same spectral composition causes different color experiences for different people

Visual perception process

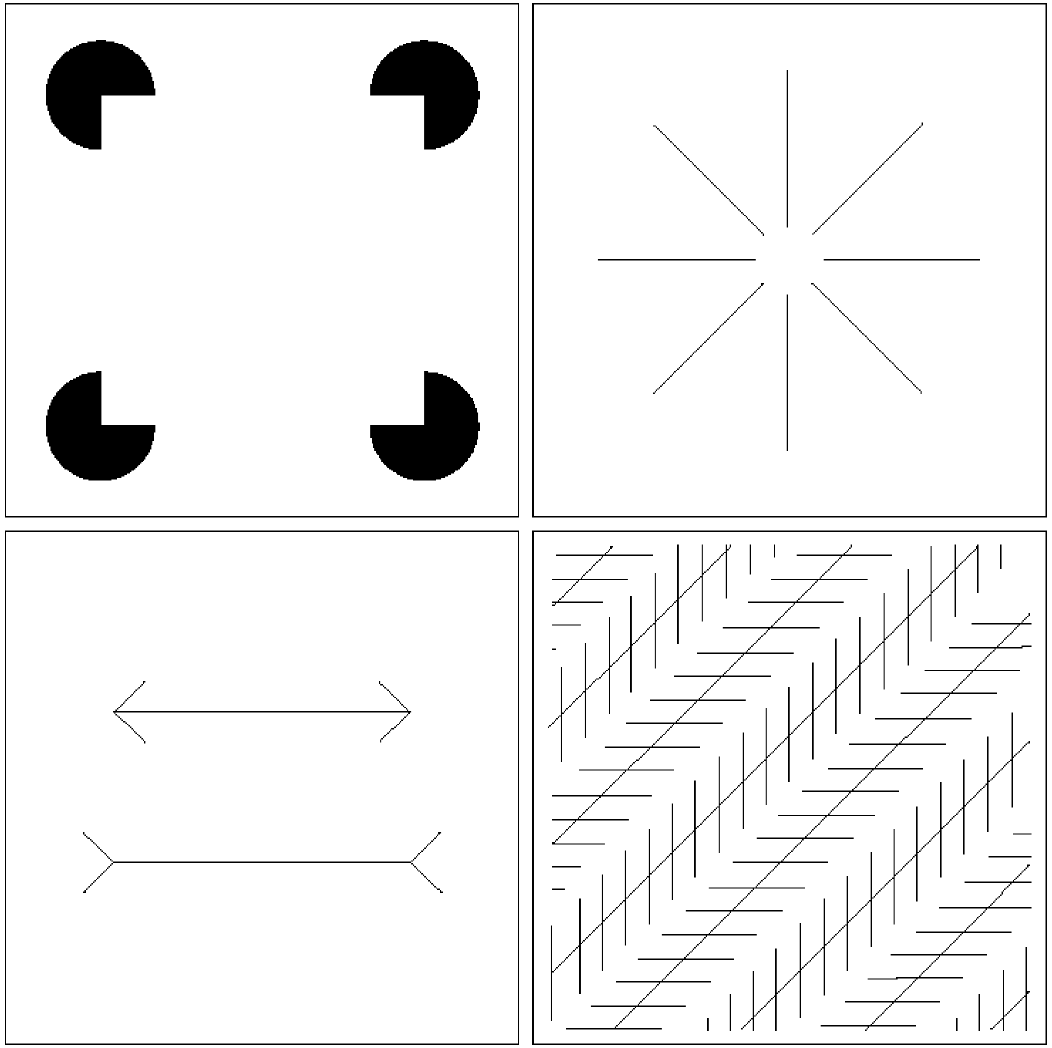
- color depends on the light illuminating the object



Visual perception process

- optical illusions
  - we perceive colors, shapes and moves that do not exist in real world

- more on optical illusions:
  https://michaelbach.de/ot/



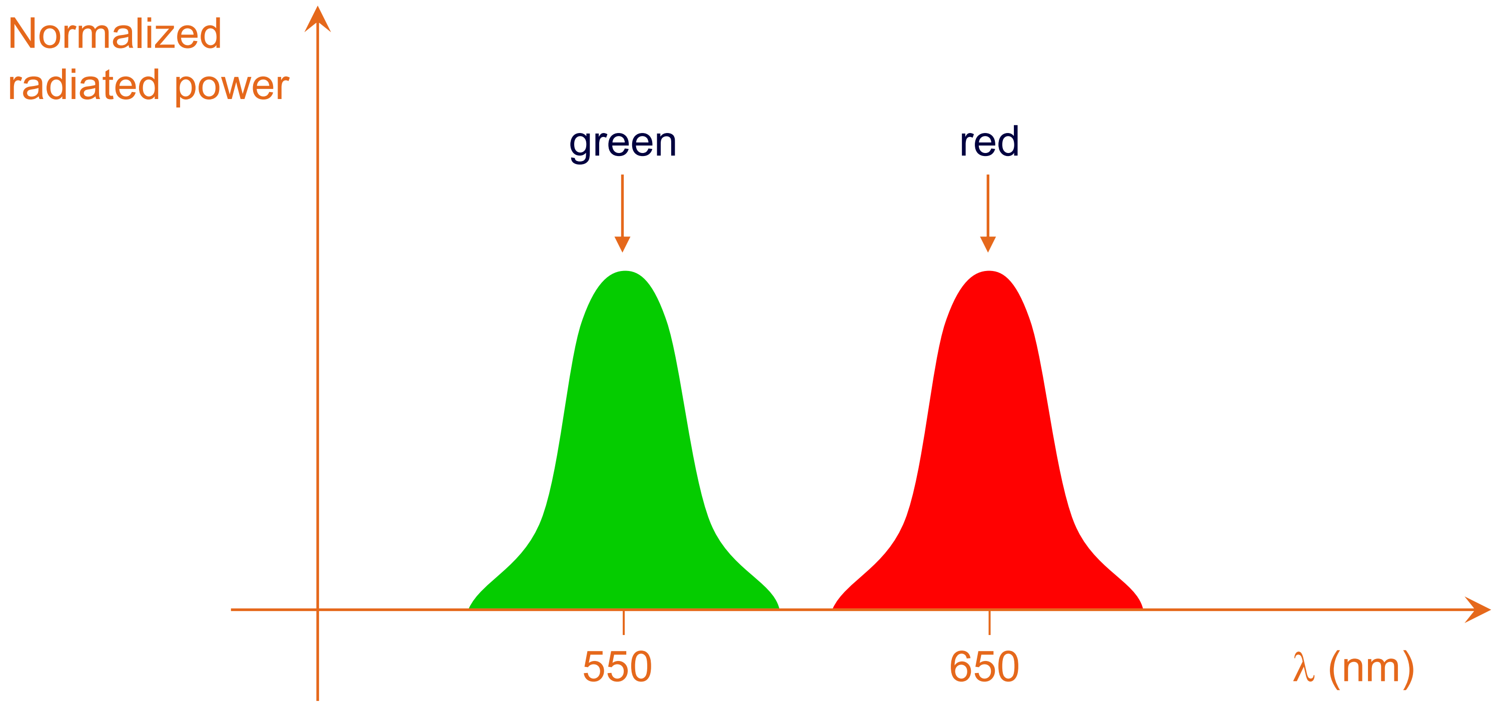
Characteristics of color

- color as subjective experience

psychophysical variable		psychological variable
dominant wavelength	⟷	hue
purity	⟷	saturation
luminance	⟷	brightness

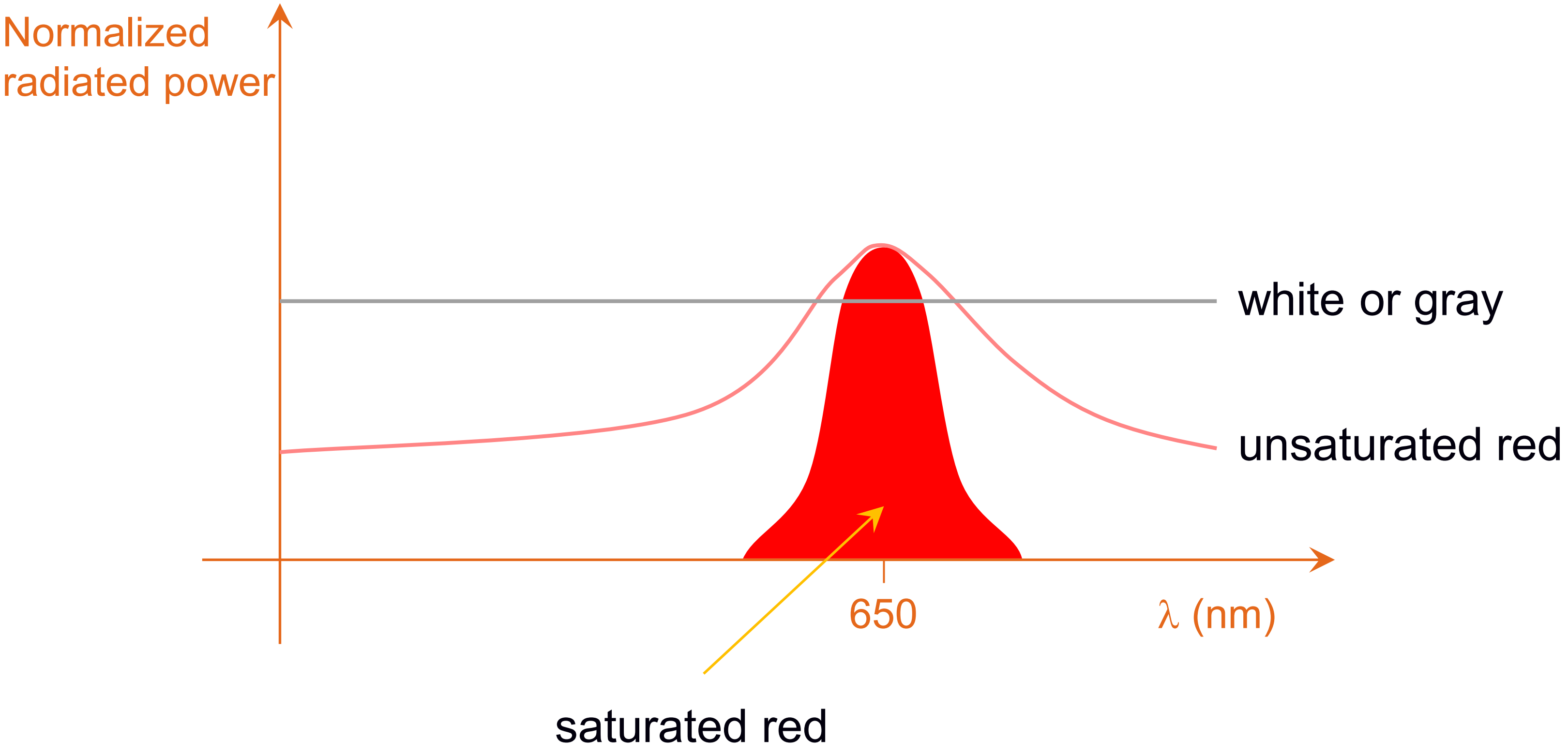
Characteristics of color

① dominant wavelength



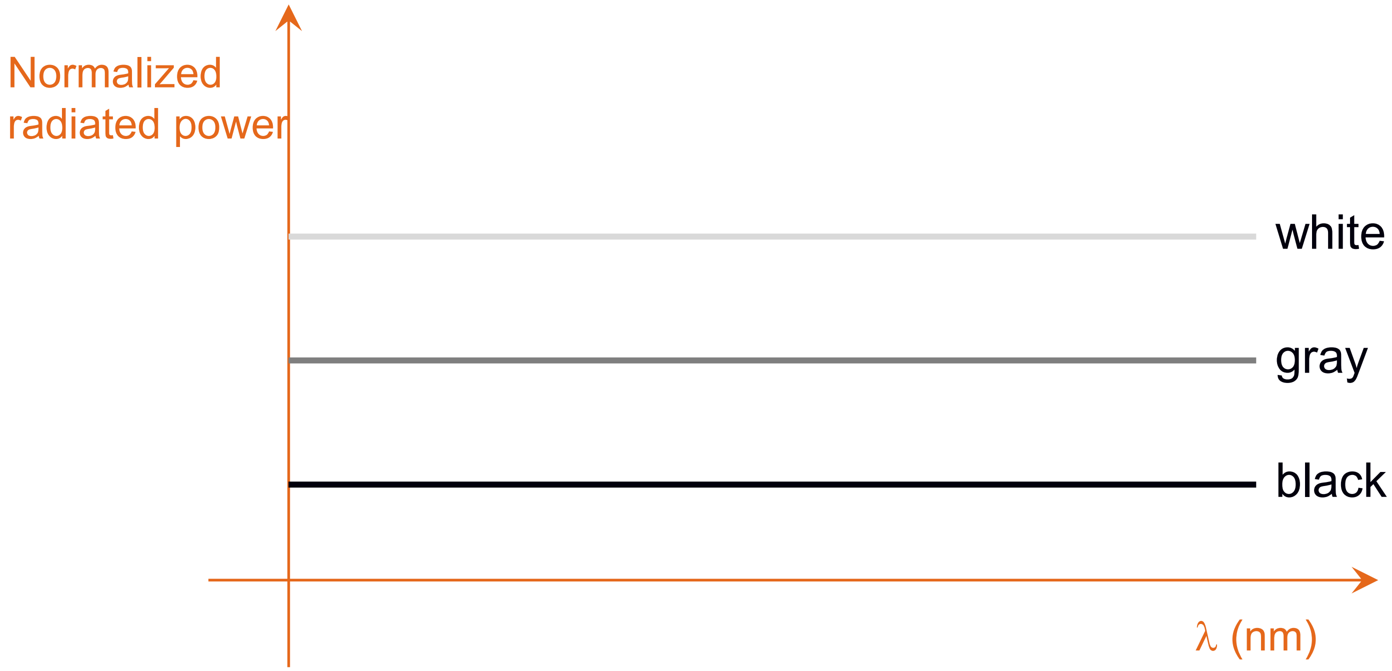
Characteristics of color

② purity



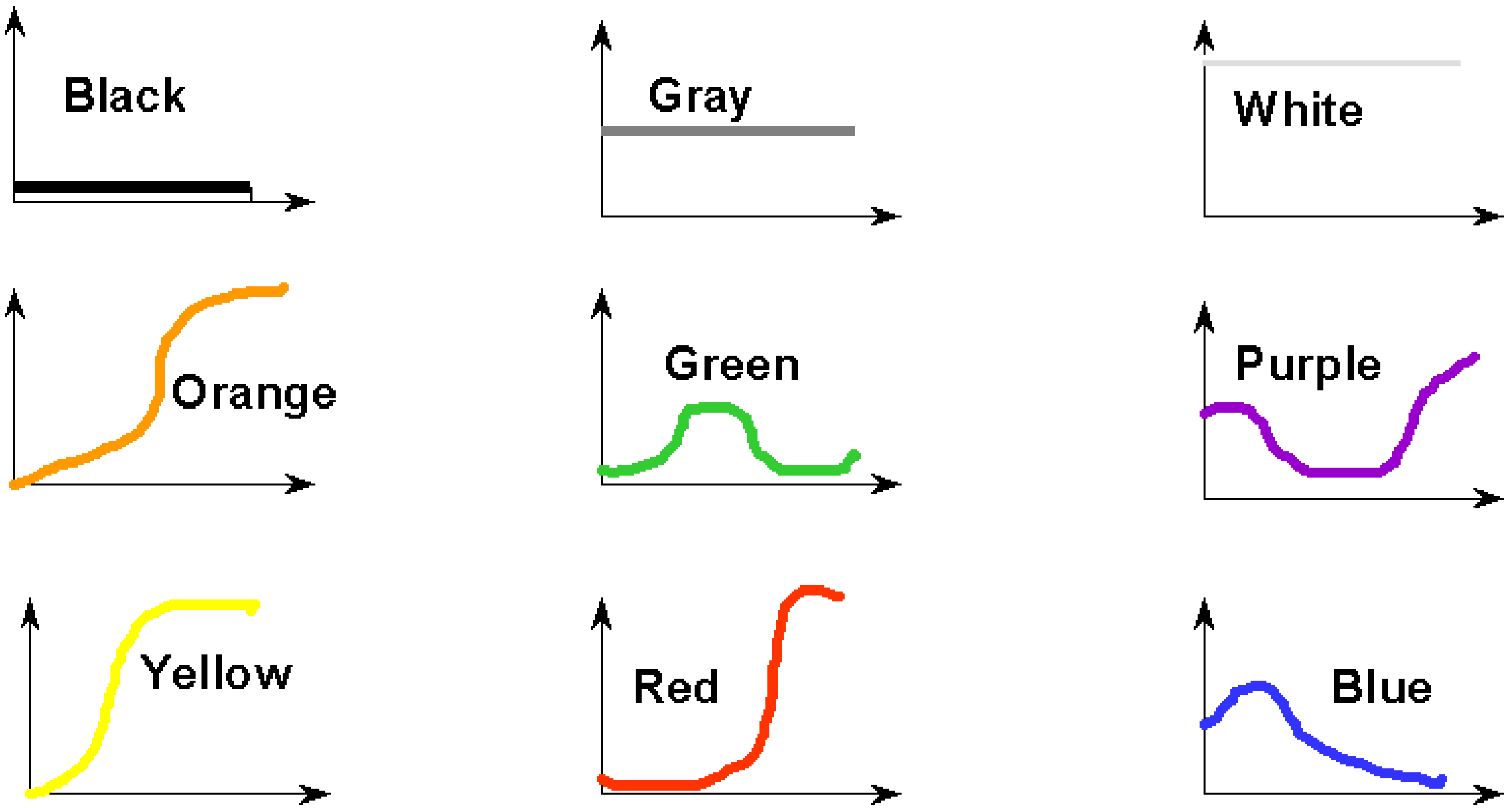
Characteristics of color

③ luminance



Characteristics of color

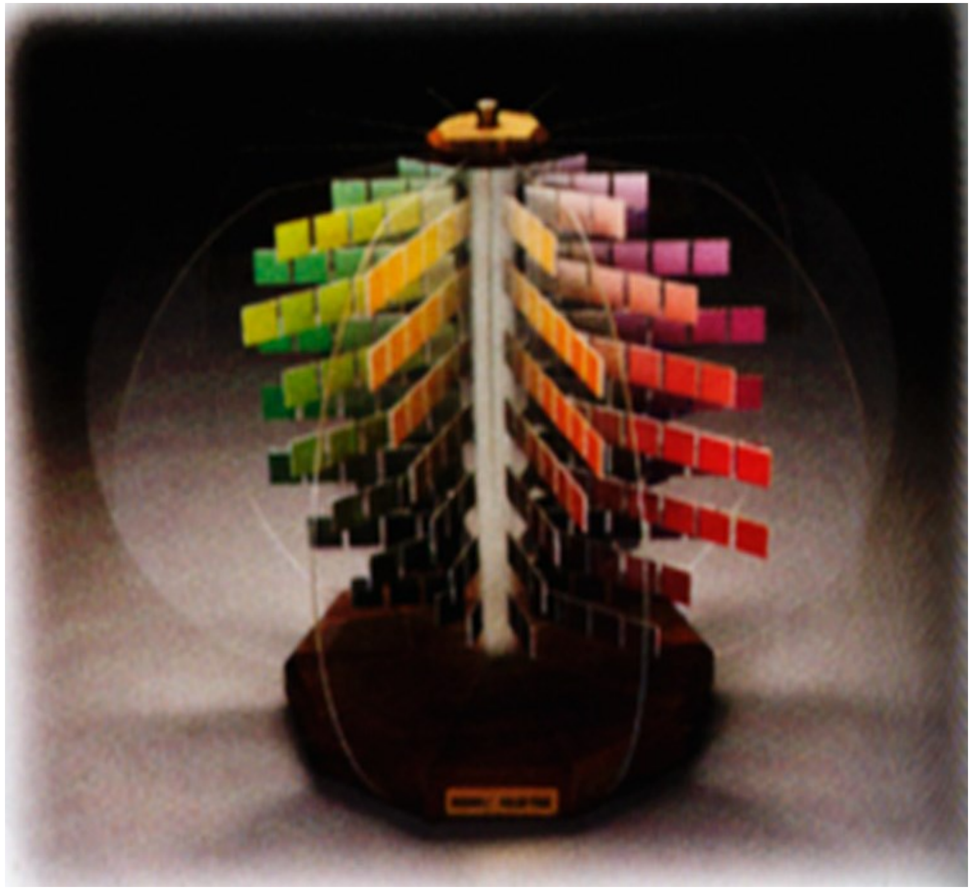
- examples

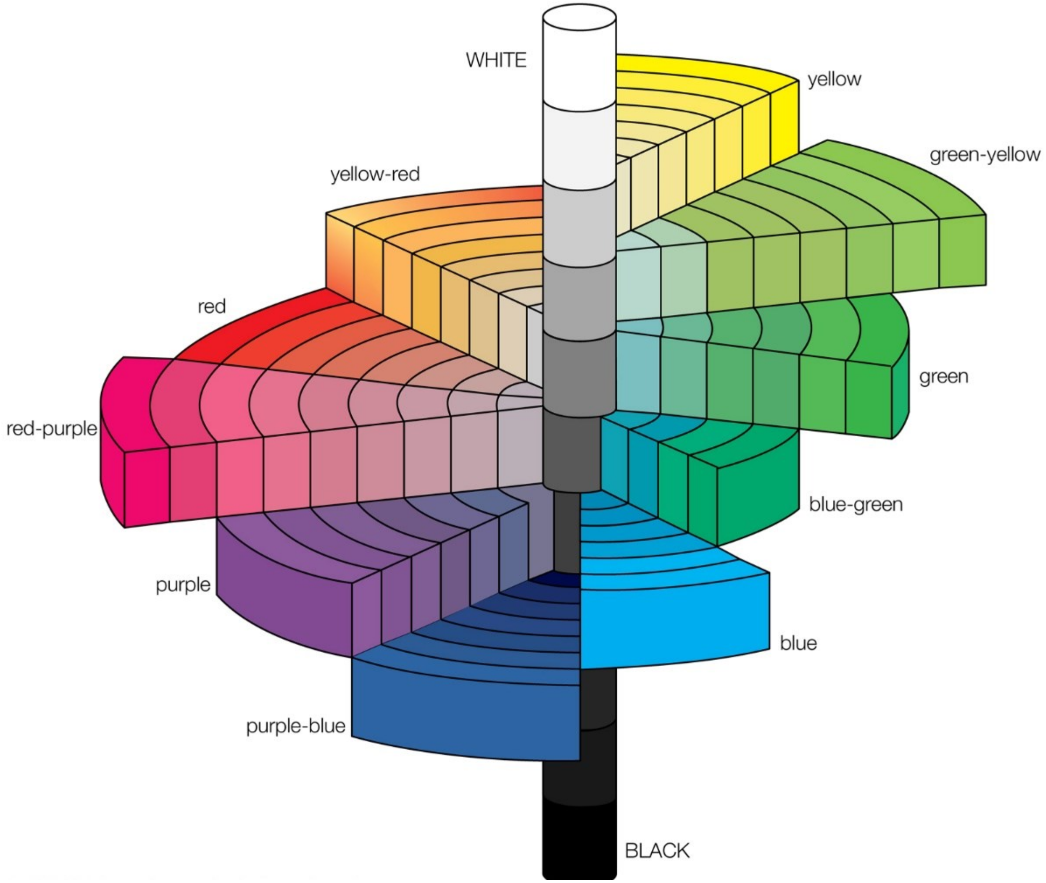


Characteristics of color

- Munsell color space
  - color space that specifies colors based on three properties of color: hue (basic color), chroma and value (lightness)
    - hue - measured by degrees around horizontal circles
    - chroma - measured radially outward from the neutral (gray) vertical axis
    - value - measured vertically on the core cylinder from 0 (black) to 10 (white)
- Munsell determined the spacing of colors along these dimensions by taking measurements of human visual responses
- Munsell colors are as close to perceptually uniform as he could make them, which makes the resulting shape of the color space quite irregular

