Colour images

Image Feature Extraction Techniques

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Before we start

Grey level images use a **single value per pixel that it is called *intensity* or *brightness***. The intensity represents the amount of light reflected or emitted by an object, and it is dependent on the object's material properties as well as on the sensitivity of the camera sensors.

Because grey level images have less noise, so they are adequate for locating low-level features like edges and corners.

On the other hand, some processes like the localisation and identification of objects can obtain clear advantage by incorporating colour information. For example, colour is an important clue in traffic sign recognition.

This lecture only introduces the fundamental concepts that are used to represent and describe colours.

Human colour perception

A. Longstaff, *Neurobiologia. Krótkie wykłady*, Wydawnictwo Naukowe PWN, Warszawa 2009:

- Czułość - s. 167
- Widzenie barwne - s. 168
- Pręciki i czopki - s. 177
- Adaptacja do ciemności - s. 181 (od ostatniego akapitu)
- Percepcja głębi - s. 167

Before we start

Colour models are not concerned much with the physical nature of electromagnetic waves (i.e. spectrometry) but the focus is on obtaining a description or catalogue that organises and depicts colour properties. Thus,

colour models provide a numerical representation for a particular colour and they define the relationship of this colour with other colours, but the representation is not concerned with the electromagnetic spectrum.

Various colour models are important since they permit analysis and study of the relationships and properties of colours.

1. The first type of model is **based on perception**. Perception models sort out colours according to the similarities we perceive, and they were developed by experiments aimed at establishing measurable links between colours.

2. The second type of model **describes colours according to the way they are used in reproduction systems** (e.g. printing and displaying).

3. The third type of model looks for **separating the brightness from the hue** (pigment). These models were created by the practical necessity of video transmission and have become very popular for video encoding.

4. The last type of colour model creates a perceptual organisation by **rearranging the colour of other models** by using a colour transformation. The aim is to create an arrangement **that is more intuitive and easy to interpret**.

Light and colours

Light can be understood as an electromagnetic wave, and when these waves hit an object some light frequencies are absorbed whilst some others are reflected towards our eye and thus creating what we perceive as colours.

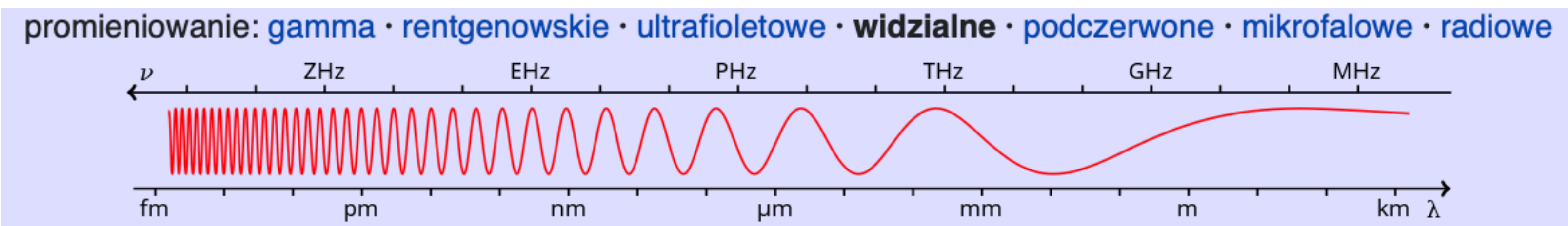
Similarly, when the reflected light hits a camera's sensor, it obtains a measure of intensity by adding energy on a range of frequencies. (measured energy over several frequencies.) This can be achieved by using filters on the top of the sensors, by using prisms to disperse the light or by including several sensors sensitive to particular frequencies on the electromagnetic spectrum. In any case, colour images are obtained by selecting different frequencies