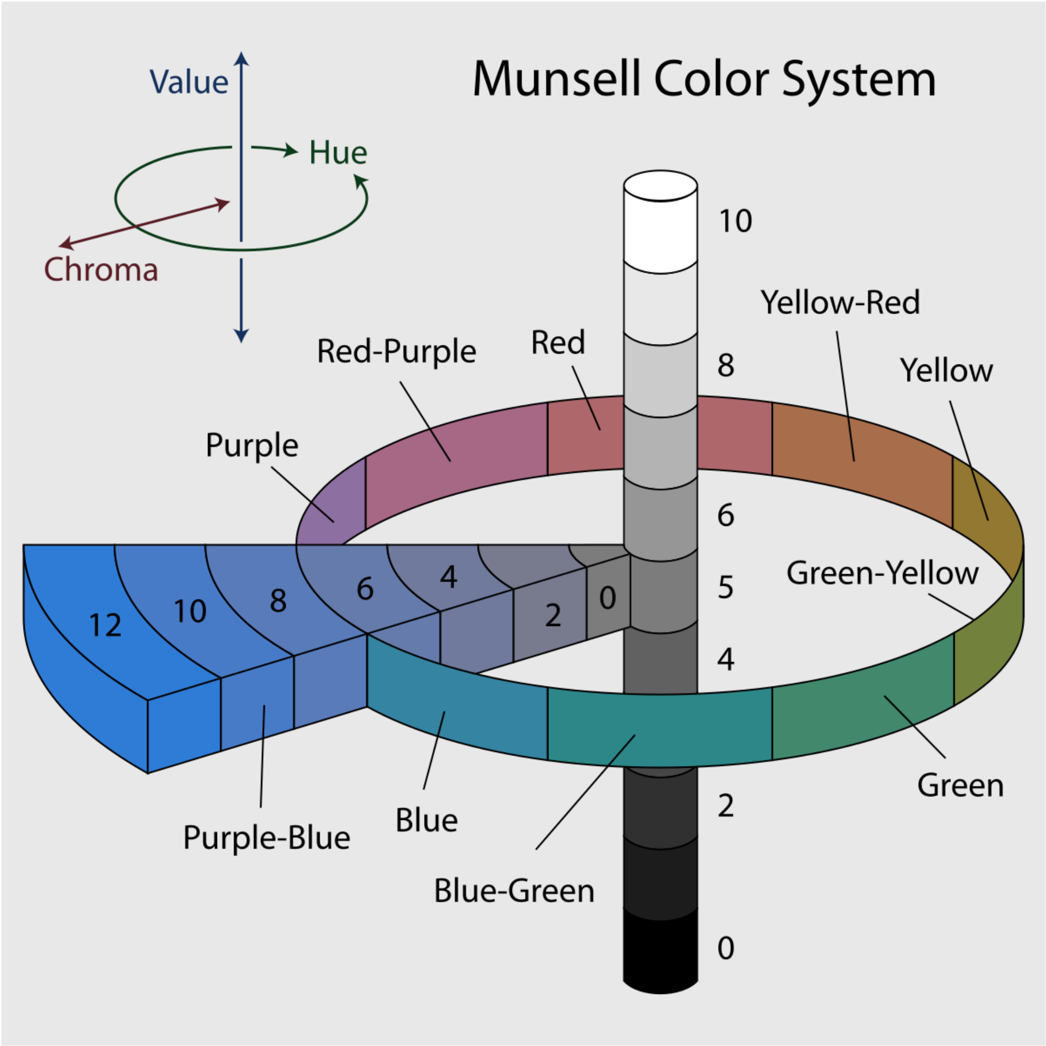
Characteristics of color





Characteristics of color

- **hue**
  - an alphanumeric system used to create equal space between colors around the perimeter of the Munsell Color Wheel
  - 10 HUE families: Red, Yellow/Red, Yellow, Yellow/Green, Green, Blue/Green, Blue, Purple/Blue, Purple, Red/Purple
- **value** scale is rated from 1 (darkest) to 10 (lightest)
- **chroma** scale assigns a relative numeric value to a color's intensity (the higher the number, the further from grey)

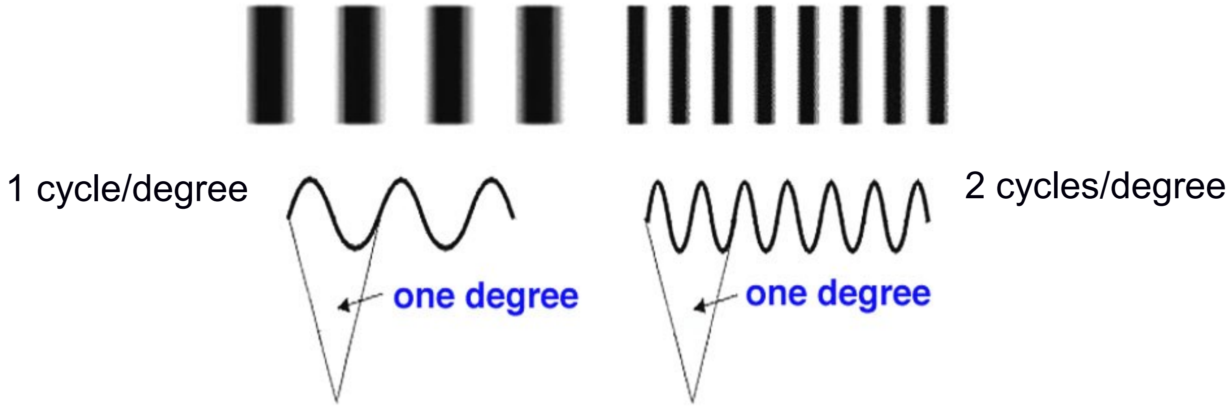


Contrast sensitivity

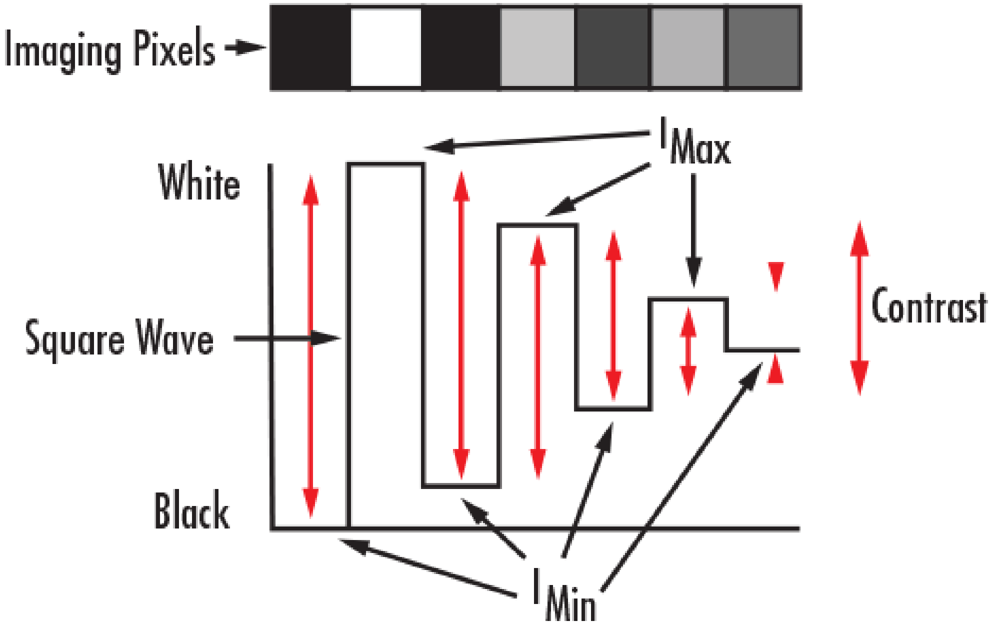
- the visual system is sensitive to contrast (relative ratio of visual stimuli) and not to the absolute amount of luminance
- contrast
  - the difference in the brightness (or color) of an object relative to other objects and the background in the field of view
- contrast sensitivity
  - determines how small the contrast can be, before the patterns merge with the uniform background and become unrecognizable
- contrast sensitivity function (CSF)
  - relates the visibility of a spatial pattern to both its size and contrast
  - more comprehensive assessment of visual function than acuity which only determines the smallest resolvable pattern size
- CSF is a function of spatial frequency
  - the spatial frequency is the number of cycles per degree of visual angle

Contrast sensitivity

- spatial frequency

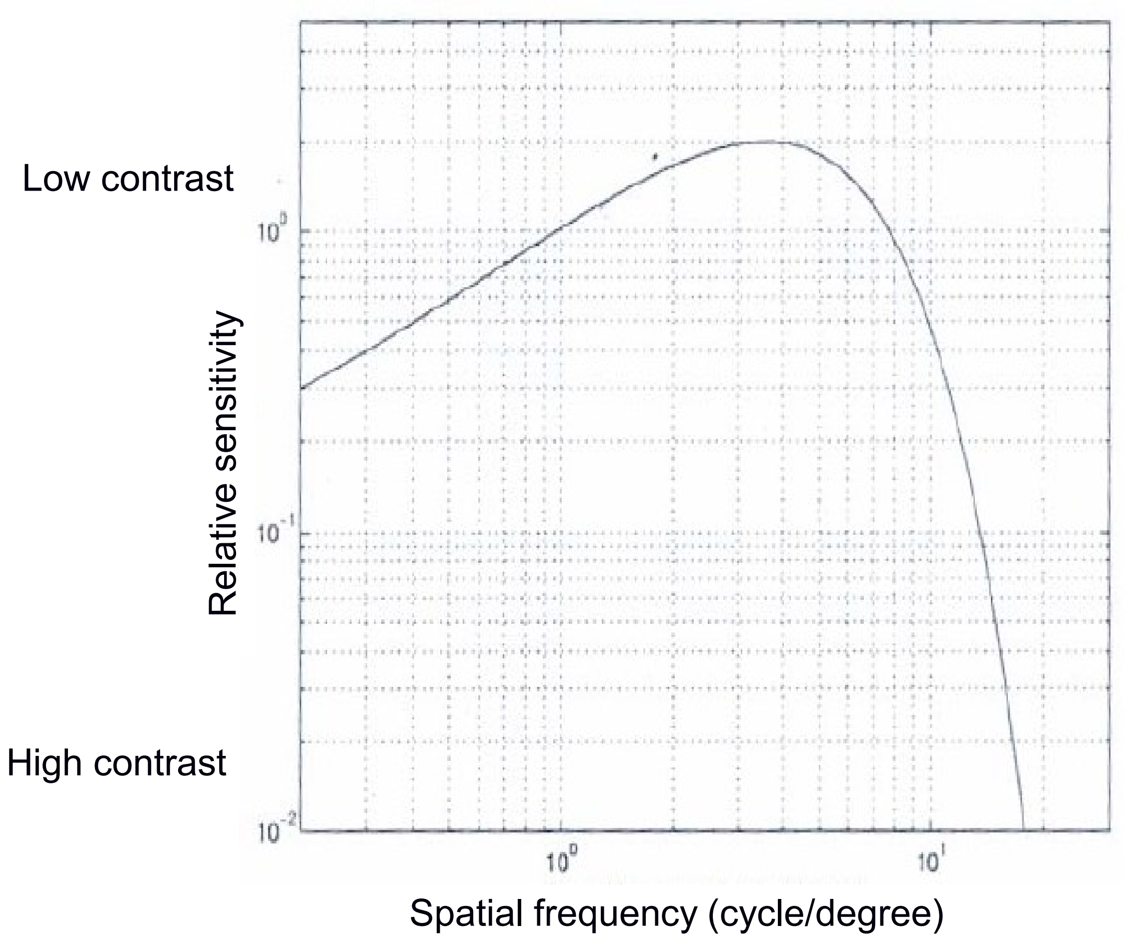


- contrast



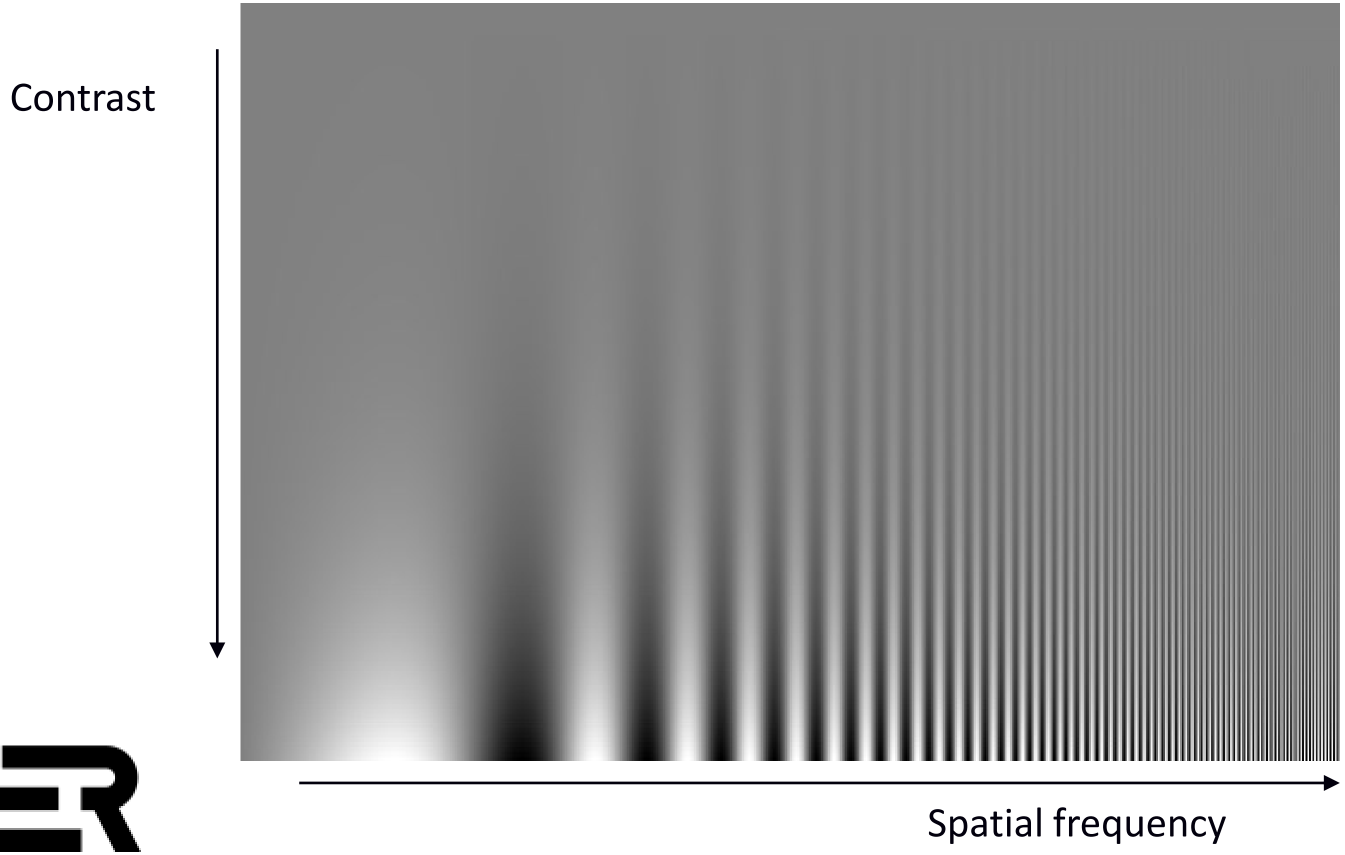
Contrast sensitivity

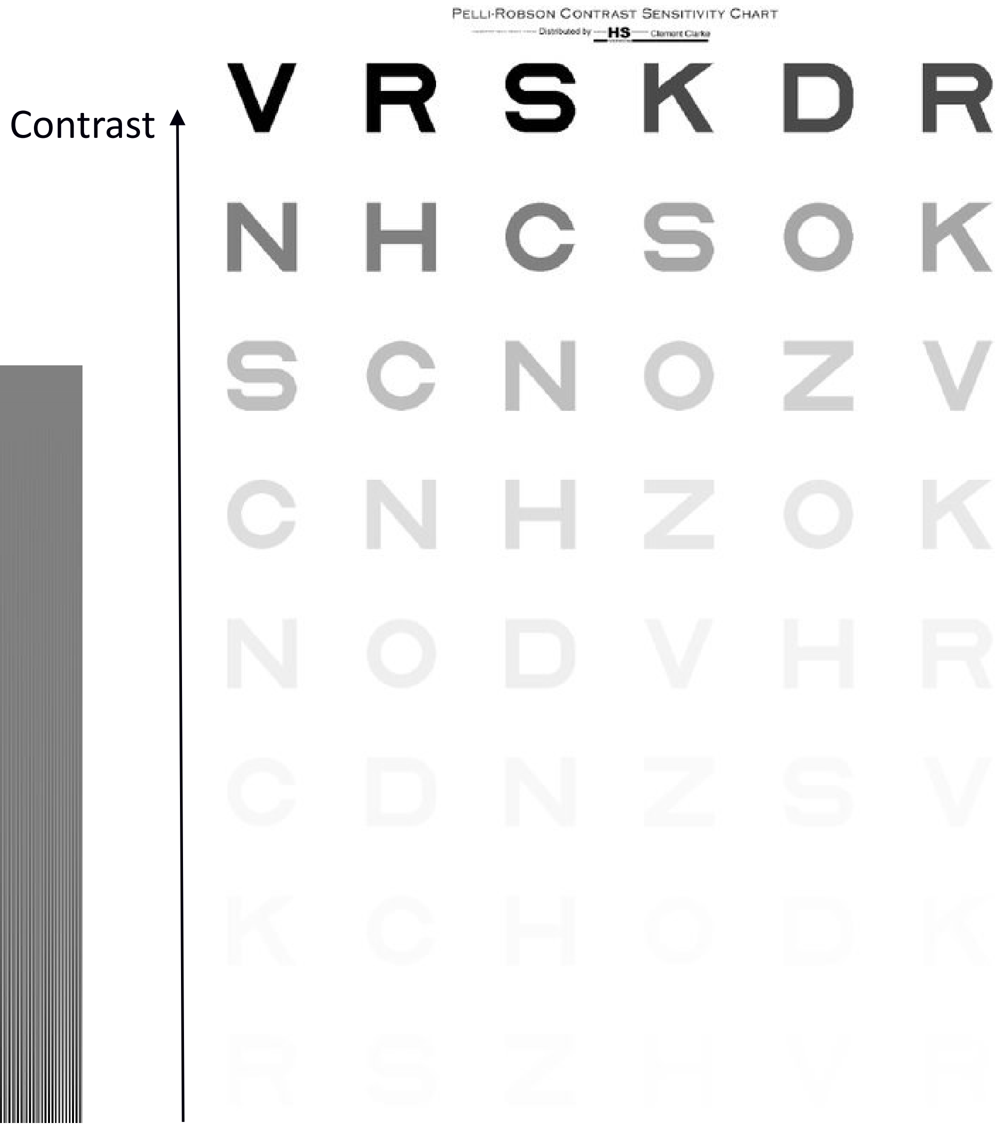
- contrast sensitivity function
  - the sensitivity is highest for spatial frequencies of 2-5 cycles/degree, and for higher and lower spatial frequencies it decreases



Contrast sensitivity

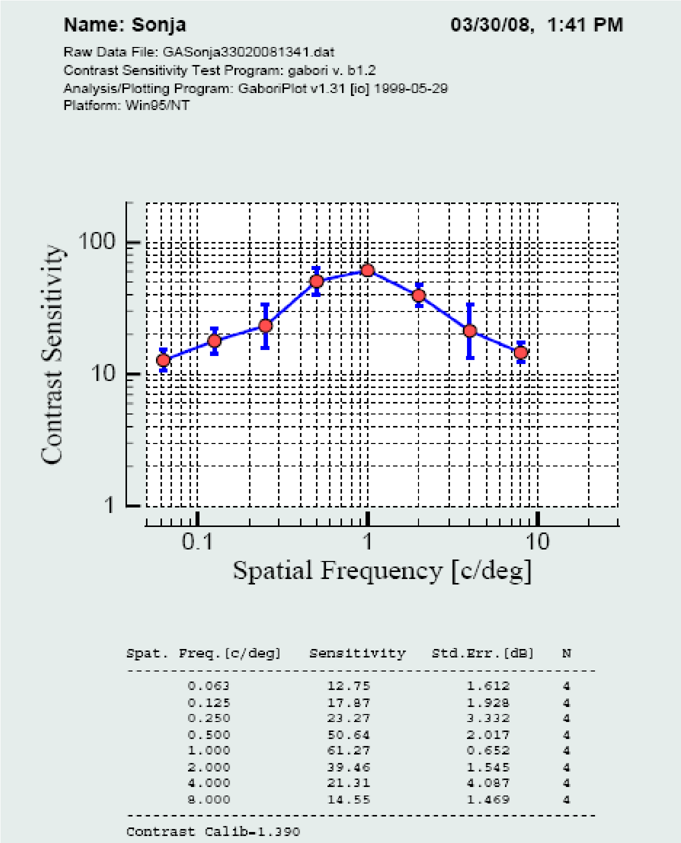
- chart for contrast sensitivity testing (*Campbell-Robson contrast sensitivity chart*)
  - the shape of the CSF is observed on the chart





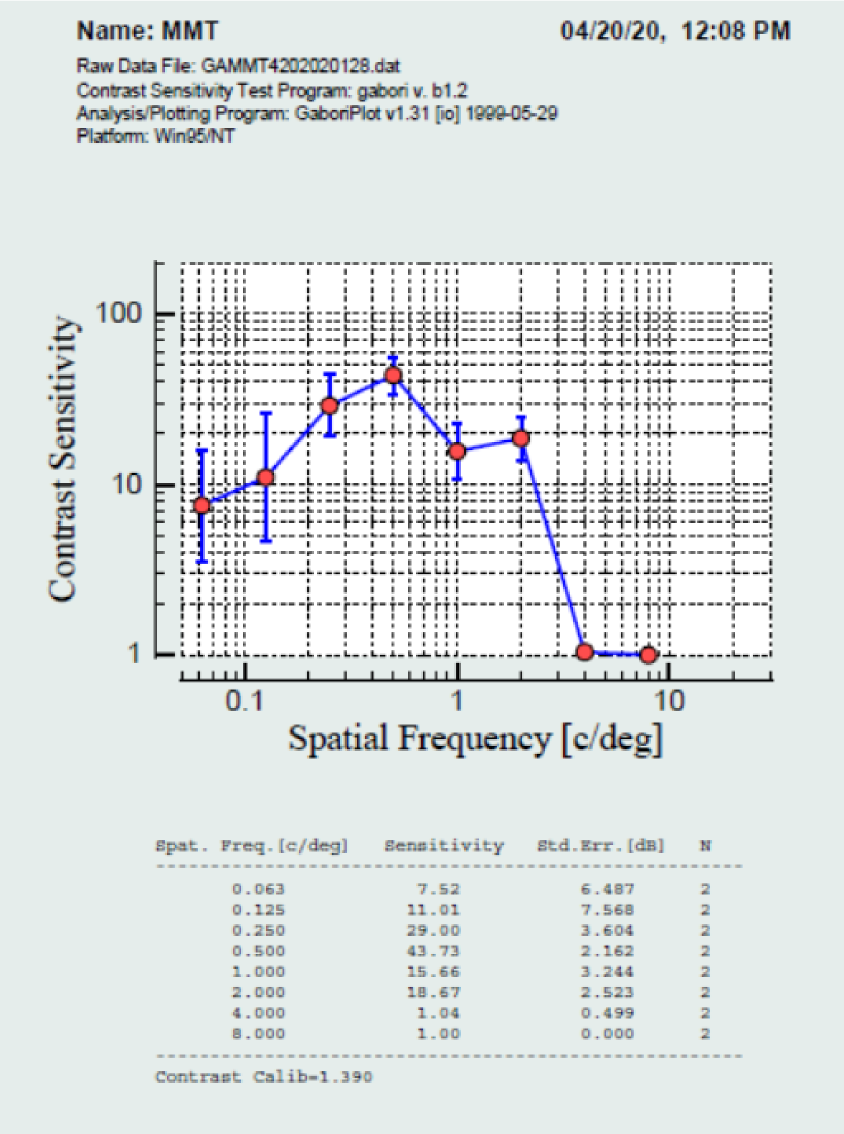
Contrast sensitivity

- determine your own contrast sensitivity function using the Gabori Attack application https://visiome.neuroinf.jp/database/item/3315



Spat. Freq.[c/deg]	Sensitivity	Std.Err.[dB]	N
0.063	12.75	1.612	4
0.125	17.87	1.928	4
0.250	23.27	3.332	4
0.500	50.64	2.017	4
1.000	61.27	0.652	4
2.000	39.46	1.545	4
4.000	21.31	4.087	4
8.000	14.55	1.469	4

Contrast Calib=1.390



Spat. Freq.[c/deg]	Sensitivity	Std.Err.[dB]	N
0.063	7.52	6.487	2
0.125	11.01	7.568	2
0.250	29.00	3.604	2
0.500	43.73	2.162	2
1.000	15.66	3.244	2
2.000	18.67	2.523	2
4.000	1.04	0.499	2
8.000	1.00	0.000	2

Contrast Calib=1.390

Contrast sensitivity

Source image

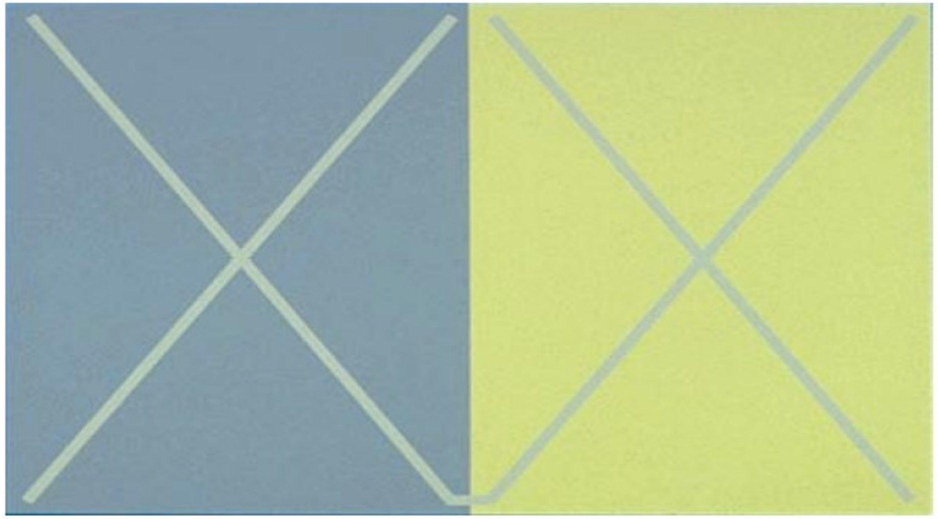
Lower contrast

Higher contrast

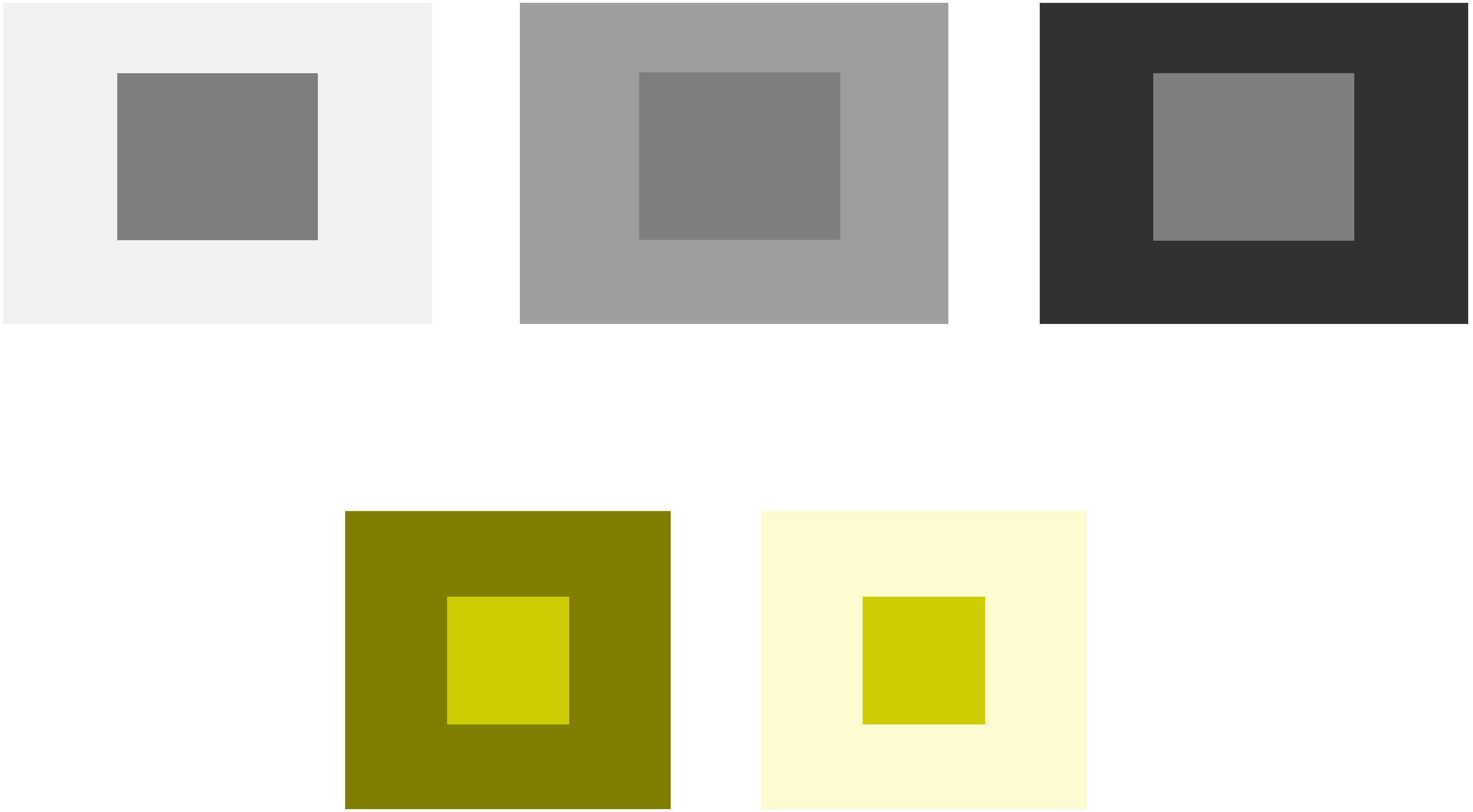
Contrast sensitivity

- an object of the same luminance is placed on three backgrounds of different luminance
- changing the background luminance affects the change in the brightness of the object

- the same color displayed on a darker and lighter background evokes a different subjective experience

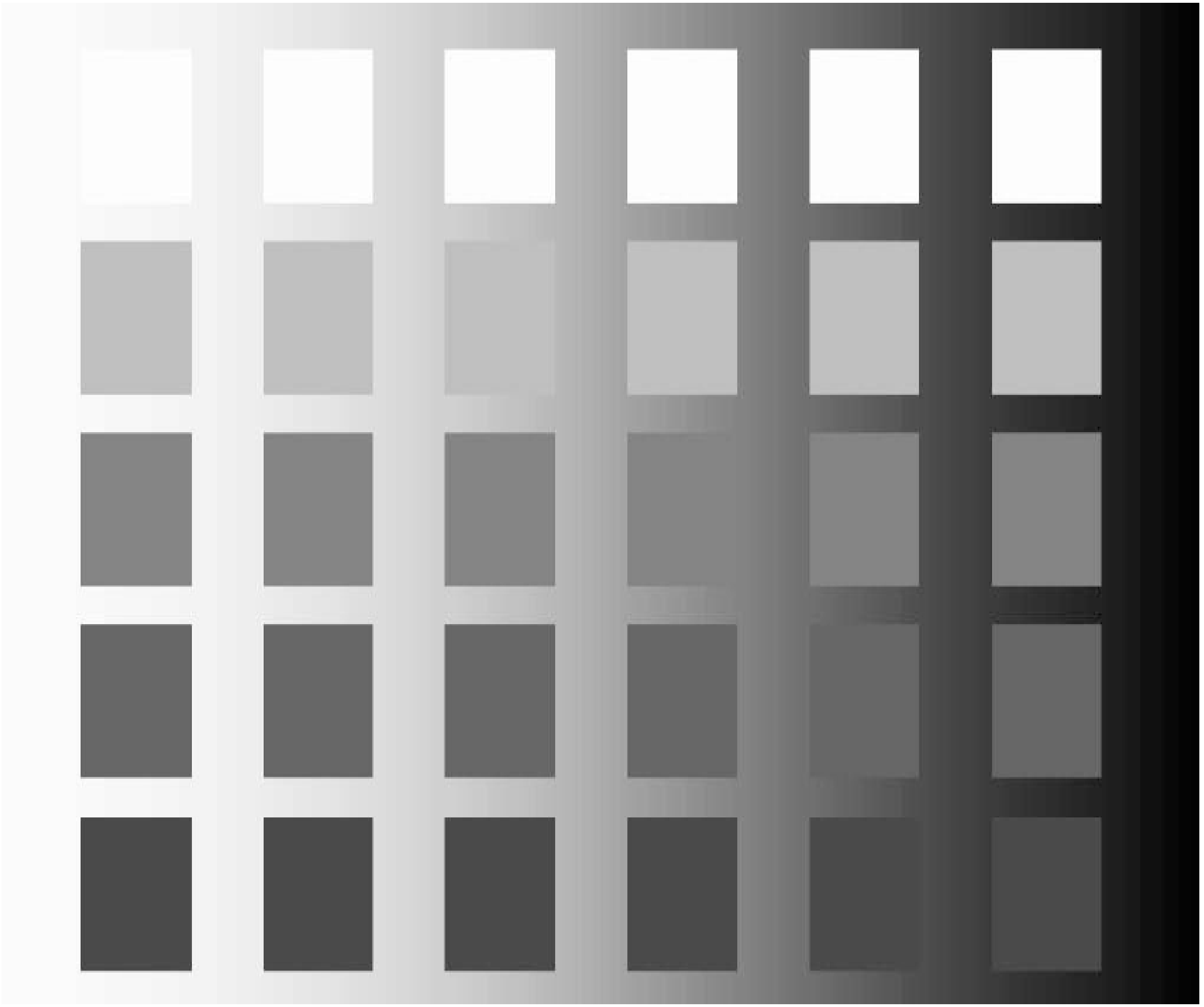


Contrast sensitivity



Contrast sensitivity

- each row has the same level of the gray
- the brightness changes depending on the level of the gray of background

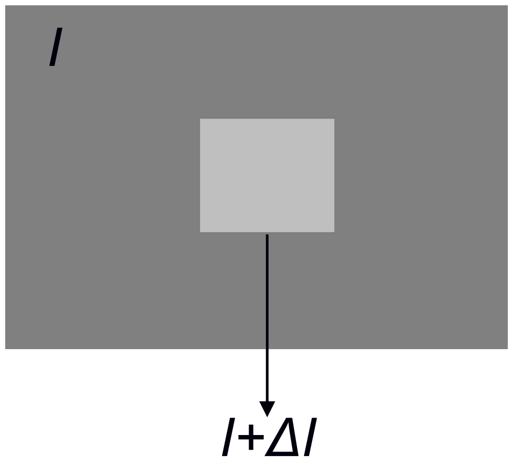


Light adaptation

- light adaptation follows Weber's law

$$\frac{\Delta I}{I} = \mathrm{k}$$

k - constant
I - luminance of the background
ΔI - change of the luminance of the object in relation to the background, which enables the observation of just noticeable difference in brightness (ΔI is the difference threshold)



- Weber’s law does not apply to very low and very high illuminations

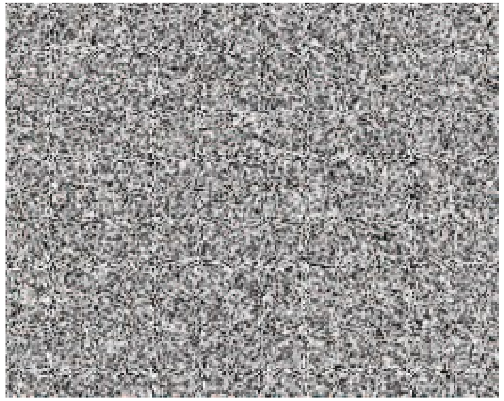
Light adaptation

- the connection between the physical world and psychic experience of that world is not linear (with the increase of the intensity of the stimulus *I,* an increasing difference threshold ΔI is needed in order to produce just noticeable difference)
- this phenomenon is called adaptation to light (luminant masking) because it allows us to observe the world in a similar way regardless of large changes in illumination during the day or from place to place

  Example: If we read a book in a room and take it out in the midday sun, the intensity of the light reflected from the pages will increase significantly, but the appearance of the page will not change significantly for us. Namely, at the same time the intensity of the light reflected from the sheets of paper and from the letters and pictures increases, so the intensity ratio between them does not change. While the ratio of these changes remains constant, the page we observe for us remains the same. If not, the sunny page of the book would look white, and when we bring it into the room gray or even black.

Masking effect

- masking refers to the ability of one signal (masker) to interfere with the perception of another signal in a certain time interval or frequency range
- when viewing an image, the masking effect is greatest when the main and masking signals have similar frequency content, spatial position and orientation
- the masking effect is best observed in areas where the image components (main and masking) have different frequency content



main signal

masking signal

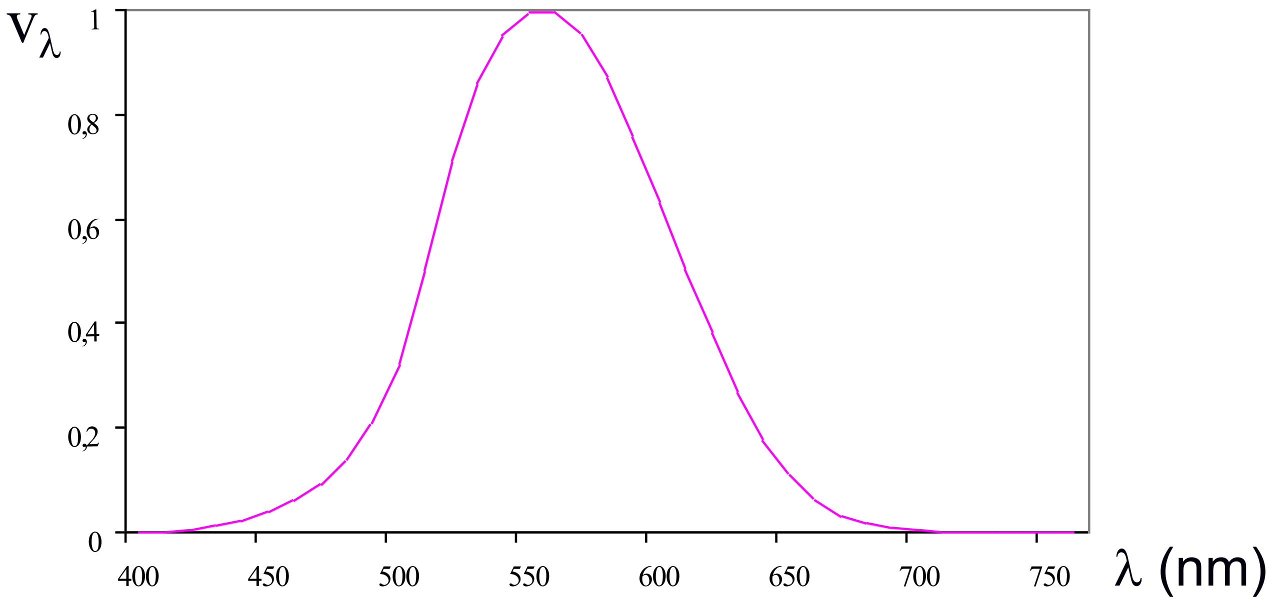
main + masking signal

Luminosity curve

- describes the average spectral sensitivity of human visual perception of brightness
  - it is based on subjective judgements of which of a pair of different-colored lights is brighter, to describe relative sensitivity to light of different wavelengths
  - light source which has a constant radiated power at all wavelengths in the visible light range (white light) is used in experiment
  - subjective experience is tested for 10 nm intervals in the range 380-780 nm
- Commission Internationale de l'Éclairage (CIE) conducted a series of tests and in 1921 determined the shape of the luminosity curve for a standard observer (average curve for 200 observers)
- the CIE photopic luminosity function v_λ is a standard function that can be used to convert radiant energy into luminous (i.e., visible) energy

Luminosity curve

- shows the relative luminosity v_λ as a function of wavelength
- v_λ is determined in relation to the luminosity of the wavelength 555 nm which causes the highest brightness
- the relative luminosity at 555 nm is equal to 1

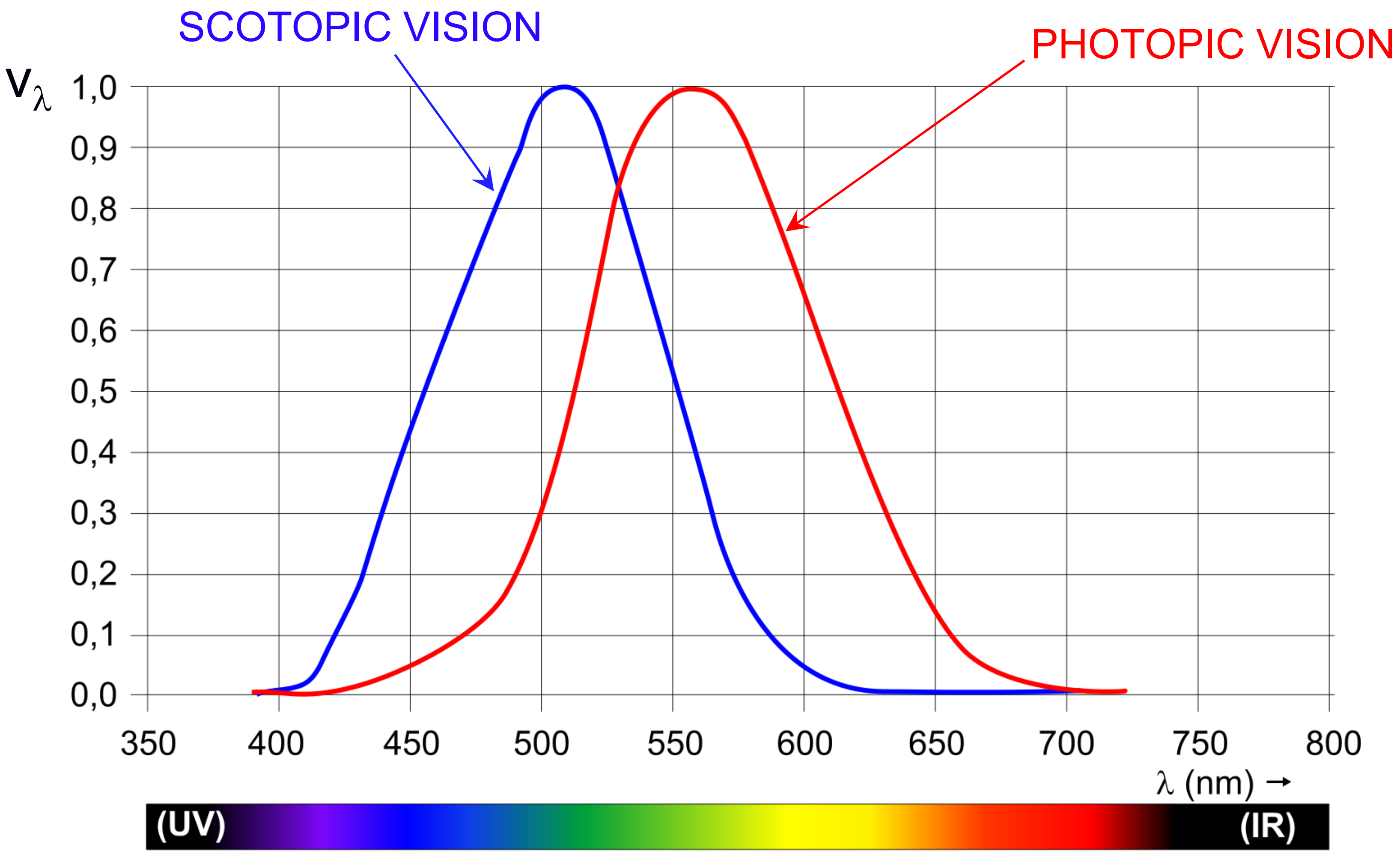


Luminosity curve

Purkinje effect

- the tendency for the peak luminance sensitivity of the eye **to shift** toward the blue end of the color spectrum at low illumination level
- it is part of dark adaptation
- standard luminosity function – rods and cones are active
  - FOTOPIC VISION
- at low illuminant levels (below 1 cd/m^2) only the rods are active, and the maximum brightness is achieved for λ = 507 nm
  - SCOTOPIC VISION
  - the luminosity curve shifts toward shorter λ

Luminosity curve



Primary colors

- eye
  - colors are produced by three types of cones (for the feeling of green, red and blue)
  - visible colors are disjointed into three components: red, green, and blue, and the brain interprets the three received information by the summation process
- assumption: all visible colors can be produced by mixing three basic monochromatic colors (primary colors) that should be carefully selected in the spectrum of red, green and blue light
- in order to select the optimal system of three primary colors, a large number of experiments were conducted by the CIE and a system of CIE primary colors is established

CIE primary colors

- CIE primary colors
  - the basic condition for choosing a system of three primary colors is that the sum of the two primary colors does not give the third primary color
  - primary colors are: red (R, Red), green (G, Green) and blue (B, Blue)
  - primary colors are defined by the wavelength of light:

$$\lambda_R = 700 \text{ nm}$$
$$\lambda_G = 546{,}1 \text{ nm}$$
$$\lambda_B = 435{,}8 \text{ nm}$$

- CIE primary colors are used in colorimetry (color measurements)
  - colors are produced by additive mixing of three primary colors (R, G and B)
  - additive color mixing - mixing of colored lights
  - by mixing primary colors, all other colors from the white light spectrum can be achieved, but also other colors that do not exist in the white light spectrum

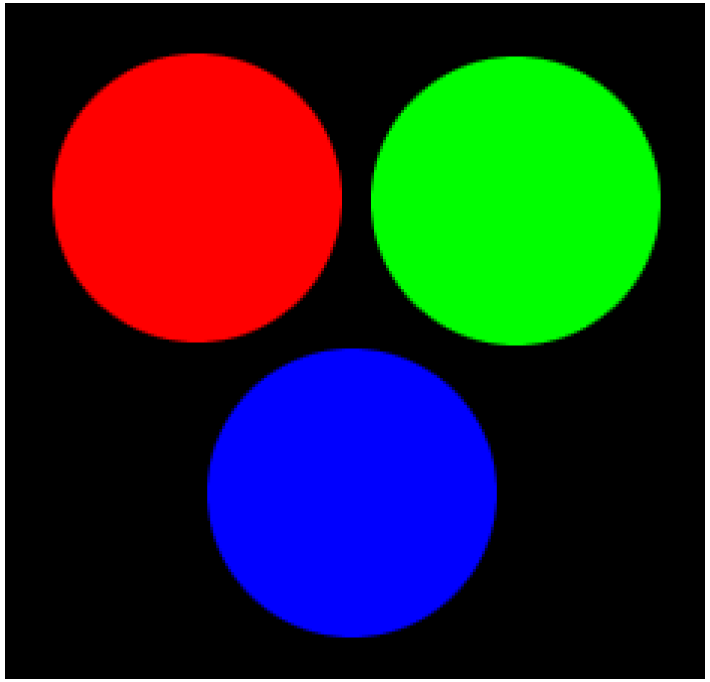
Additive color mixing

- additive mixing
  - in areas where the primary colors overlap the eye experiences a fictional color that is not present in light sources
    - R+G=yellow
    - R+B=purple
    - B+G=cian
    - R+G+B=white
  - complementary colors
    - pairs of colors which, when combined or mixed, cancel each other out (lose hue) by producing white color

      R+cian=white

      G+purple=white

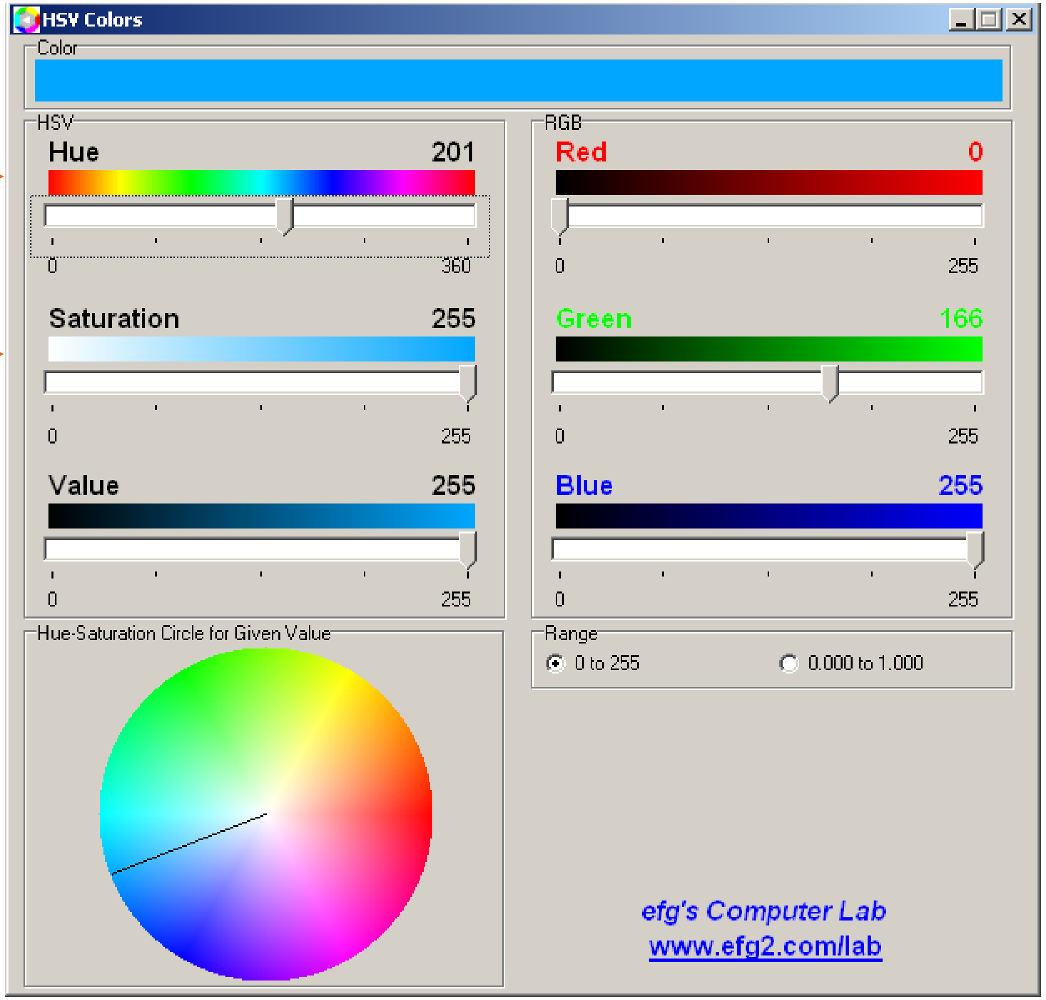
      B+yellow=white
  - the formation of a color image in display devices (monitors, projectors) is based on additive color mixing