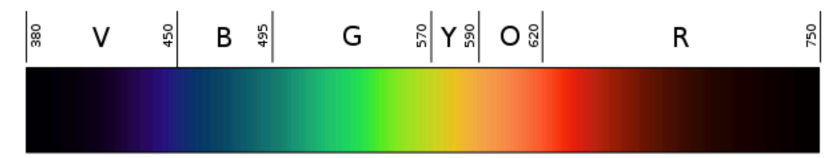
Since colour cameras have several sensors per pixel over a specific frequency range, then colour images contain information about the luminance intensities over several frequencies. A colour model gives meaning to this information by organising colours in a way that can be related to the colours we perceive. In colour image processing, colours are not described by a frequency signature, but they are described and organised according to our perception. **The description of how light is perceived by the human eye is based on the tristimulus theory.**

Tristimulus theory

Electromagnetic waves

Electromagnetic waves have an infinite range of frequencies, but the human eye can only perceive the range of frequencies in the visible spectrum which ranges from about 400 to 700 nm. Each frequency defines a different colour as illustrated below:





Color	Wavelength (nm)	Frequency (THz)	Photon energy (eV)
violet	380–450	670–790	2.75–3.26
blue	450–485	620–670	2.56–2.75
cyan	485–500	600–620	2.48–2.56
green	500–565	530–600	2.19–2.48
yellow	565–590	510–530	2.10–2.19
orange	590–625	480–510	1.98–2.10
red	625–750	400–480	1.65–1.98

Generally, we refer to **light** as the electromagnetic waves that transfer energy in this part of the spectrum. Electromagnetic waves beyond the visual spectrum have special names like Xrays,vgamma rays, microwaves, or ultraviolet light.

In the visible spectrum, each wavelength is perceived as a colour; the extreme values are perceived as violet and red and between them there are greens and yellows.

However, not all the colours that we perceive are in the visible spectrum, but many colours are created when light with different wavelengths reaches our eye at the same time. For example, pink or white are perceived from a mix of light at different frequencies. If you look carefully at the image on the right you will notice that there is no white on the right image.

In addition to new colours, mixtures of colours can produce colours that we cannot distinguish as new colours, but they may be perceived as a colour in the visible spectrum.

Tristimulus theory

Because our own (human) representation of colour is created, as you know, by three types of cell receptors in our eyes that are sensitive to a range of frequencies near blue, red and green so we (humans) decided, instead of describing colours by frequency content or radiometric properties, represented colors by three stimuli according to the way we perceive them biologicaly. This way of organising colours is known as trichromatic or tristimulus representation.

The tristimulus representation was widely used by artists in the 18th century and was experimentally developed by physicists. The theory was formally developed by Thomas Young and Hermann von Helmholtz.

In 1802, Young postulated the existence of three types of photoreceptors (now known as cone cells) in the eye, each of which was sensitive to a particular range of visible light.

Hermann von Helmholtz developed the theory further in 1850: that the three types of cone photoreceptors could be classified as short-preferring (violet), middle-preferring (green), and long-preferring (red), according to their response to the wavelengths of light striking the retina. The relative strengths of the signals detected by the three types of cones are interpreted by the brain as a visible color.

The following assumptions apply in this representation:

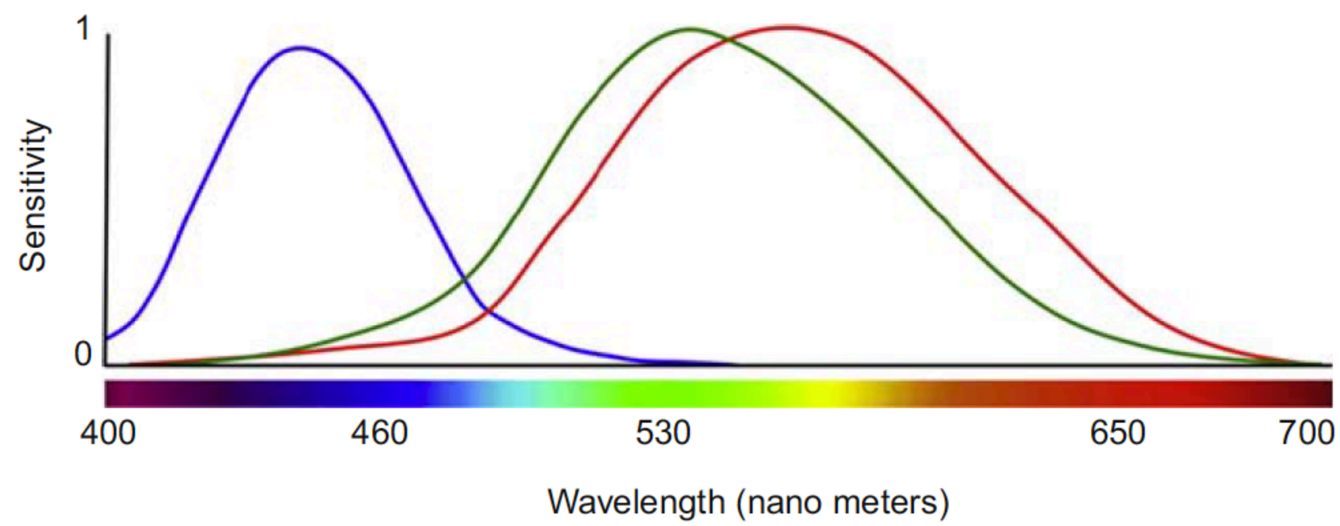
1. Yll the colours we perceive can be represented by a mixture of three primary colours.

2. The colour space is linear. That is, the mixture is defined by summations and the addition of two colours is achieved by adding its primary components.

Grassmann’s law of linearity (1853) was developed empirically and establishes that colours are combined linearly [Other: 7].

Tristimulus theory

In addition to these principles, the tristimulus representation establishes how the primaries are defined by considering the sensitivity of each cell receptor to each frequency in the visual spectrum. Each receptor defines a tristimulus response curve as



That is, the blue receptor will generate a high response for energy around 430 nm, the green and the red around 550 and 560 nm, respectively. **The receptors integrate the values in all frequencies and provide a single value, thus the same response can be obtained by different stimulus**.

For example, the blue receptor will provide the same response for a light with a high value at 400 nm and for a light with lower intensity at 430 nm. **That is, the response does not provide information about the frequencies that compose a colour, but just about the intensity along a frequency range.**

Tristimulus theory

It is important to mention that **colour sensitivity is not the same for all people**, so the curves only represent mean values for normal colour vision.

Also, it is known that colour perception is more complex than the summation of three response curves and the perception of a colour is affected by other factors such as the surrounding regions (i.e. context), region sizes, light conditions, as well as more abstract concepts such as memory (temporal stimulus).

Tristimulus theory

In spite of this complexity, **the tristimulus principles are the fundamental basis of our understanding of colour**. Furthermore, the tristimulus representation is not limited to understanding the perception of colours by the human eye, but the sensors in colour cameras and colour reproduction systems are based on the same principles. That is, according to the tristimulus theory, these systems only use three values to capture and re-create all the visible colours. **This does not imply that the theory describes the nature of light composition or the true perception of the human eye, and it only provides a mechanism to represent the perception of colours.**

Tristimulus theory

According to the tristimulus theory, all the possible colours we perceive can be defined in a three-dimensional linear space. That is, if $[c_1, c_2, c_3]$ define colour components (or weights) and $[B_1, B_2, B_3]$ some base colours (or primaries), then a colour is defined by the colourimetric equation defined by:

$$C = c_1B_1 + c_2B_2 + c_3B_3$$

It is important to notice that the equality does not mean that the algebraic summation in the right side gives a numerical value C that can be used to represent or recreate the colour. **The symbol C is not a value or a colour representation - it is a colour**; the equation expresses the idea that three stimuli are combined by superposition of lights recreate the perception of the colour C. The actual representation of the colour is given by the triplet $[c_1, c_2, c_3]$.