Additive color mixing

hue (201)

saturation (255)

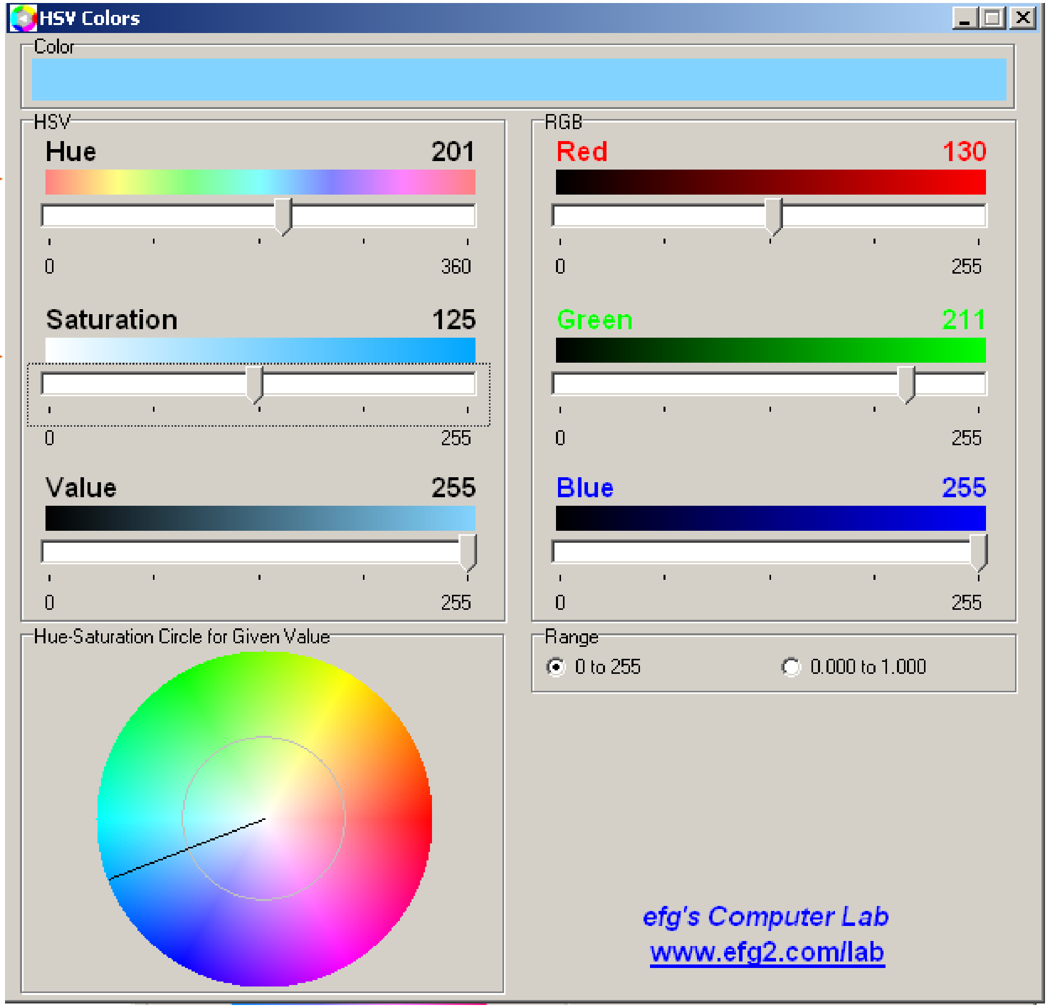


primary colors

Additive color mixing

hue (201)

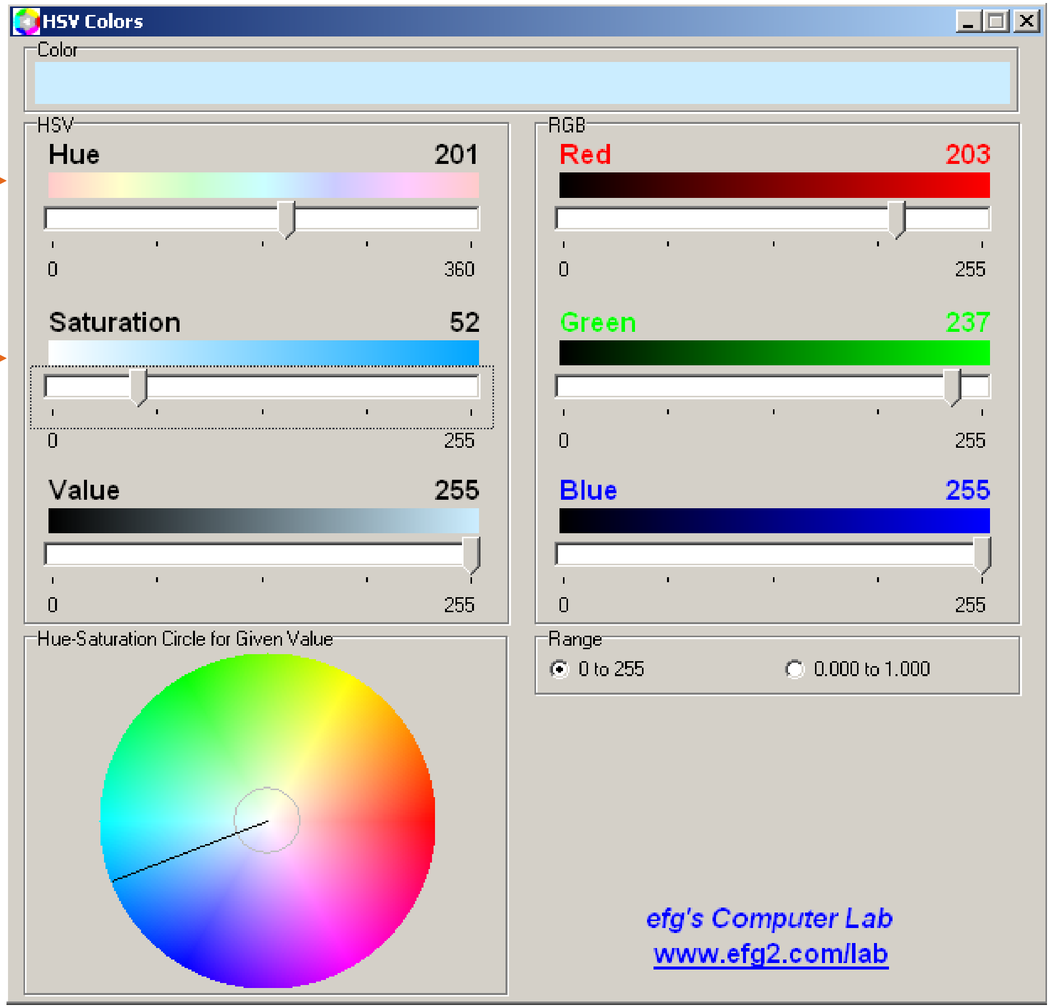
saturation (125)



Additive color mixing

hue (201)

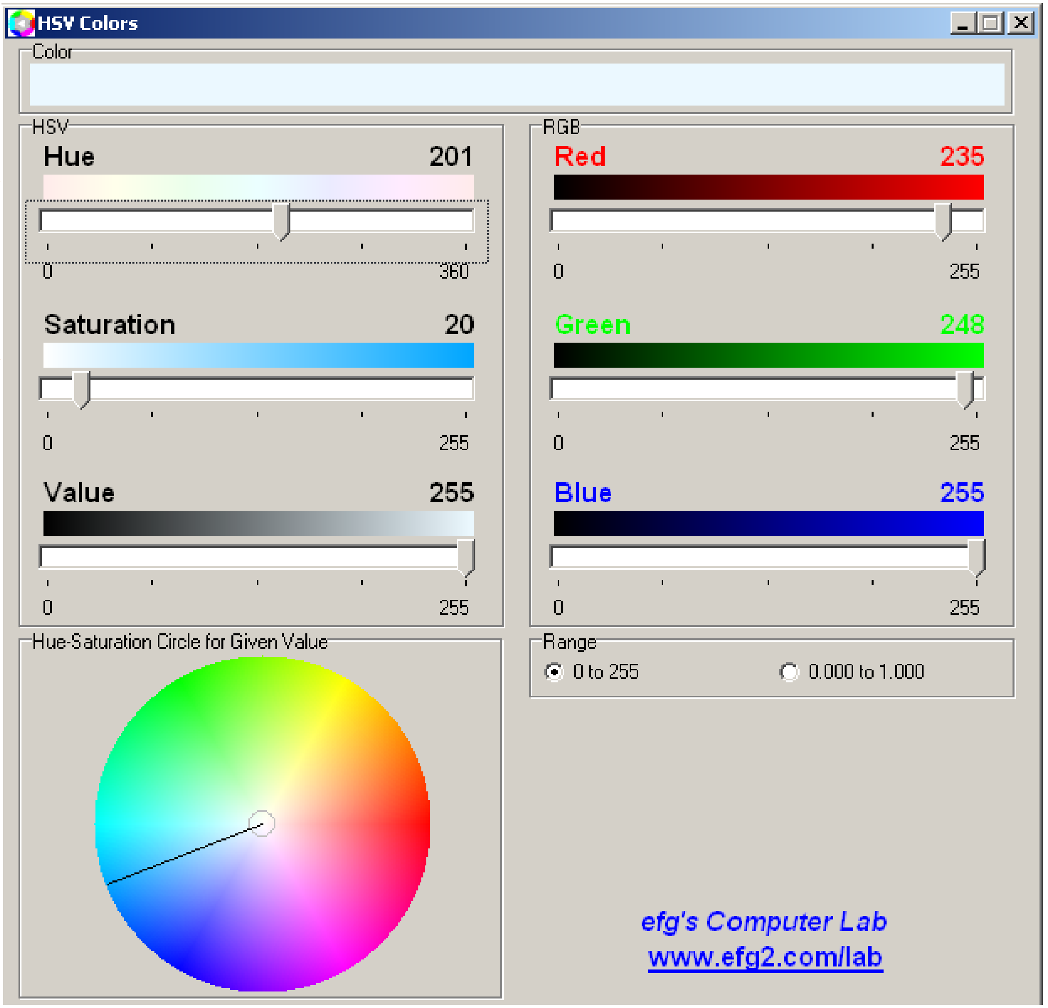
saturation (52)



Additive color mixing

hue (201)

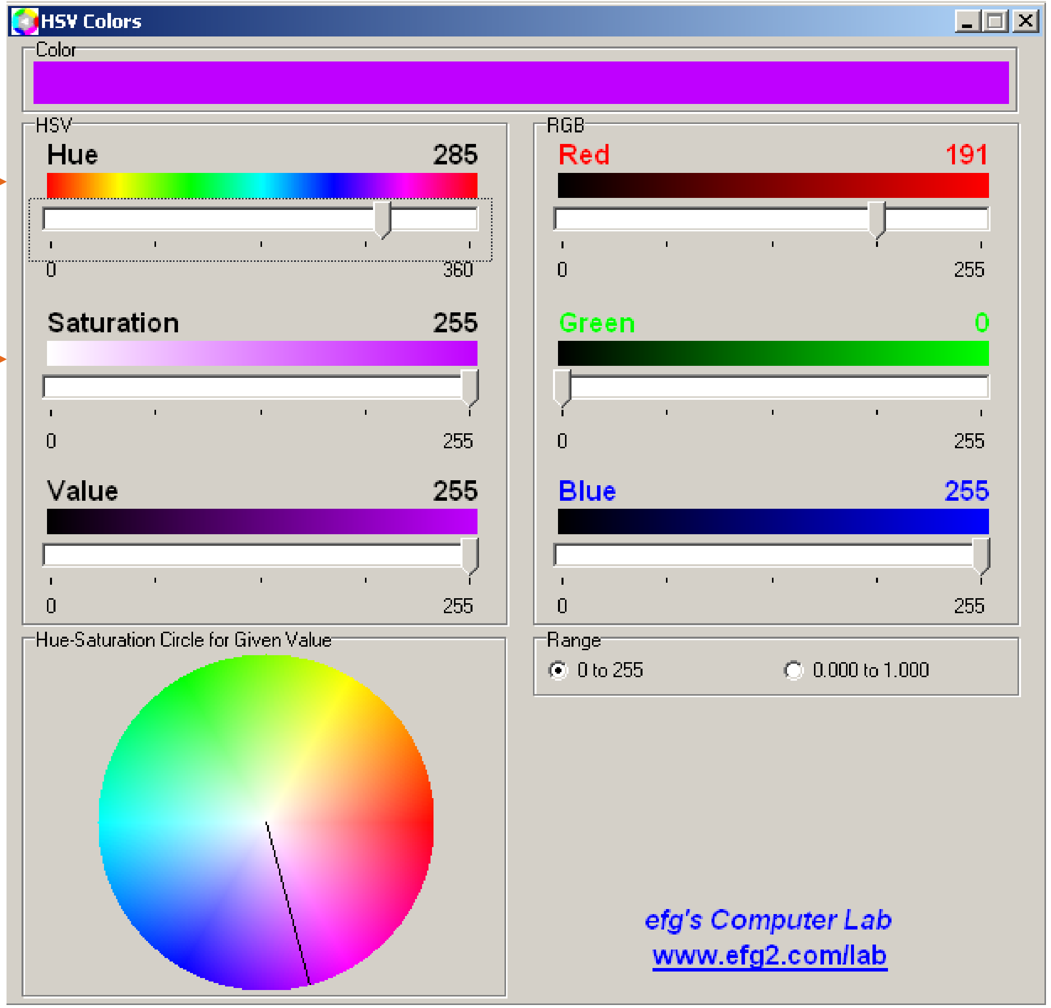
saturation (20)



Additive color mixing

hue (285)

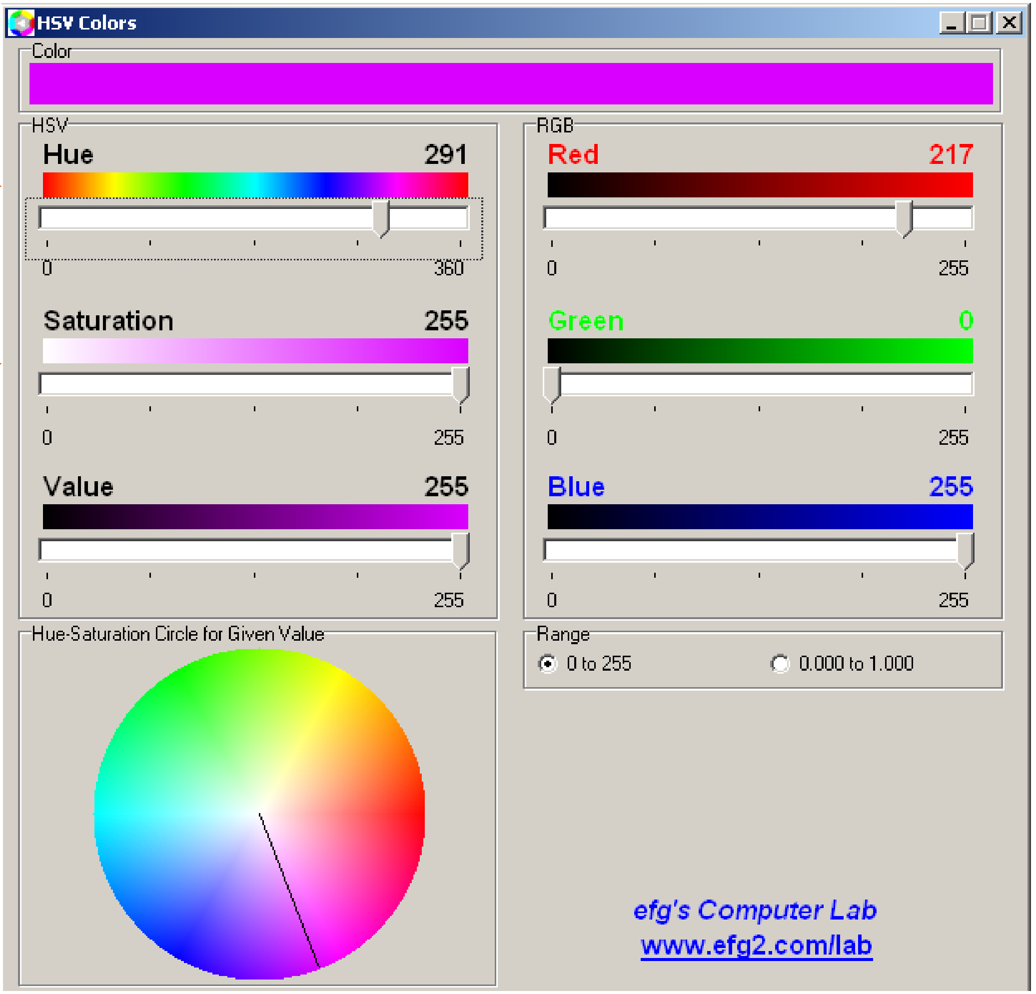
saturation (255)



Additive color mixing

hue (291)

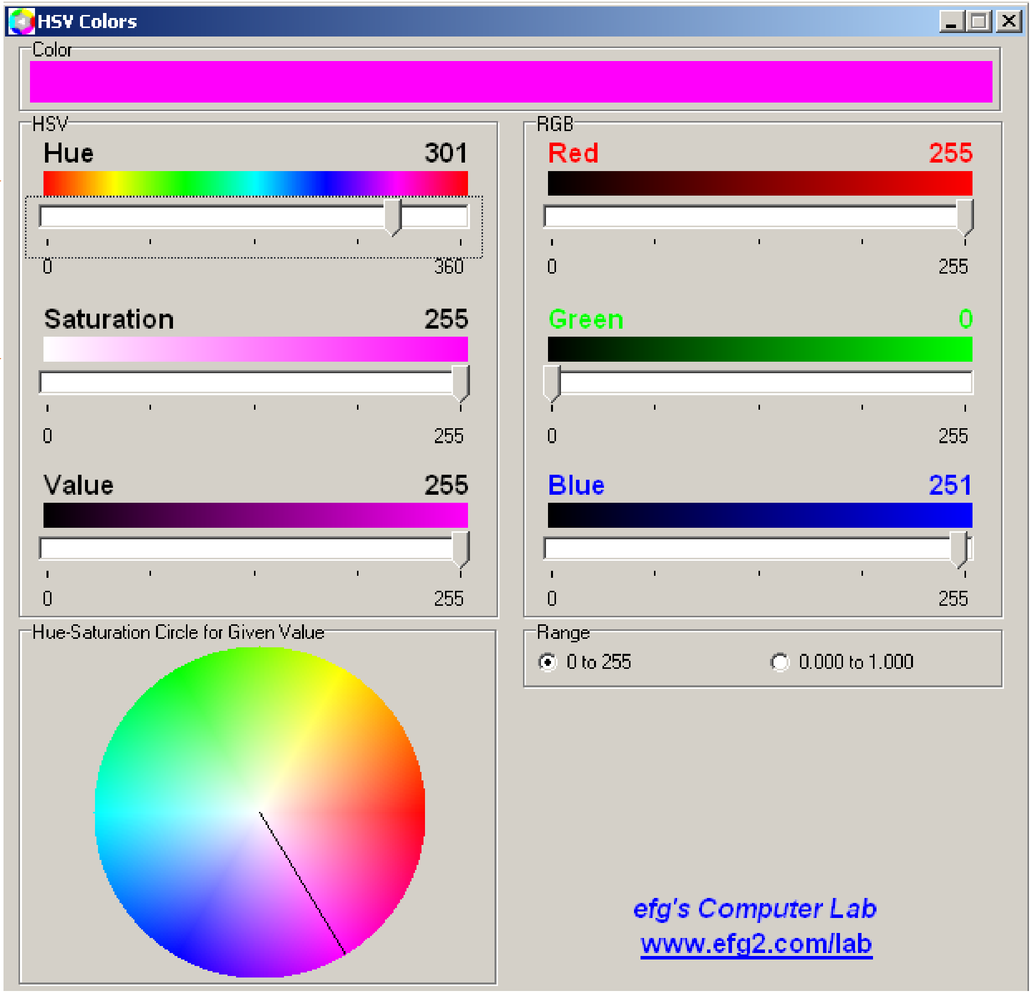
saturation (255)



Additive color mixing

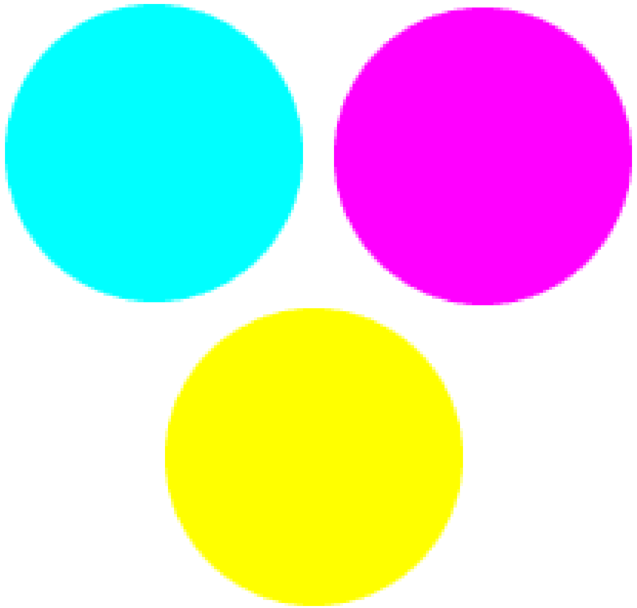
hue (301)

saturation (255)



Subtractive color mixing

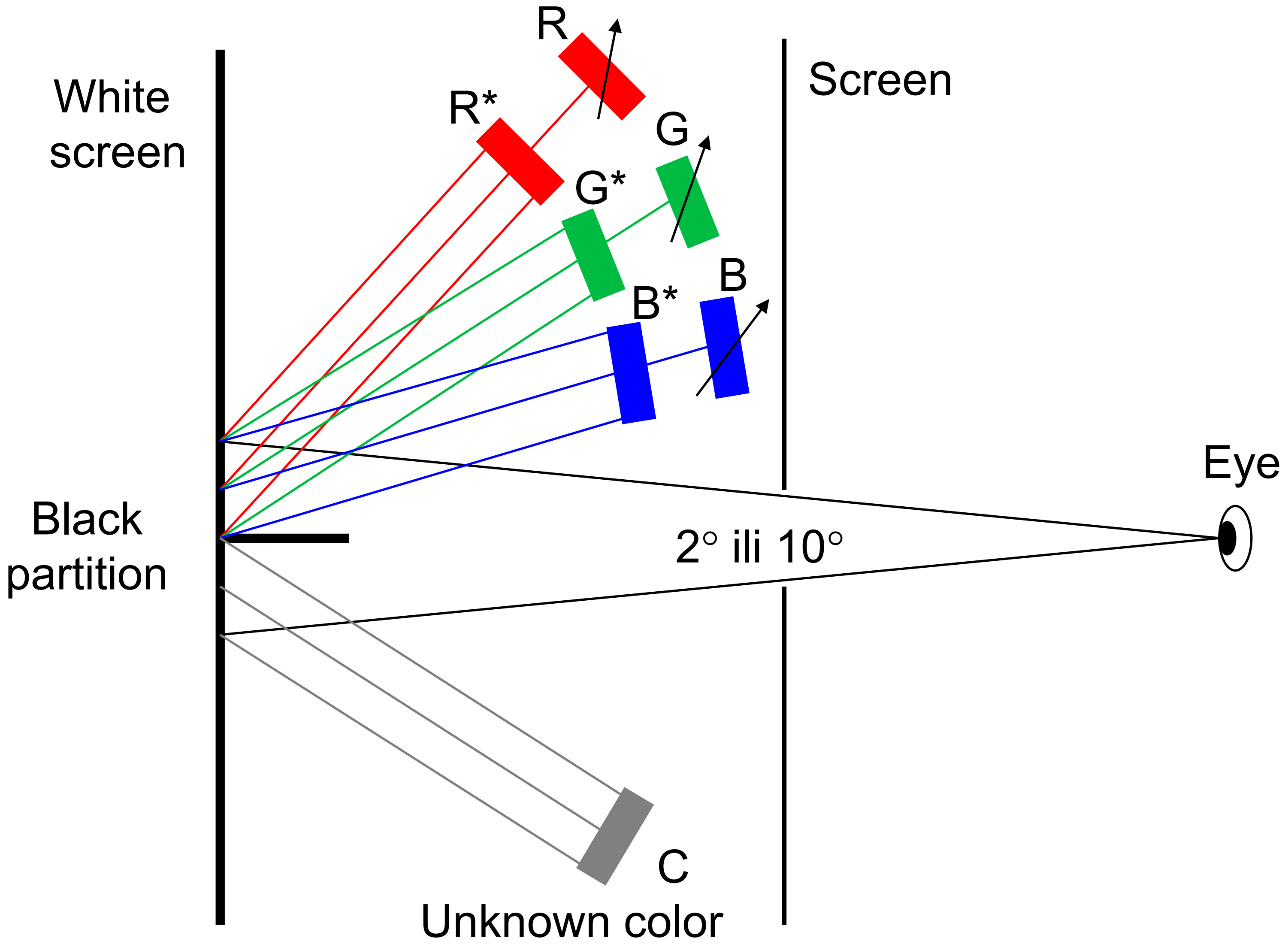
- subtractive color mixing
    - used in painting
  - primary colors are: cian, purple and yellow
    - cian+yellow=G
    - cian+purple=B
    - purple+yellow=R
  - by mixing the three subtractive primary colors a black colored area is formed



Colorimetry

- COLORIMATRY – color measurement
  - the basis of colorimetry is the comparison of colors and the determination of physical stimuli that cause equal sensations of hue and saturation
  - color measurement is based on comparison by equality: unknown spectral color from the white light spectrum is compared with the color obtained by additive mixing of primary colors
  - in colorimetry, CIE primary colors are used (red (R) - 700 nm, green (G) - 546.1 nm, blue (B) - 438.8)
- tristimulus colorimeter (additive colorimeter)
  - a device for color matching
  - unknown color (C) is compared with the color created by mixing the three primary colors (R, G and B)
  - the observer was asked to adjust the amount of the three primary colors separately until the light produced by mixing the primary colors was equal to the unknown color
  - in this way the amount of primary colors in an unknown color is determined

Colorimetry



Colorimetry

- for matching with unknown color C we need:
  R amount of red primary R*
  G amount of green primary G*
  B amount of blue primary B*

$$\mathrm{C} = \mathrm{R{\cdot}R^*} + \mathrm{G{\cdot}G^*} + \mathrm{B{\cdot}B^*}$$

$\mathrm{R^*, G^*, B^*}$ - unit amounts of primary colors
$\mathrm{R, G, B}$ – tristimulus values of C

- to determine R*, G* and B* instead of unknown color, the referent white (W) light source is used
- by adjusting the light source for red, green and blue, the amounts of primary R, G and B are changed until a reference white is obtained
- the required amount of each primary colors for matching with the referent white is taken as its unit value (R = 1, G = 1, B = 1; W = 1R* + 1G* + 1B*)
- the unit amount of primary color can be expressed in units of luminous flux [lm], luminance [cd/m^2] or luminous intensity [cd]

Colorimetry

- color-matching experiment gives the amounts of red, green and blue primary color in unknown color C

$$\boldsymbol{m} = \mathbf{R} + \mathbf{G} + \mathbf{B}$$

  - ***m*** is overall tristimulus value of color C

- if **C*** represents unit amount of color C in R*G*B* system then follows

$$\mathbf{C} = \boldsymbol{m}\cdot\mathbf{C}^* = \mathbf{R}\cdot\mathbf{R}^* + \mathbf{G}\cdot\mathbf{G}^* + \mathbf{B}\cdot\mathbf{B}^*$$

- the referent white in this system is:

$$\mathrm{W} = m\cdot\mathrm{W}^* = 1\cdot\mathrm{R}^* + 1\cdot\mathrm{G}^* + 1\cdot\mathrm{B}^*$$

  - overall tristimulus value of the referent white (W) is *m*=3

Colorimetry

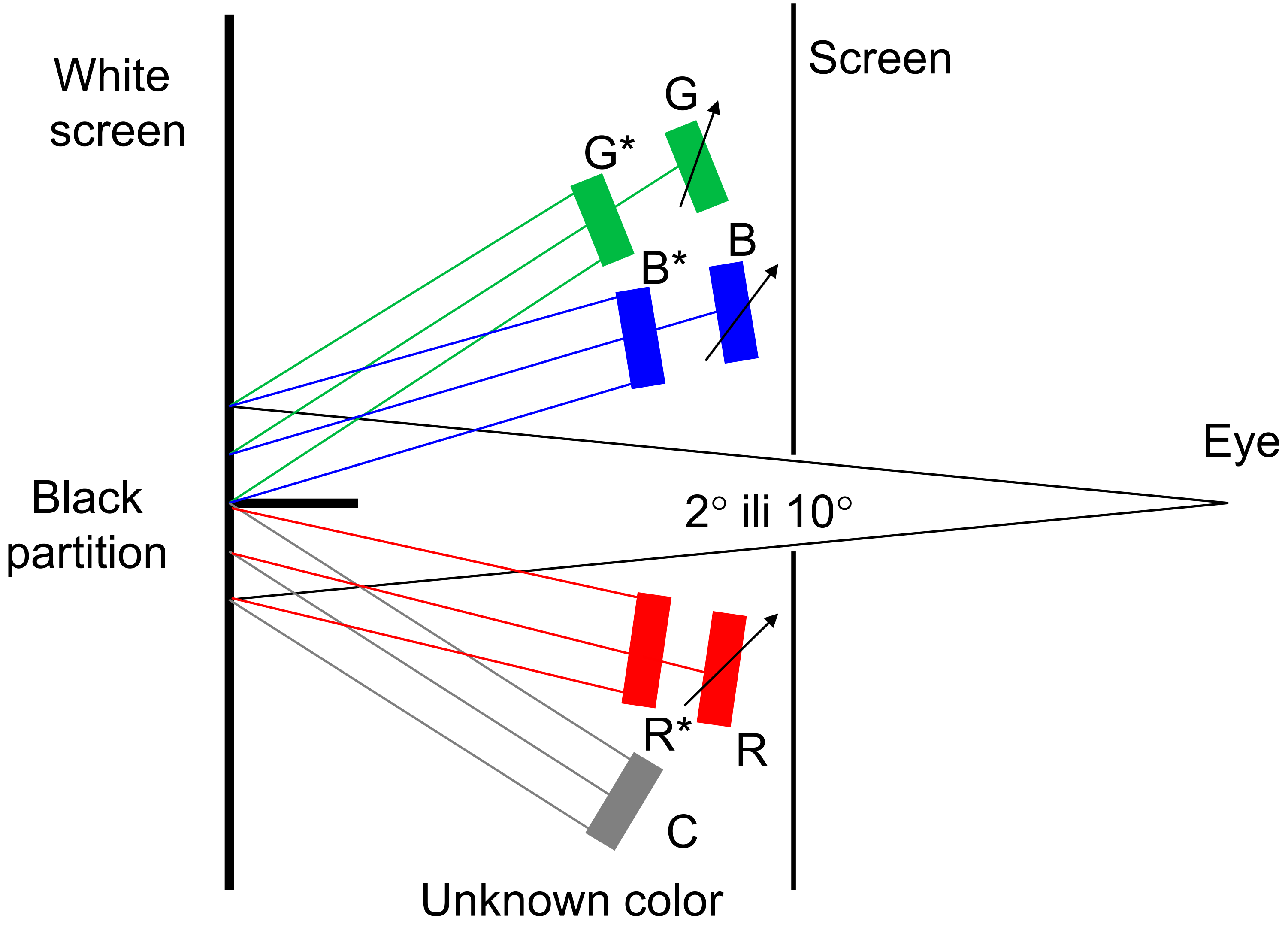
- unknown color can be more saturated than the color C that can be produced by mixing R*, G* i B* u colorimeter
- in this case C should be illuminated with complementary light
- one of the primary color should be moved to the unknown color side (for example RR*)
  - by adding RR* to color C, color C becomes less saturated and can be matched with the mixture of remaining components

$$\mathbf{C + R{\cdot}R^* = G{\cdot}G^* + B{\cdot}B^*}$$

$$\mathbf{C = G{\cdot}G^* + B{\cdot}B^* - R{\cdot}R^*}$$

  - the concept of a negative amount of color is introduced

Colorimetry



Colorimetry

- unit equation
  - the unknown color was determined using three parameters
  - if we want to geometrically represent colors we have to use a spatial coordinate system
  - if we want to display colors in a two-dimensional coordinate system, it is necessary to reduce the triple values to two independent quantities

$$\mathrm{C} = m \cdot \mathrm{C}^* = \mathrm{R} \cdot \mathrm{R}^* + \mathrm{G} \cdot \mathrm{G}^* + \mathrm{B} \cdot \mathrm{B}^* \quad \Big/ \quad m = \mathrm{R} + \mathrm{G} + \mathrm{B}$$

$$1 \cdot \mathrm{C}^* = \frac{\mathrm{R}}{m} \mathrm{R}^* + \frac{\mathrm{G}}{m} \mathrm{G}^* + \frac{\mathrm{B}}{m} \mathrm{B}^*$$

Colorimetry

- we can write

$$r = \frac{\mathrm{R}}{\mathrm{m}} = \frac{\mathrm{R}}{\mathrm{R}+\mathrm{G}+\mathrm{B}}$$

$$g = \frac{\mathrm{G}}{\mathrm{m}} = \frac{\mathrm{G}}{\mathrm{R}+\mathrm{G}+\mathrm{B}}$$

$$b = \frac{\mathrm{B}}{\mathrm{m}} = \frac{\mathrm{B}}{\mathrm{R}+\mathrm{G}+\mathrm{B}}$$

- then follows:

$$1 \cdot \mathrm{C}^* = r \cdot \mathrm{R}^* + g \cdot \mathrm{G}^* + b \cdot \mathrm{B}^*$$

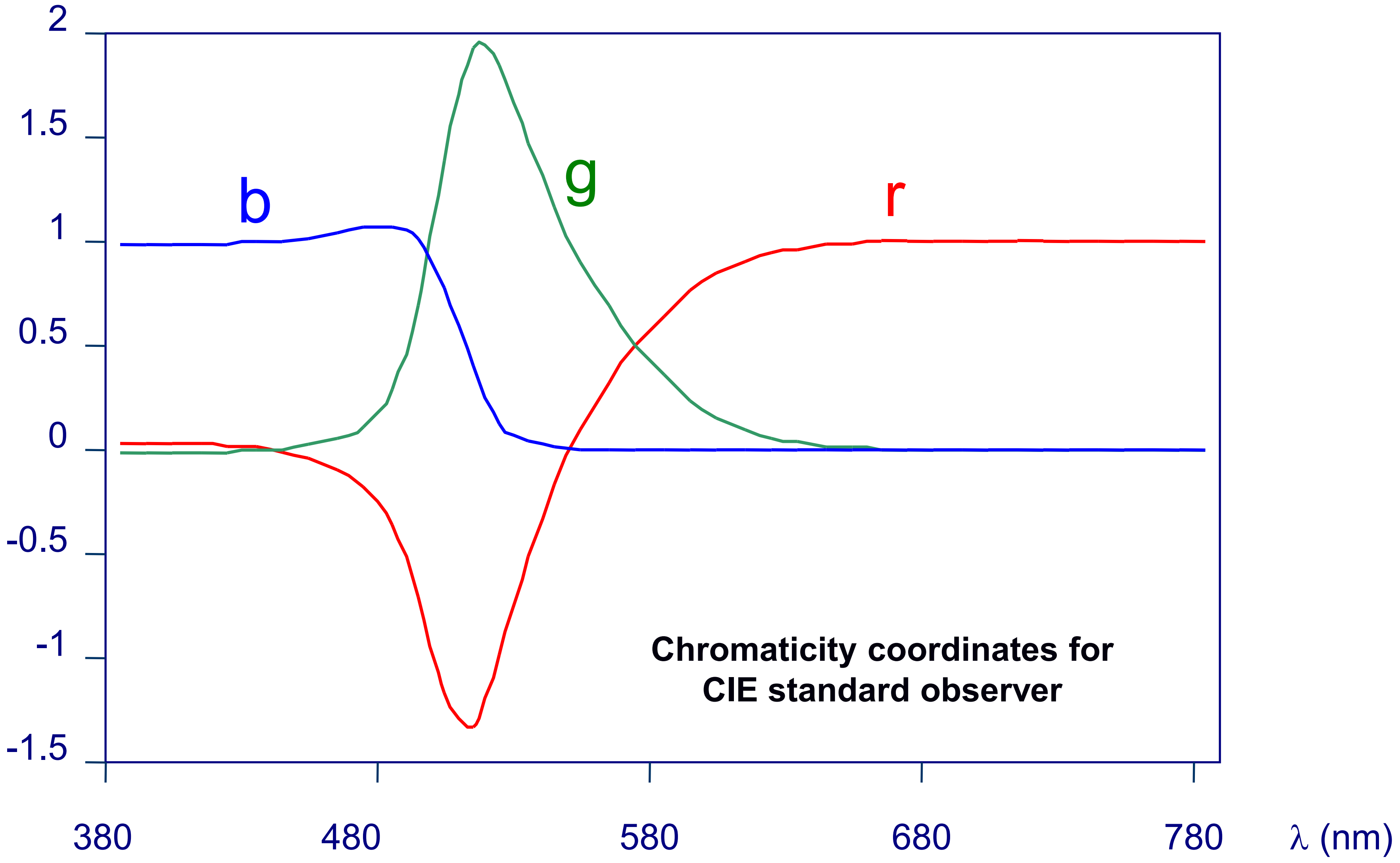
UNIT EQUATION: $r + g + b = 1$

chromaticity coordinates
or trichromatic coefficients

Colorimetry

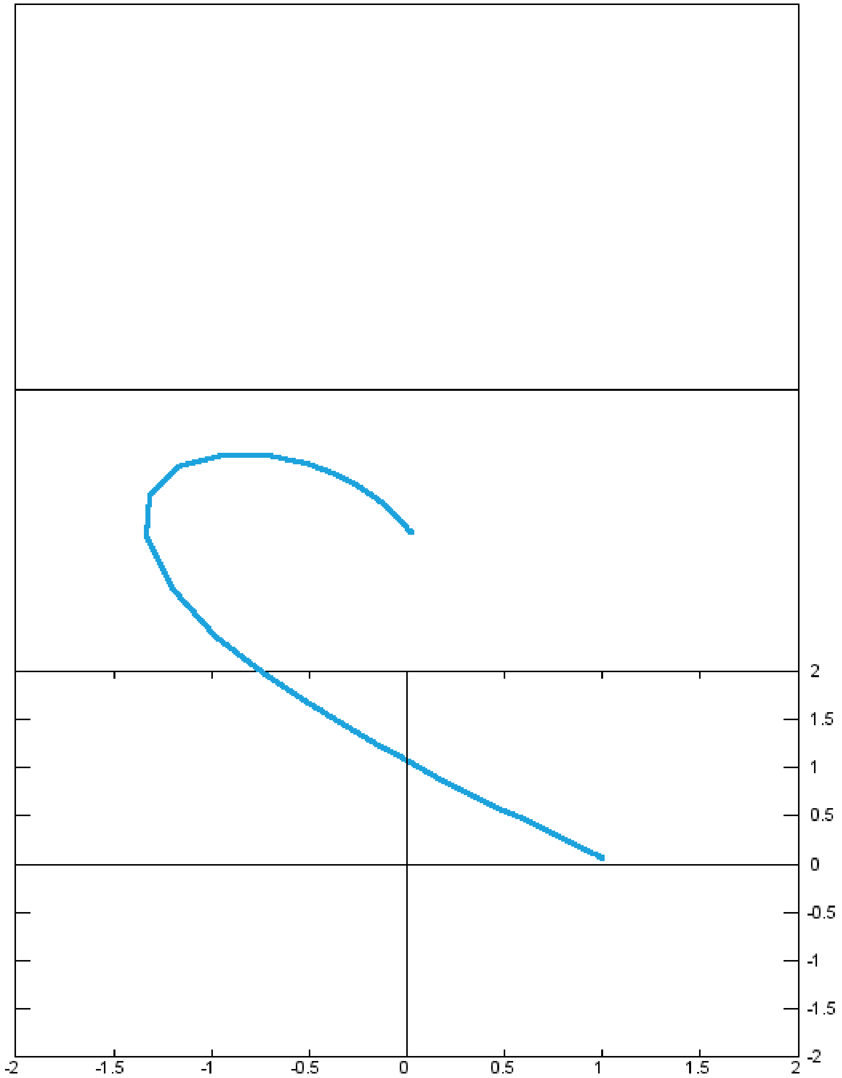
- in the 1931 CIE experiment, monochromatic spectral colors were used as unknown colors C
  - monochromatic <u>spectral colors</u> are formed by dividing the spectrum of white light into narrow intervals (5 nm or 10 nm)
  - each interval represents one monochromatic spectral color
  - spectral colors are fully saturated colors
  - if the values of R, G and B are determined experimentally for spectral colors, for other colors they can be determined by calculations
- for each spectral color, R, G, and B are determined experimentally
  - r, g and b are calculated from R, G and B
    - in the green-blue region the matching cannot be achieved with positive amounts of R*, G* and B* (r has a region with negative values)

Colorimetry



Colorimetry

- every value of rgb can be ploted as a point in three dimensions
- this gives us a curve that represents the chromaticity of each spectral wavelength of light, also called a <u>spectral locus</u>



Colorimetry

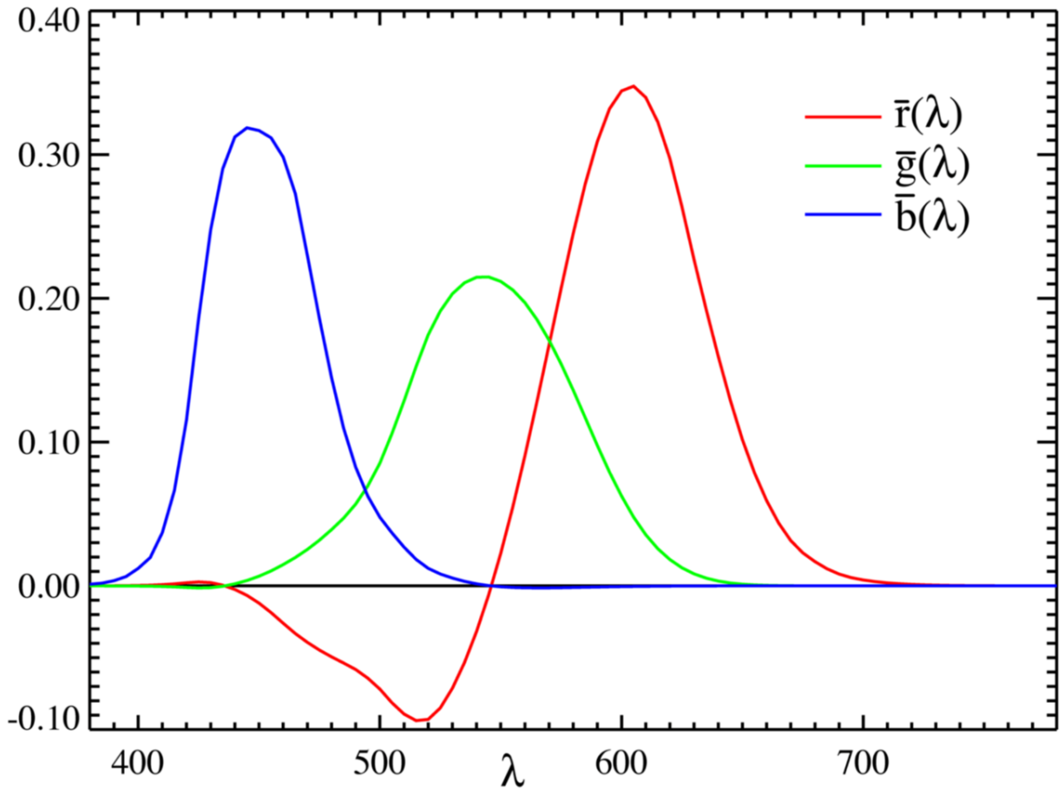
- spectral color C_λ with radiant power P=1W, is denoted as: $\overline{C_\lambda}$
- R, G i B components of this color are known as distribution coefficients: $\bar{r}$, $\bar{g}$ i $\bar{b}$
- we can write:

$$\overline{C_\lambda} = \bar{r} \cdot R^* + \bar{g} \cdot G^* + \bar{b} \cdot B^*$$

$$\bar{r} + \bar{g} + \bar{b} \neq 1$$

Colorimetry

- distribution coefficients define color matching curves
  - distribution coefficients are calculated from chromaticity coordinates
  - the areas under the curves are equal



Colorimetry

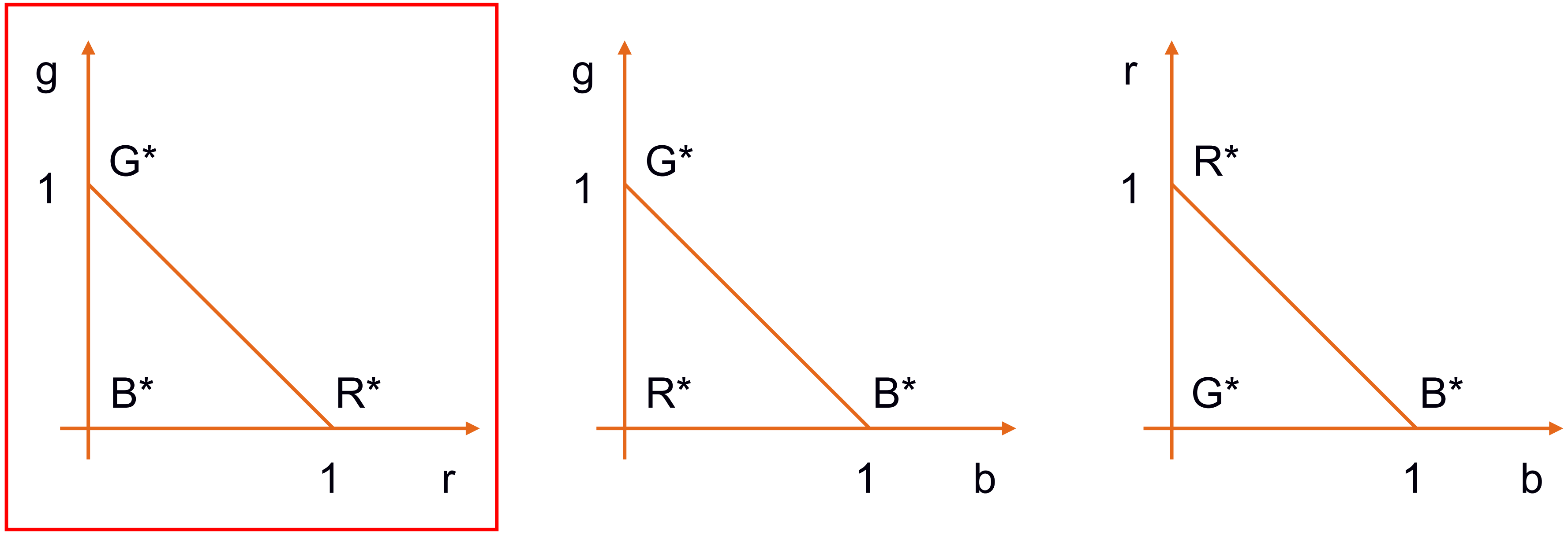
- table with chromaticity coordinates (trichromatic coefficients) and distribution coefficients for the 1931 CIE standard observer in the RGB system