To be more precise and to avoid confusion, you should rather write:

$$S \equiv rR + gG + bB$$

which simply means that the stimulus S, known as a colour, is matched by (that is the symbol $\equiv$) r amounts of the R primary, g amounts of the G primary, and b amounts of the B primary.

The base colours B_1, B_2 and B_3 can be defined according to the visual system by considering the responses of the receptors in the human eye. That is, **by considering as primaries the colours that we perceive as *red*, *green* and *blue*.**

However, there are other interpretations that give particular properties to the colour space and that define different colour models.

Tristimulus theory

Colour space dimensionality

A way to understand colour models is to consider them as created by geometric transformations. If you can imagine that you can arrange all the colours that you can see in an enclosed space, then a colour model will order those colours by picking up each colour and give it the co-ordinates $[c_1, c_2, c_3]$ in a space delineated by $[B_1, B_2, B_3]$.

Because there are three components per colour, then a colour space can be shown in a three-dimensional graph. However, since the interpretation of three-dimensional data is difficult, often the data are shown using **two-dimensional** graphs - it depends on the model.

The first model with strong significance in modern theory of colour is the CIE XYZ model. This model was developed from the CIE RGB model, and it has been used as basis of other modern colour representations. In order to explain these colour models it is important to have an understanding of the luminosity function.

Tristimulus theory

Luminosity function

The expression:

$$C = c_1B_1 + c_2B_2 + c_3B_3$$

provides a framework to develop colour models by adding three components. **However, this expression is related to the hue of a colour, but not to its brightness.**

This can be seen by considering what happens to a colour when its components are multiplied by the same constant. Since multiplication does not change the colour wavelength and the equation is linear, we could expect to obtain a brighter (or darker) version of the colour proportional to the constant.

However, **since the human eye does not have the same sensitivity to all frequencies, then the resulting colour brightness actually depends on composition**. For example, since the human eye is more sensitive to colours whose wavelength is close to green, then **colours having a large green component will increase their intensity significantly when the components are increased**. For the same increment in the components, **blue colours will show less intensity**. Colours composed of several frequencies can shift in hue according to the sensitivity to each frequency to the human eye.

Tristimulus theory

Luminosity function

A luminous efficiency function or luminosity function represents the average spectral sensitivity of human visual perception of light. 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**.

Spectral sensitivity is the relative efficiency of detection, of light or other signal, as a function of the frequency or wavelength of the signal.

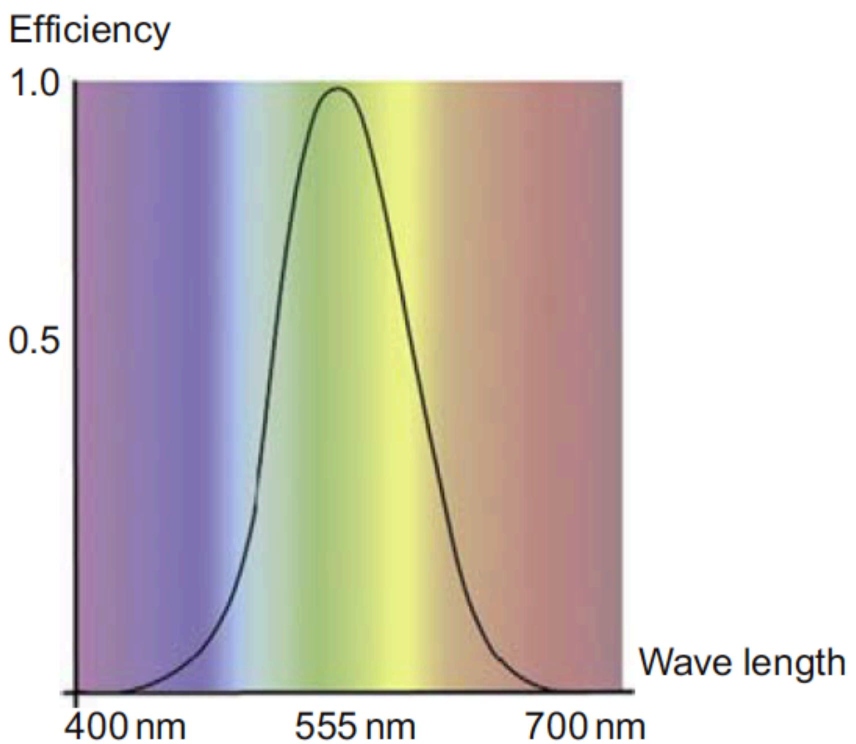
The *luminosity* or *luminous efficiency* function is denoted as V_λ, and describes the average sensitivity of the human eye to a colour's wavelength. This function was determined experimentally by the following procedure.