CIE 1931 Standard Observer and *RGB* Coordinate Systems

Trichromatic coefficients			λ, nm	Distribution coefficients (equal-energy stimulus)		
r	g	b		$\bar{r}$	$\bar{g}$	$\bar{b}$
0.0272	−0.0115	0.9843	380	0.00003	−0.00001	0.00117
0.0263	−0.0114	0.9851	390	0.00010	−0.00004	0.00359
0.0247	−0.0112	0.9865	400	0.00030	−0.00014	0.01214
0.0225	−0.0109	0.9884	410	0.00084	−0.00041	0.03707
0.0181	−0.0094	0.9913	420	0.00211	−0.00110	0.11541
0.0088	−0.0048	0.9960	430	0.00218	−0.00119	0.24769
−0.0084	−0.0048	1.0036	440	−0.00261	0.00149	0.31228
−0.0390	0.0218	1.0172	450	−0.01213	0.00678	0.31670
−0.0909	0.0517	1.0392	460	−0.02608	0.01485	0.29821
−0.1821	0.1175	1.0646	470	−0.03933	0.02538	0.22991
−0.3667	0.2906	1.0761	480	−0.04939	0.03914	0.14494
−0.7150	0.6996	1.0154	490	−0.05814	0.05689	0.08257
−1.1685	1.3905	0.7780	500	−0.07173	0.08536	0.04776
−1.3371	1.9318	0.4053	510	−0.08901	0.12860	0.02698
−0.9830	1.8534	0.1296	520	0.09264	0.17468	0.01221
−0.5159	1.4761	0.0398	530	−0.07101	0.20317	0.00549
−0.1707	1.1628	0.0079	540	−0.03152	0.21466	0.00146
0.0974	0.9051	−0.0025	550	0.02279	0.21178	−0.00058
0.3164	0.6881	−0.0045	560	0.09060	0.19702	−0.00130
0.4973	0.5067	−0.0040	570	0.16768	0.17087	−0.00135
0.6449	0.3579	−0.0028	580	0.24526	0.13610	−0.00108
0.7617	0.2402	−0.0019	590	0.30928	0.09754	−0.00079
0.8475	0.1537	−0.0012	600	0.34429	0.06246	−0.00049
0.9059	0.0949	−0.0008	610	0.33971	0.03557	−0.00030
0.9425	0.0580	−0.0005	620	0.29708	0.01828	−0.00015
0.9649	0.0354	−0.0003	630	0.22677	0.00833	−0.00008
0.9797	0.0205	−0.0002	640	0.15968	0.00334	−0.00003
0.9888	0.0113	−0.0001	650	0.10167	0.00116	−0.00001
0.9940	0.0061	−0.0001	660	0.05932	0.00037	0.00000
0.9966	0.0035	0.0001	670	0.03149	0.00011	0.00000
0.9984	0.0016	0.0000	680	0.01687	0.00003	0.00000
0.9996	0.0004	0.0000	690	0.00819	0.00000	0.00000
1.0000	0.0000	0.0000	700	0.00410	0.00000	0.00000
1.0000	0.0000	0.0000	710	0.00210	0.00000	0.00000
1.0000	0.0000	0.0000	720	0.00105	0.00000	0.00000
1.0000	0.0000	0.0000	730	0.00052	0.00000	0.00000
1.0000	0.0000	0.0000	740	0.00025	0.00000	0.00000
1.0000	0.0000	0.0000	750	0.00012	0.00000	0.00000
1.0000	0.0000	0.0000	760	0.00006	0.00000	0.00000
1.0000	0.0000	0.0000	770	0.00003	0.00000	0.00000
1.0000	0.0000	0.0000	780	0.00000	0.00000	0.00000
Algebraic sum				1.89088	1.89107	1.88942

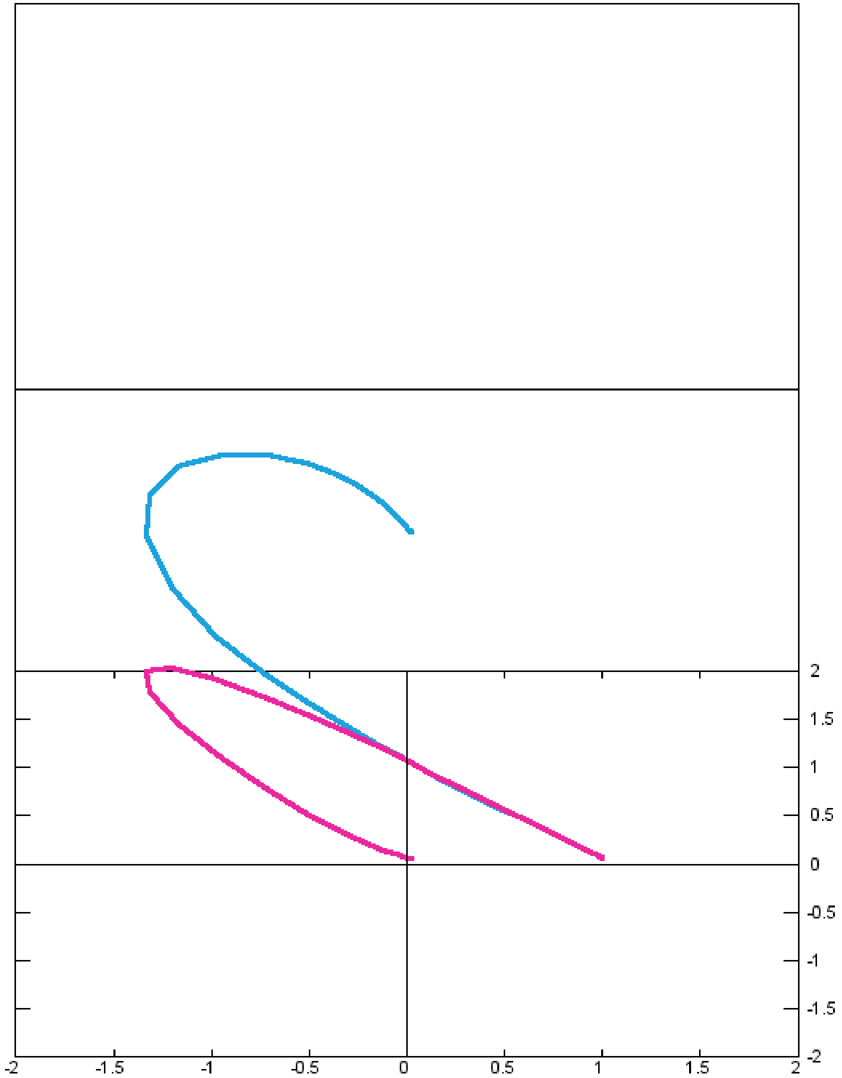
Colorimetry

- $r + g + b = 1$
- it is enough to know two chromaticity coordinates to determine the third
- we can safely drop a dimension without losing information
- there are three possible simplified representations (rg representation is most often used)



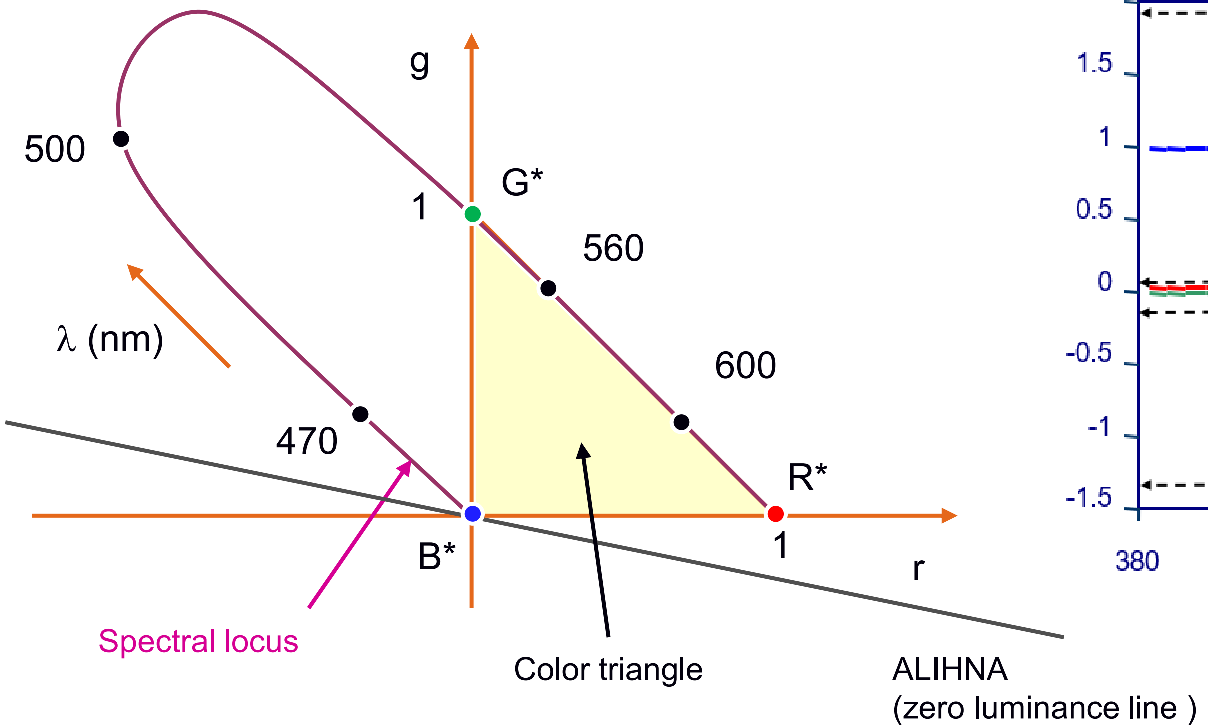
Colorimetry

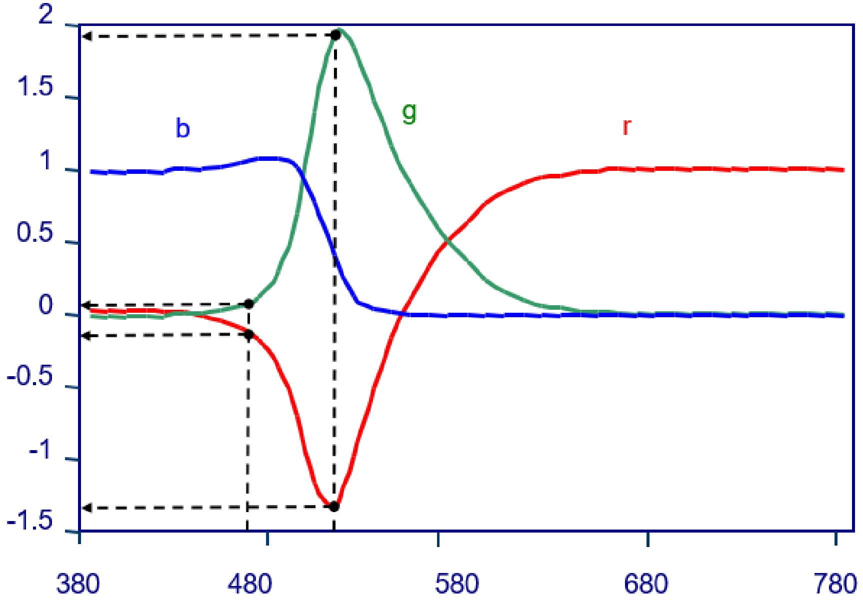
- b-axis is converted to all zeroes
- rg is plotted in two dimensions (this i called a projection to the rg-plane)
- it is our first chromaticity diagram



Colorimetry

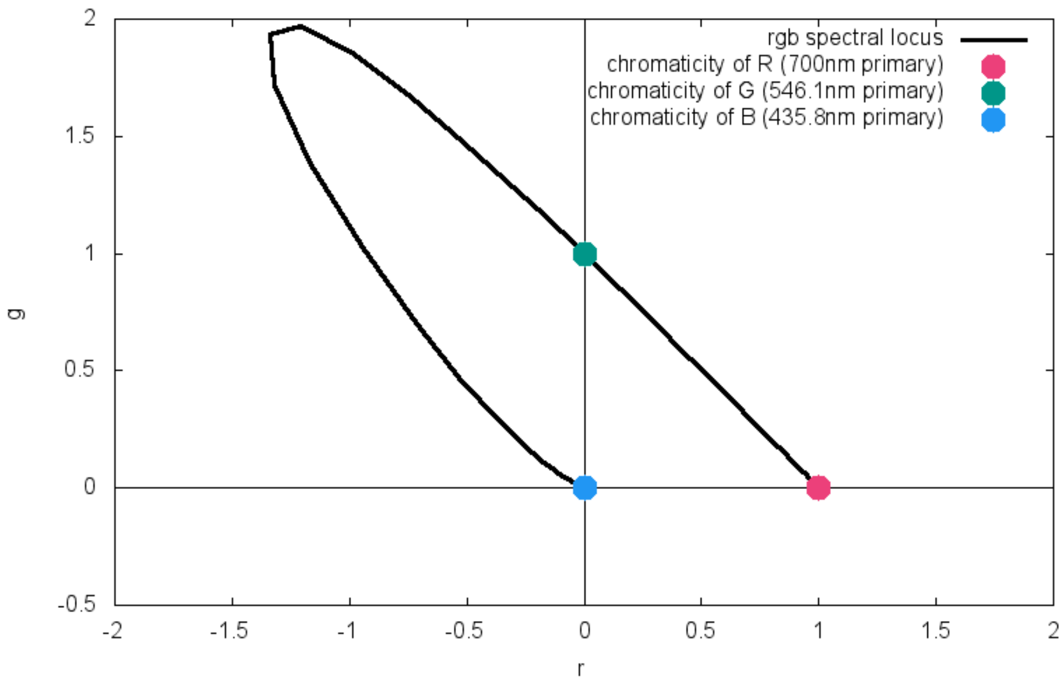
- chromaticity coordinates for spectral colors in rg-chromaticity diagram





Colorimetry

- chromaticity coordinates for spectral colors in rg-chromaticity diagram
  - every point on the outer curve is the chromaticity coordinate of a spectral color
  - every point inside the curve is a chromaticity of a non-spectral color
  - every point outside the curve is an imaginary chromaticity that is meaningless and has no realizable color
  - original RGB primaries, are spectral colors, so they fall on the curve
  - every point inside the triangle formed by the primaries is a chromaticity that can be created with those lights
  - points inside the curve but not the triangle are real chromaticities but you would need different primary lights to create them



Colorimetry

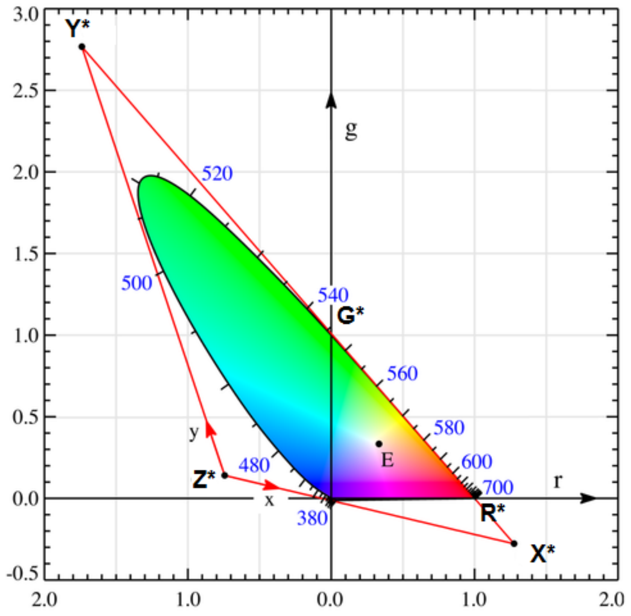
- the disadvantage of the RGB color system is that the chromatic coordinates r, g and b have negative values, which makes the calculations complex
  - the spectral curve extends beyond the color triangle
  - the vertices of the color triangles are determined by the unit quantities of the primary colors (R *, G *, B *)
  - colors located within the color triangle can be represented by positive amounts of primary
- the RGB system is transformed into an XYZ system
  - X, Y, Z - non-physical (non-existent) primaries (mathematical abstraction that facilitates calculations)
  - the r, g and b chromaticity coordinates are transformed into the x, y and z chromaticity coordinates

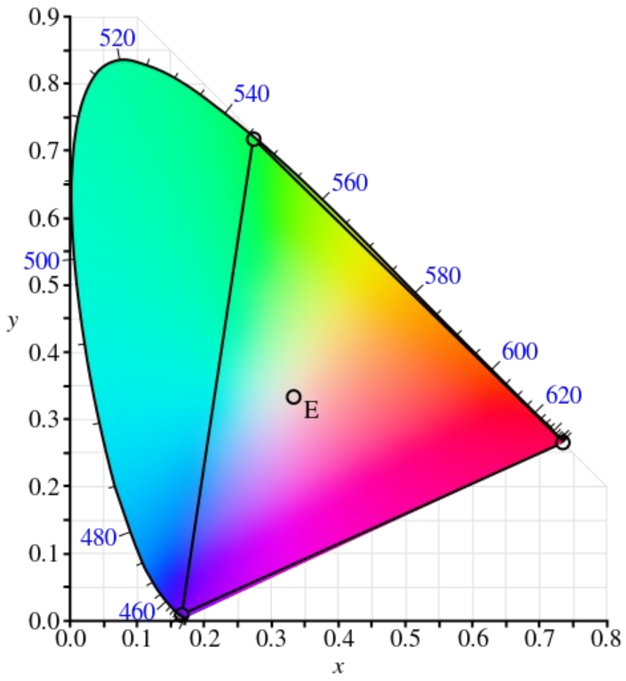
Colorimetry

- properties of the XYZ system
  - the spectral locus lies within the XYZ color triangle (all colors can be represented by positive amounts of primary XYZ)
  - the same relationships apply as in the RGB system

$$C = m \cdot C^* = X \cdot X^* + Y \cdot Y^* + Z \cdot Z^* \qquad m = X + Y + Z$$

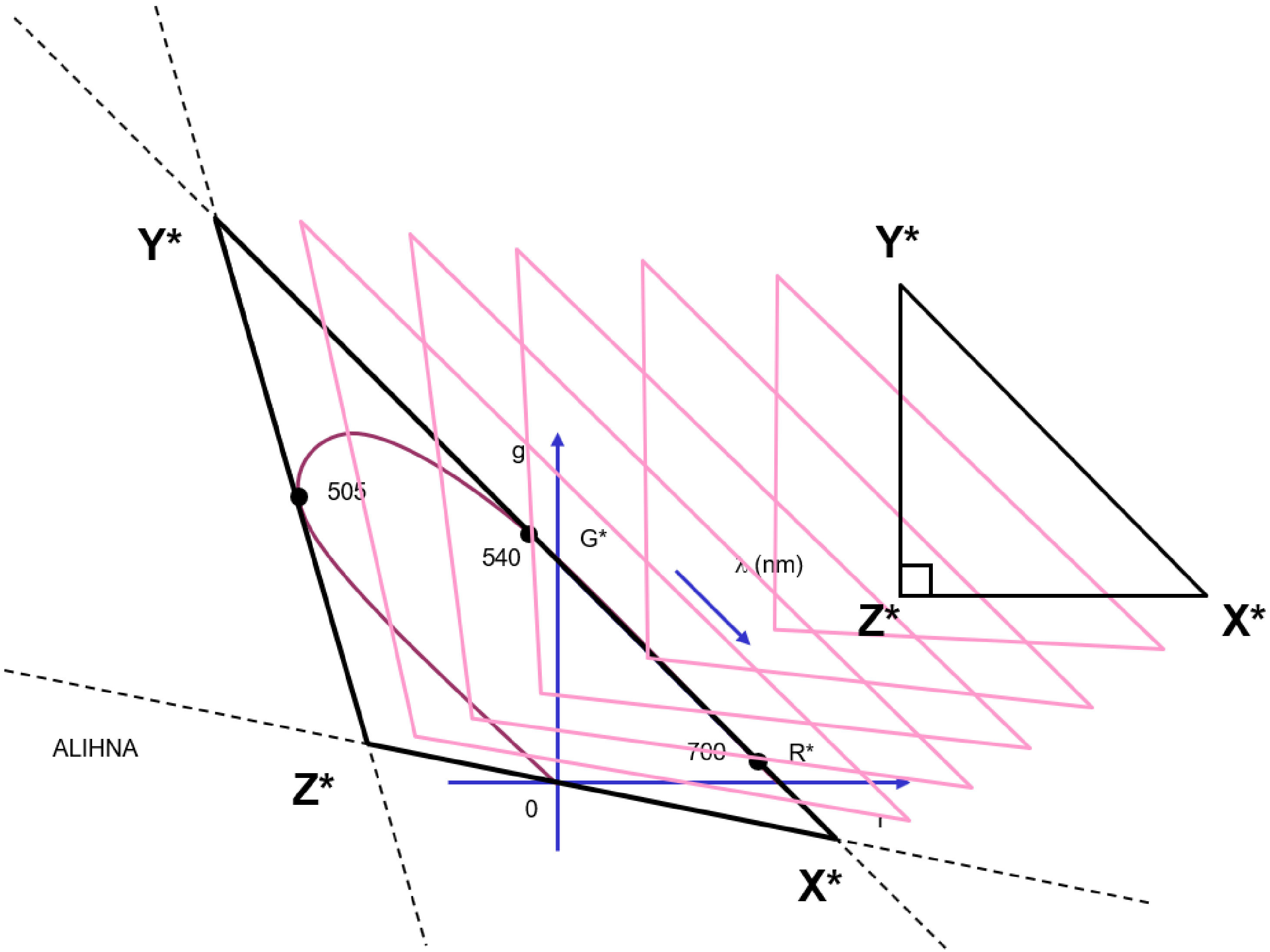
$$C^* = x \cdot X^* + y \cdot Y^* + z \cdot Z^* \qquad x + y + z = 1$$



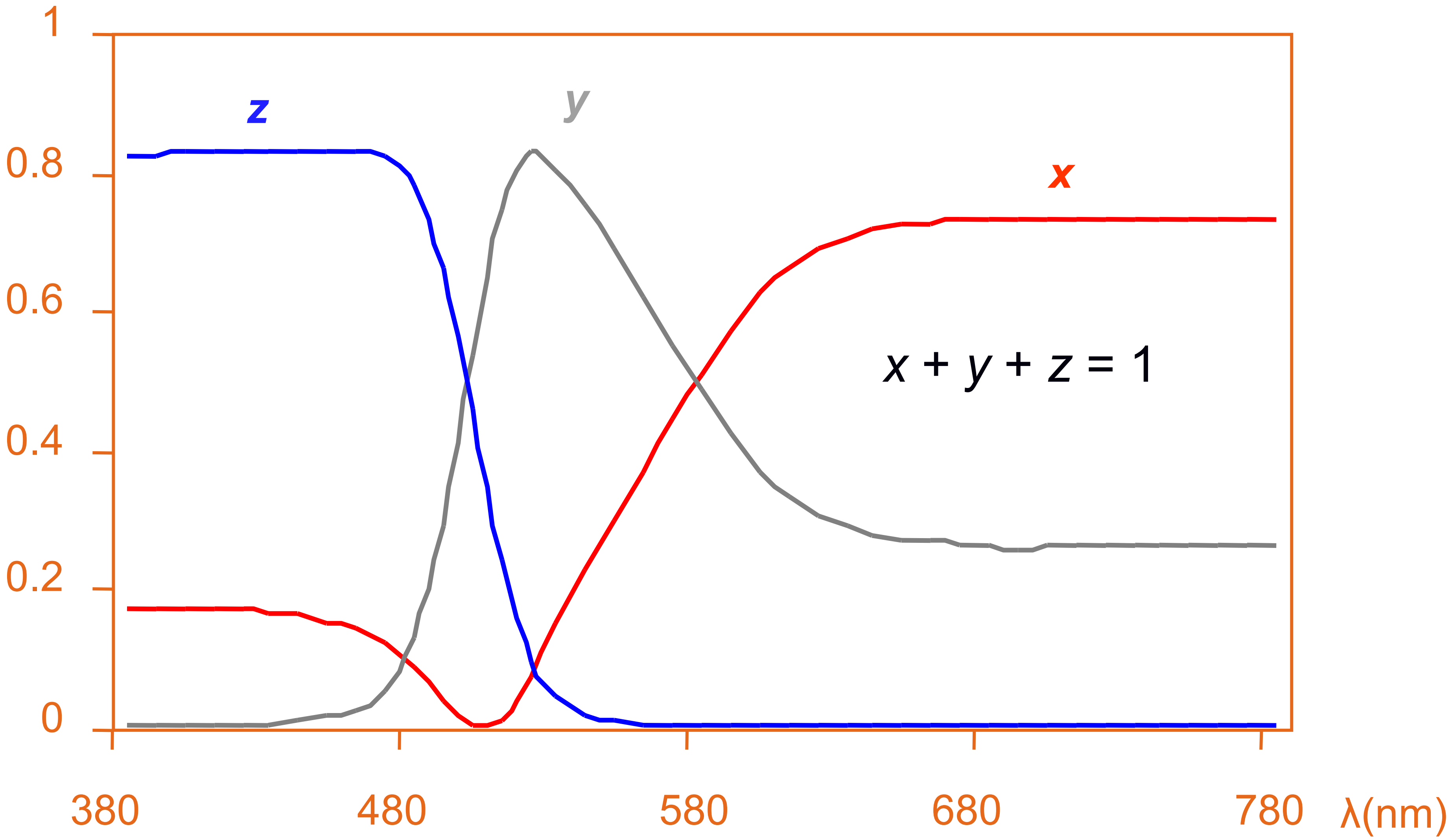


Colorimetry

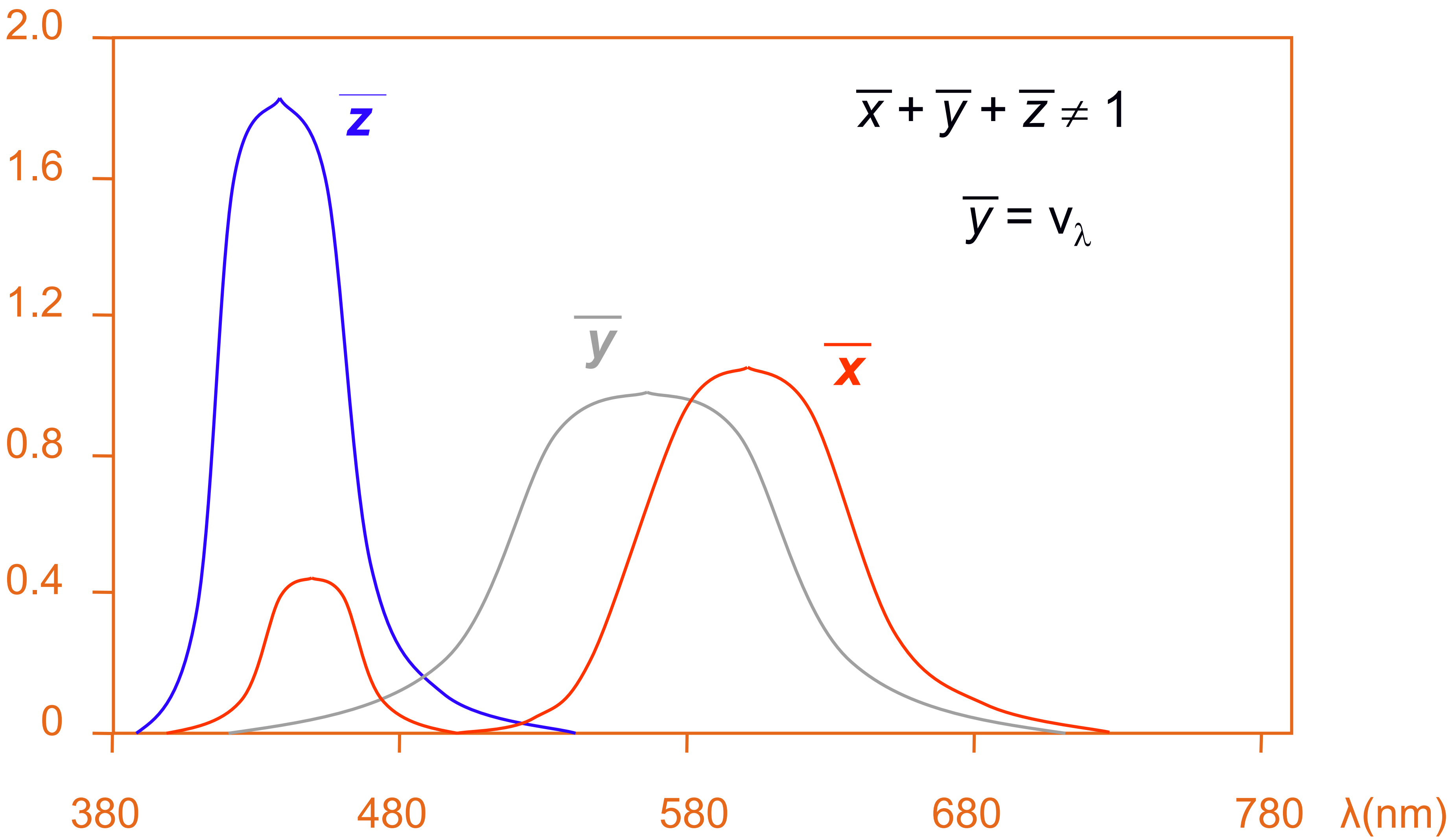
- construction of XYZ system



Colorimetry



Colorimetry



Colorimetry

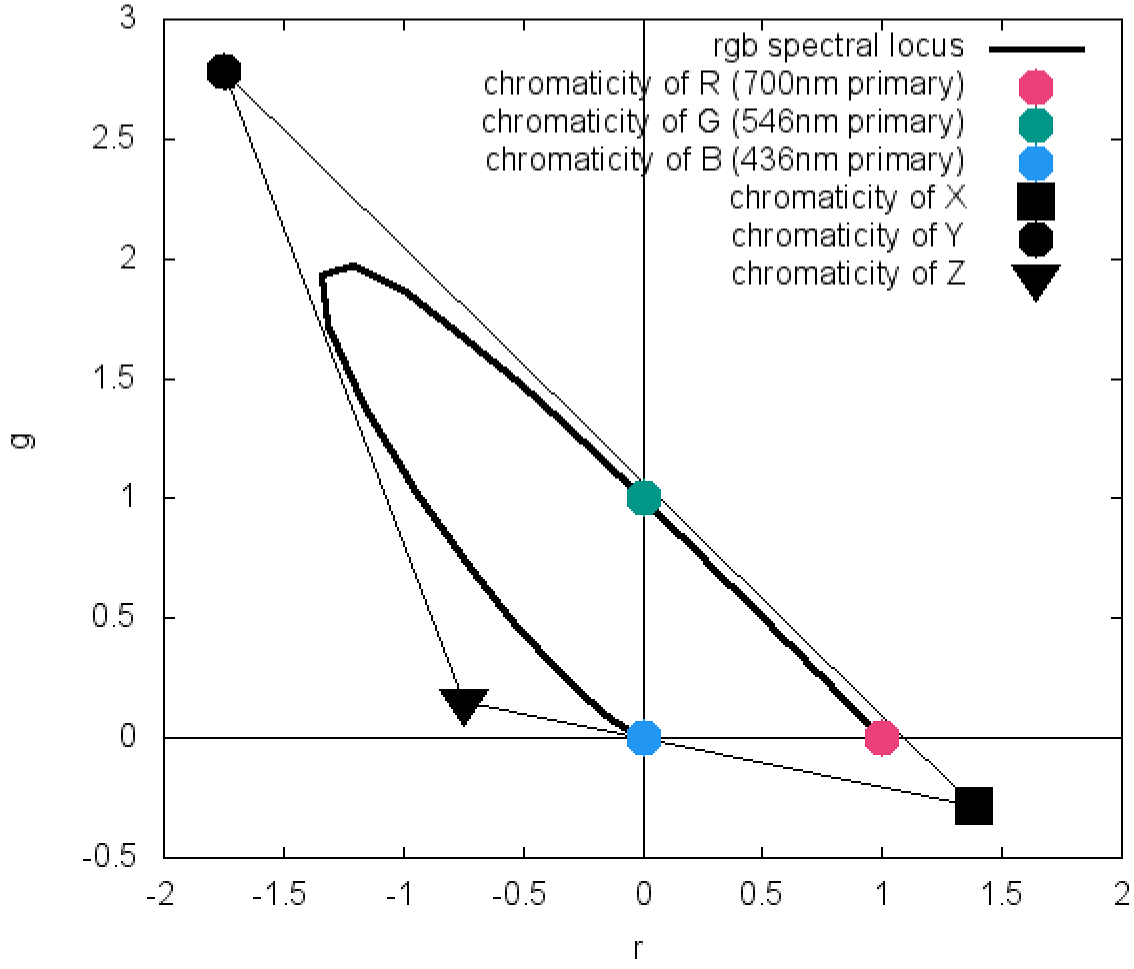
- table with chromaticity coordinates (trichromatic coefficients) and distribution coefficients for the 1931 CIE standard observer in the XYZ system

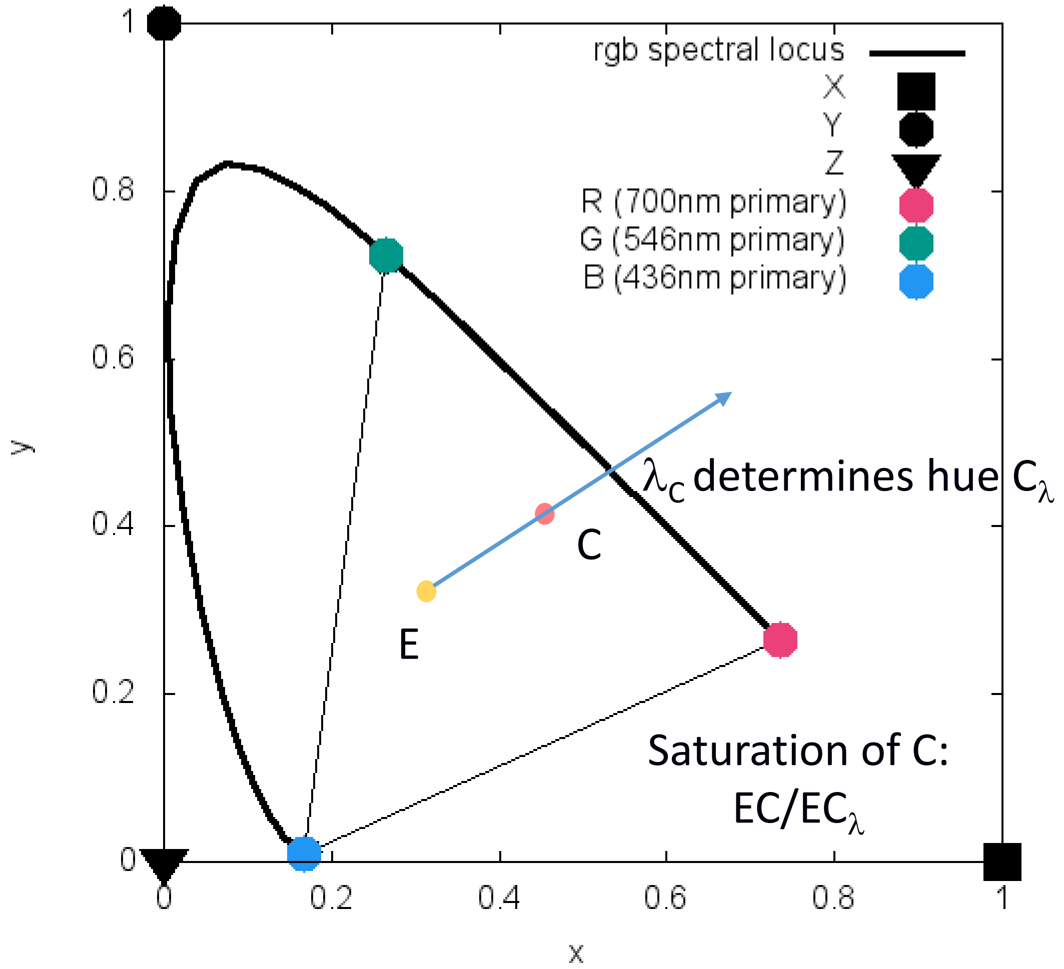
x	y	z	λ, nm	$\bar{x}$	$\bar{y}$	$\bar{z}$
0.1741	0.0050	0.8209	380	0.0014	0.0000	0.0065
0.1738	0.0049	0.8213	390	0.0042	0.0001	0.0201
0.1733	0.0048	0.8219	400	0.0143	0.0004	0.0679
0.1726	0.0048	0.8226	410	0.0435	0.0012	0.2074
0.1714	0.0051	0.8235	420	0.1344	0.0040	0.6456
0.1689	0.0069	0.8242	430	0.2839	0.0116	1.3856
0.1644	0.0109	0.8247	440	0.3483	0.0230	1.7471
0.1566	0.0177	0.8257	450	0.3362	0.0380	1.7721
0.1440	0.0297	0.8263	460	0.2908	0.0600	1.6692
0.1241	0.0578	0.8181	470	0.1954	0.0910	1.2876
0.0913	0.1327	0.7760	480	0.0956	0.1390	0.8130
0.0454	0.2950	0.6596	490	0.0320	0.2080	0.4652
0.0082	0.5384	0.4534	500	0.0049	0.3230	0.2720
0.0139	0.7502	0.2359	510	0.0093	0.5030	0.1582
0.0743	0.8338	0.0919	520	0.0633	0.7100	0.0782
0.1547	0.8059	0.0394	530	0.1655	0.8620	0.0422
0.2296	0.7543	0.0161	540	0.2904	0.9540	0.0203
0.3016	0.6923	0.0061	550	0.4334	0.9950	0.0087
0.3731	0.6245	0.0024	560	0.5945	0.9950	0.0039
0.4441	0.5547	0.0012	570	0.7621	0.9520	0.0021
0.5125	0.4866	0.0009	580	0.9163	0.8700	0.0017
0.5752	0.4242	0.0006	590	1.0263	0.7570	0.0011
0.6270	0.3725	0.0005	600	1.0622	0.6310	0.0008
0.6658	0.3340	0.0002	610	1.0026	0.5030	0.0003
0.6915	0.3083	0.0002	620	0.8544	0.3810	0.0002
0.7079	0.2920	0.0001	630	0.6424	0.2650	0.0000
0.7190	0.2809	0.0001	640	0.4479	0.1750	0.0000
0.7260	0.2740	0.0000	650	0.2835	0.1070	0.0000
0.7300	0.2700	0.0000	660	0.1649	0.0610	0.0000
0.7320	0.2680	0.0000	670	0.0874	0.0320	0.0000
0.7334	0.2666	0.0000	680	0.0468	0.0170	0.0000
0.7344	0.2656	0.0000	690	0.0227	0.0082	0.0000
0.7347	0.2653	0.0000	700	0.0114	0.0041	0.0000
0.7347	0.2653	0.0000	710	0.0058	0.0021	0.0000
0.7347	0.2653	0.0000	720	0.0029	0.0010	0.0000
0.7347	0.2653	0.0000	730	0.0014	0.0005	0.0000
0.7347	0.2653	0.0000	740	0.0007	0.0003	0.0000
0.7347	0.2653	0.0000	750	0.0003	0.0001	0.0000
0.7347	0.2653	0.0000	760	0.0002	0.0001	0.0000
0.7347	0.2653	0.0000	770	0.0001	0.0000	0.0000
0.7347	0.2653	0.0000	780	0.0000	0.0000	0.0000
	Sum			10.6836	10.6857	10.6770

Colorimetry

- the CIE chromaticity diagram is obtained by transforming the rg-chromaticity diagram into an xy-chromaticity diagram in which the XYZ triangle is right triangle
- horseshoe diagram is the name for the area bounded by a spectral curve and a straight line connecting the edges of the spectral locus
- for the unknown color C in the horseshoe diagram the following values are read:
  - **HUE**
    - determined by drawing a half-line from the point of reference white (E) through an unknown color (C)
    - at the point where the half-line intersects the spectral curve, we can read the wavelength λ_C which determines hue C_λ
  - **SATURATION**
    - depends on the length of the EC
    - the greater this length, the greater the saturation
    - the closer the unknown color is to the spectral curve, the saturation of unknown color is greater

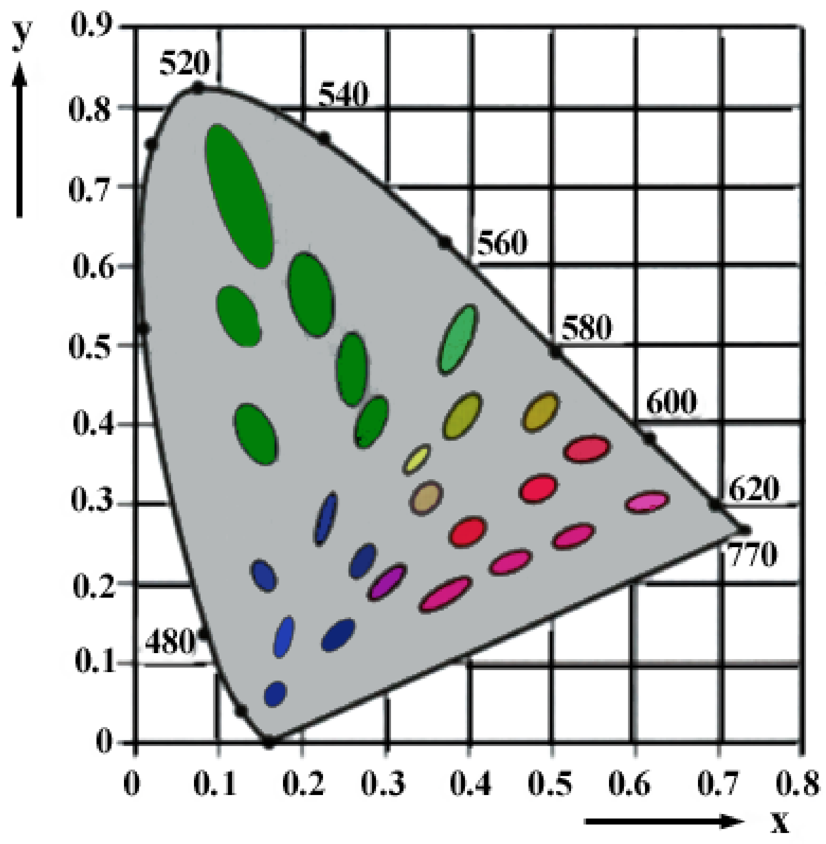
Colorimetry





Colorimetry

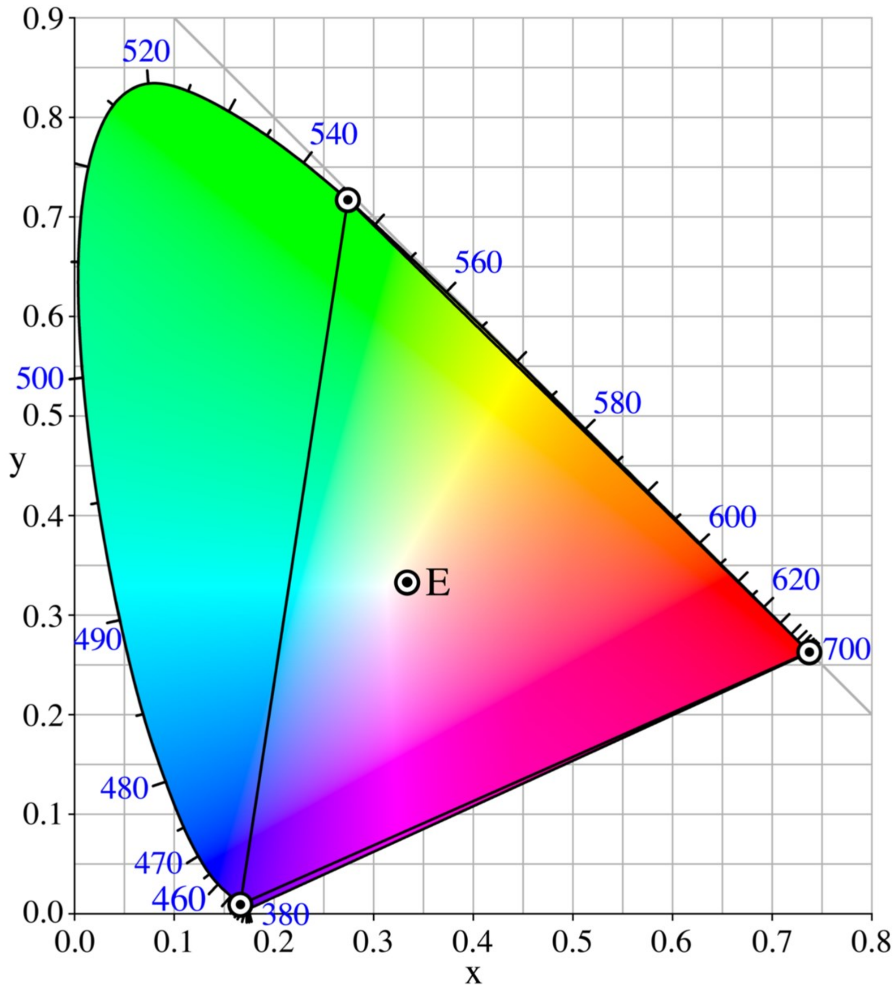
- shortcomings of color representation in the CIE chromaticity diagram
  - perceptual inequality
    - the areas of the same color are not the same in all parts of the diagram (the largest are in the green area and the smallest in the blue area)
  - the dominant wavelengths are unequally distributed around the edge of the diagram



Colorimetry

- RGB color triangle in CIE chromaticity diagram

	x	y	z
R*	0,73	0,27	0
G*	0,27	0,72	0,01
B*	0,16	0,01	0,83

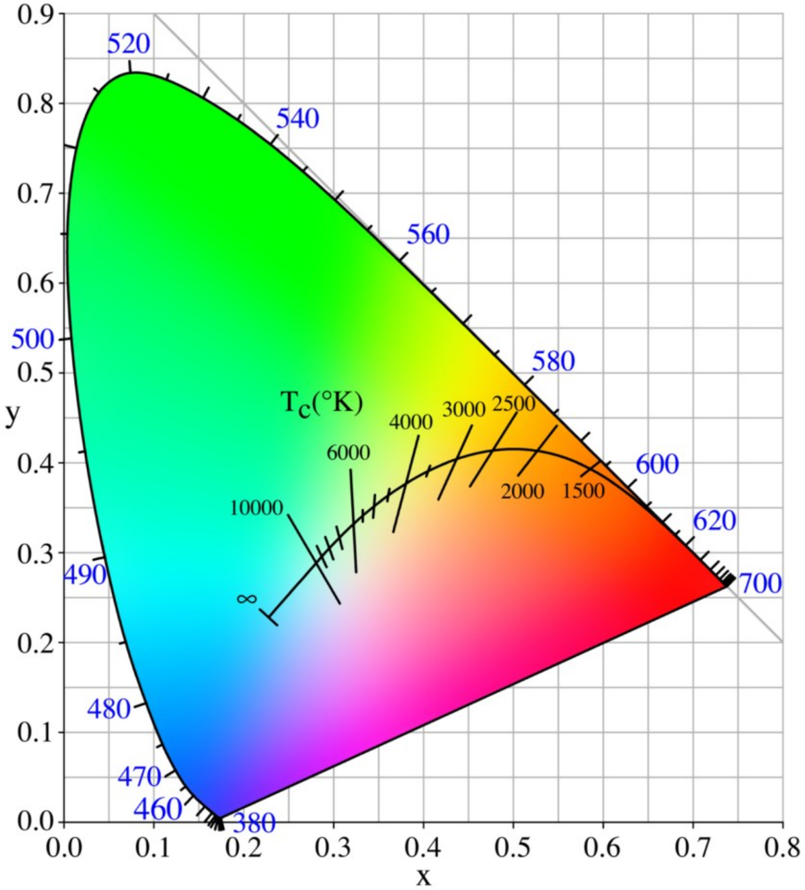


Colorimetry

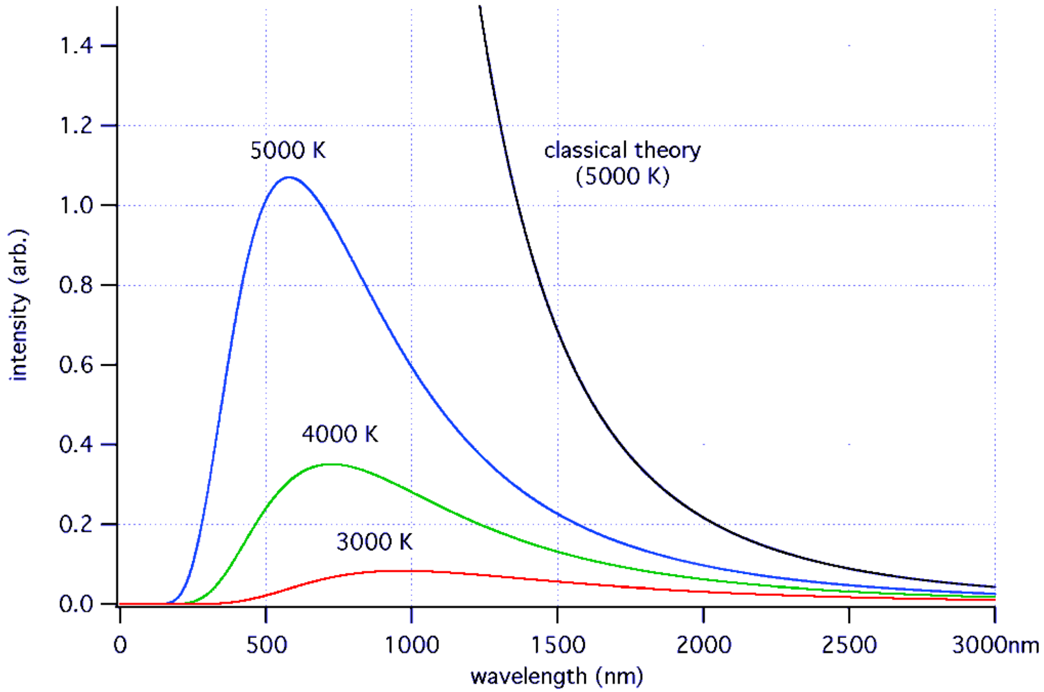
- all values depend on the definition of the referent white
- referent white is produced with standard illuminant: E, A, B, C, D
  - standard illuminant is defined by the color temperature
    - the temperature of a black body in K which heated to that temperature gives a certain chromaticity
    - the color produced by black body radiation in the visible light region is described by chromaticity coordinates
    - the chromaticity coordinates of the colors that are results of black body radiation at different temperatures lie on a curve called the Planckian locus
    - the spectral distribution of the radiant power of a black body at a given temperature changes with a change in wavelength in the visible light range

Colorimetry

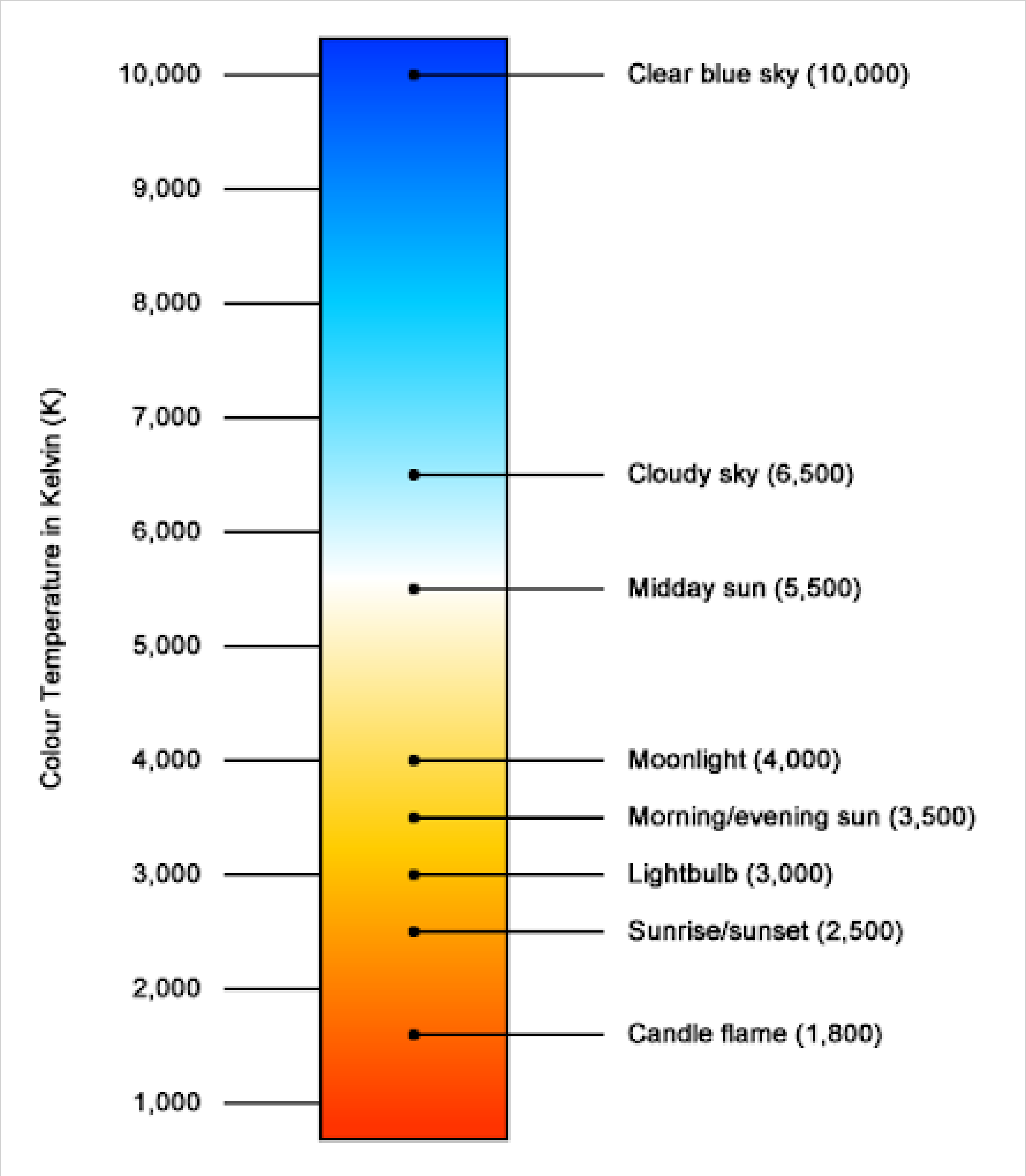
- Planckian locus



- power spectral distribution of black body radiation



Colorimetry



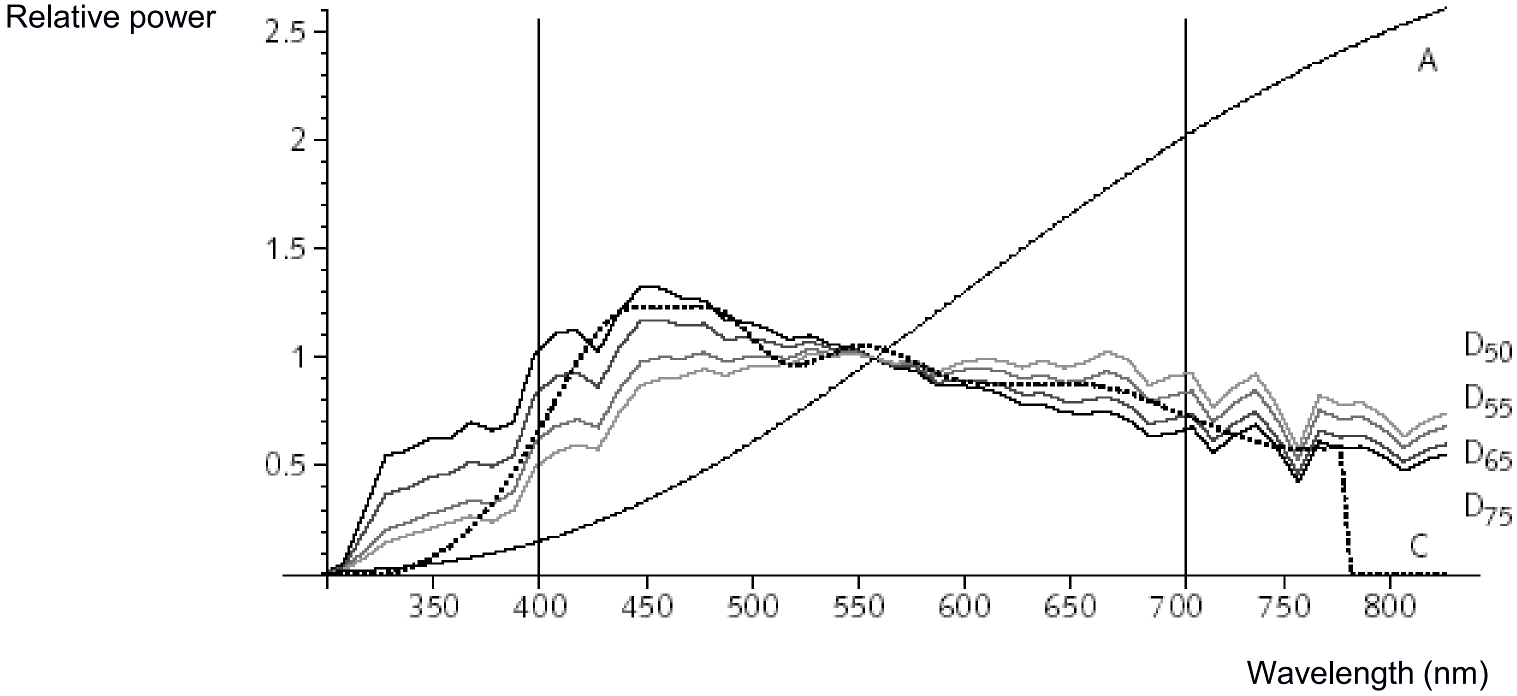
Colorimetry

- standard illuminant

Type	Color temperature [K]	CIE chromaticity coordinates (1931.)	
		x_w	y_w
Illuminant A	2856	0,4757	0,40745
Illuminant B	4874	0,34842	0,35161
Illuminant C	6774	0,31006	0,31616
Illuminant D65	6504	0,3127	0,3291
Illuminant D65	6504	0,312713	0,329016
Direct Sunlight	5335	0,3362	0,3502
Light from overcast sky	6500	0,3134	0,3275
Light from north sky on a 45-degree plane	10000	0,2773	0,2934
Illuminant E	5400	1/3	1/3

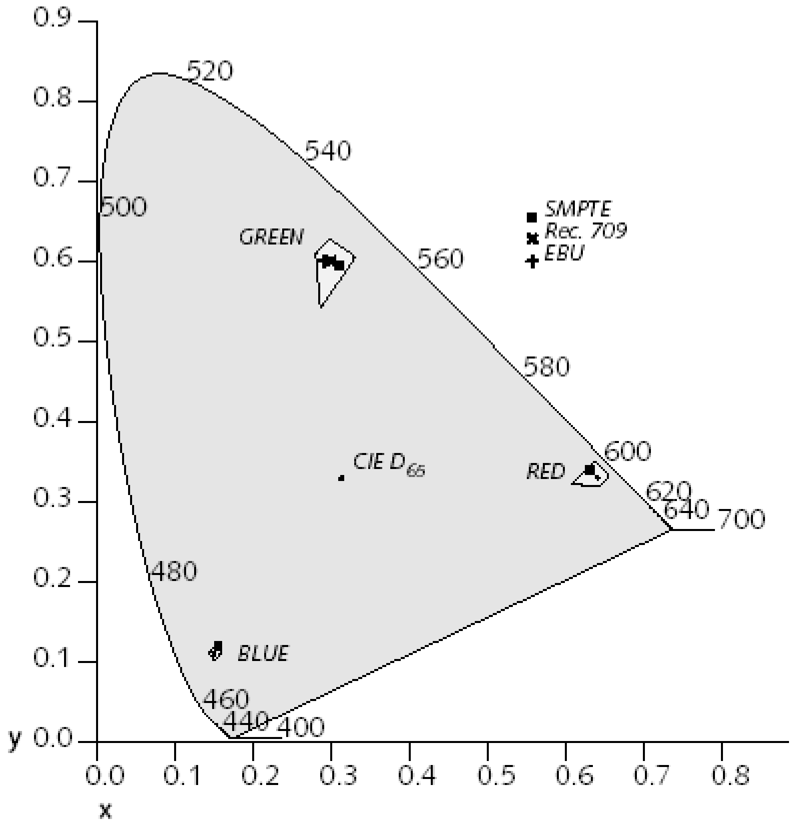
Colorimetry

- power spectral distribution of CIE standard illuminant



Colorimetry

- application of chromaticity diagram
  - comparison of the range of colors that can be displayed with differently defined primary colors



NTSC primary colors (white-C)

R:	xr=0.67	yr=0.33
G:	xg=0.21	yg=0.71
B:	xb=0.14	yb=0.08

SMPTE primary colors (white-D65)

R:	xr=0.630	yr=0.340
G:	xg=0.310	yg=0.595
B:	xb=0.155	yb=0.070

EBU primary colors (white-D65)

R:	xr=0.64	yr=0.33
G:	xg=0.29	yg=0.60
B:	xb=0.15	yb=0.06

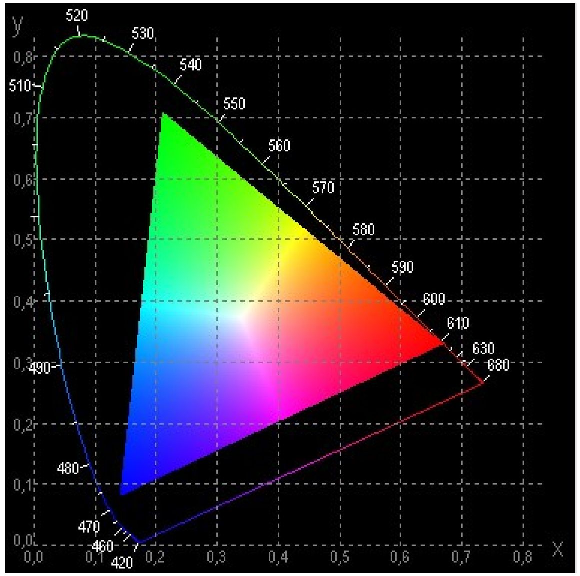
ITU-R BT.709 primary colors (white-D65)

R:	xr=0.64	yr=0.33
G:	xg=0.30	yg=0.60
B:	xb=0.15	yb=0.06

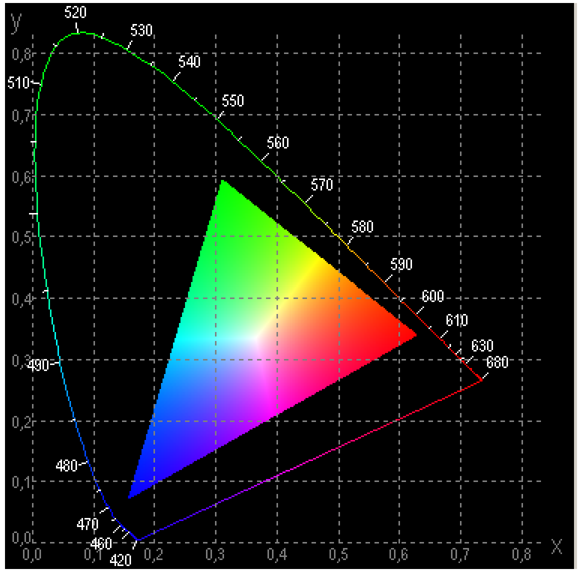
Colorimetry

- color triangle in chromaticity diagram for different systems of primary colors
  - a larger area of the color triangle means that it is possible to display a larger number of colors

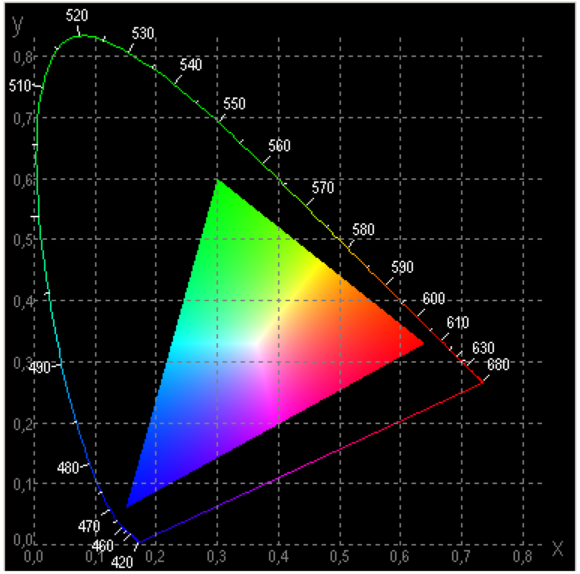
NTSC primari



SMPTE primari



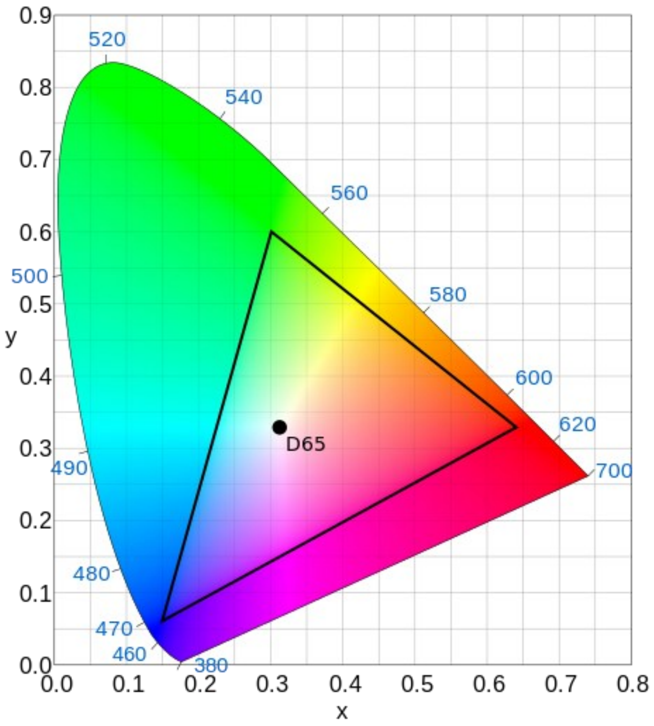
EBU primari



Colorimetry

- color triangle in chromaticity diagram for HDTV (Rec. ITU-R BT.709)

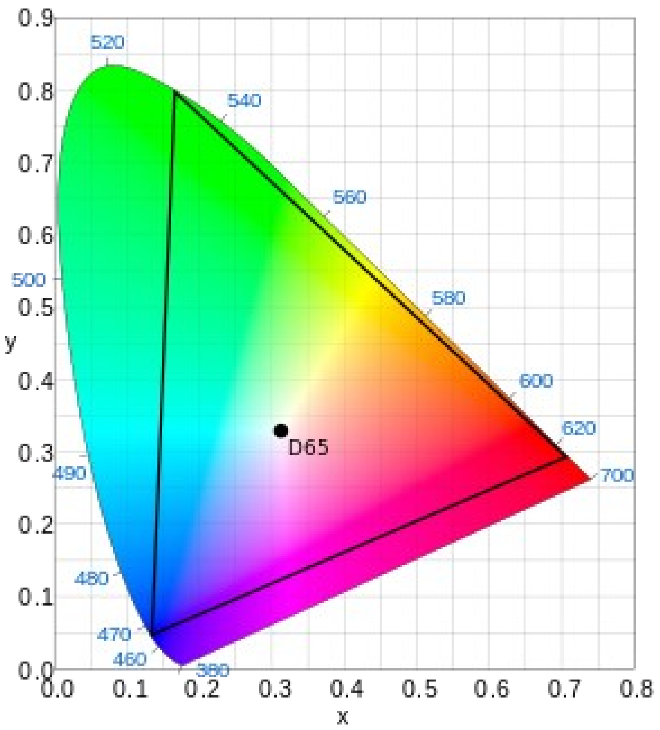
Color space	Referent white		Chromaticity coordinates of primary colors					
	x_W	y_W	x_R	y_R	x_G	y_G	x_B	y_B
ITU-R BT.709	0.3127	0.3290	0.64	0.33	0.30	0.60	0.15	0.06



Colorimetry

- color triangle in chromaticity diagram for UHDTV (Rec. ITU-R BT.2020)

Color space	Referent white		Chromaticity coordinates of primary colors					
	x_W	y_W	x_R	y_R	x_G	y_G	x_B	y_B
ITU-R BT.2020	0.3127	0.3290	0.708	0.292	0.170	0.797	0.131	0.046



- primary colors are defined by wavelenghts of light

  λ_R = 630 nm
  λ_G = 532 nm
  λ_B = 467 nm

Colorimetry

- the XYZ color space is not perceptually uniform and is not directly related to the psychophysical experience of color
- the CIE XYZ system from 1931 was transformed in 1976 into the CIE L*a*b* (CIELAB) color space

    L* - lightness – changes from 0 (black) to 100 (white)

    a* - red-green axis

    b* - yellow-blue axis

    - a* = b* = 0 – achromatic samples
    - CIELAB color space is similar to Munsell's color space
- L*, a* i b* are determined from XYZ

    $L^* = 116(Y/Y_n)^{1/3} - 16$

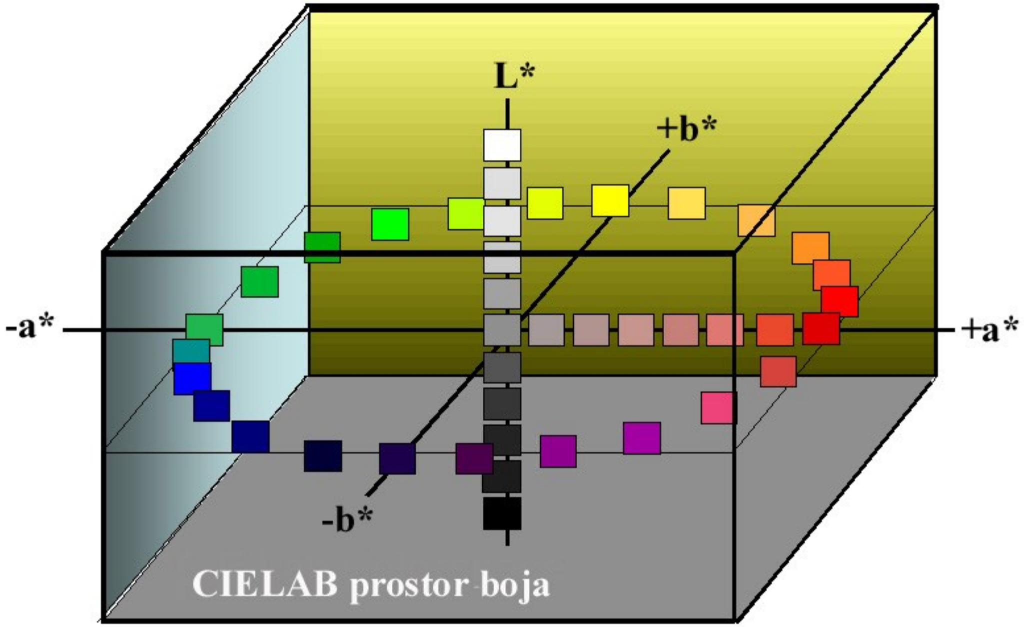
    $a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$

    $b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$

    - X_n, Y_n i Z_n are tristimulus values of referent white

Colorimetry

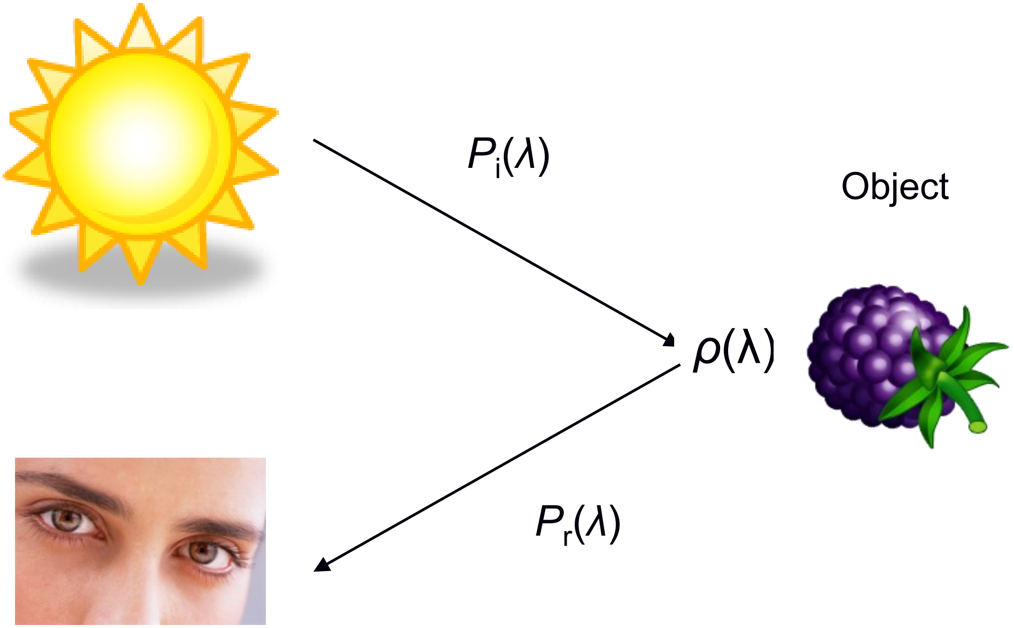
- CIE L*a*b* color space
  - lightness: 0 (black) to 100 (white)
  - saturation increases by moving the color sample away from the achromatic axis and approaching the edge of the space
- the CIELAB color space has better visual uniformity than the CIE chromaticity diagram
  - the geometric distance between the colors matches the colorimetric differences better



Colorimetry

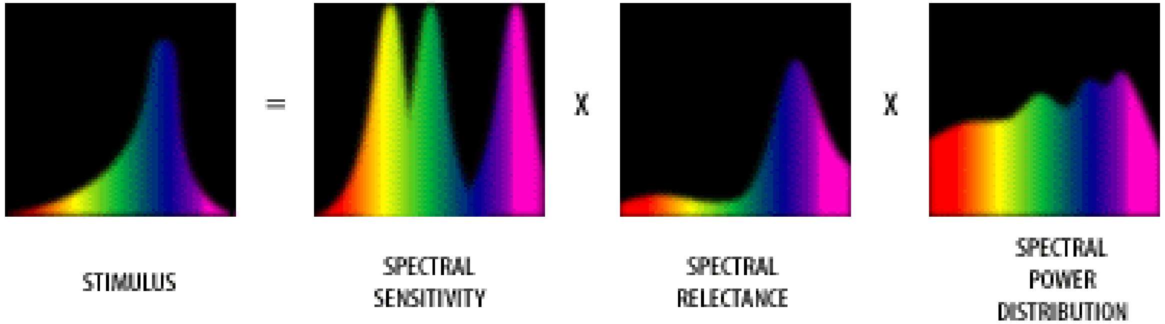
- visual perception

Light source



$$R = \int P_i(\lambda)\, \rho(\lambda)\, r(\lambda)\, d\lambda$$
$$G = \int P_i(\lambda)\, \rho(\lambda)\, \bar{g}(\lambda)\, d\lambda$$
$$B = \int P_i(\lambda)\, \rho(\lambda)\, \bar{b}(\lambda)\, d\lambda$$

Visual system



Web-pages

- book "*The Joy of Visual Perception*"

  http://www.yorku.ca/eye/thejoy.htm

- introduction to color

  https://www.cs.rit.edu/~ncs/color/

- color science

  https://colorusage.arc.nasa.gov/color_science.php

- colorimetry

  https://medium.com/hipster-color-science/a-beginners-guide-to-colorimetry-401f1830b65a

  https://openphotographyforums.com/forums/threads/metrics-for-hue-and-saturation.12588/

- additive color mixing

  https://www.physicsclassroom.com/Physics-Interactives/Light-and-Color/RGB-Color-Addition/RGB-Color-Addition-Interactive