- First, the frequency of a light of constant intensity was changed until observers perceived the maximum brightness. The maximum was obtained with a wavelength of 555 nm.
- Secondly, a different light's wavelength was chosen and the power was adjusted until the perceived intensity of the new wavelength was the same as the 555 nm.

Thus, the luminous efficiency for the light at the chosen wavelength was defined as the:

ratio between the power at the maximum and the power at the wavelength.

The experiments for several wavelengths produce the general form illustrated on the right side. This figure represents the daytime efficiency (i.e. photopic vision). The luminosity function is normalised, thus it represents the relative intensity rather than the actual visible energy or power perceived by the human eye.



Tristimulus theory

Luminosity function

In the description of colour models, **the luminous efficiency is used to provide a reference for the perceived brightness**.

This is achieved by relating the colour components to the luminous efficiency via the luminance coefficients $[v_1, v_2, v_3]$. These **coefficients define the contribution of each base colour to the brightness** as:

$$V = v_1 c_1 + v_2 c_2 + v_3 c_3$$

For example, the luminance coefficients $[1,4,2]$ indicate that the second component contributes four times more to the brightness than the first one. Thus, **an increase in the second component will create a colour that is four times brighter than the colour created by increasing the first one the same amount**.

It is important to emphasise that this function describes our perception of brightness and not the actual radiated power.

Perception-based colour models: CIE RGB and CIE XYZ

CIE RGB and CIE XYZ

The CIE RGB and CIE XYZ colour models (defined in 1931 by the Commission Internationale de L'Eclairage (CIE)) define colour according to the colourimetric equation.

Both models provide a description of the colours according to human perception and they characterise the same colour's properties, nevertheless **they use different base colours**:

- the CIE RGB uses visible physical colours; the CIE RGB is the physical model developed based on perception experiments,
- the XYZ uses imaginary or inexistent colours that only provide a theoretical basis; the CIE XYZ is theoretically derived from the CIE RGB.

The general motivation to develop the CIE XYZ is **to have a colour space with better descriptive properties**. However, **in order to achieve that description, the base colours are shifted out of the visible spectrum**.

Colour matching experiments

CIE RGB colour model: Wrighte-Guild data

The base of the CIE RGB colour space is denoted by the triplet $[R, G, B]$ and its components are denoted as $[r, g, b]$. Thus, the definition for this model is written as:

$$C = rR + gG + bB.$$

This model is based on how colours are perceived by the human eye, and **it was developed using colour matching experiments**.

In the CIE RGB colour model experiments, a person was presented with two colours:

- the first colour defines a target colour with a single known frequency wavelength
- and the second is produced by combining the light of three sources defined by the base colours.

To determine the composition of the target colour, **the intensity of the base colours is changed until the colour produced by the combination of lights matches the target colour**.

The intensities of the composed sources define the colour components of the target colour.

Colour matching experiments

Important result: need for substraction of light values

An **important result** of the colour matching experiments **was the observation that many colours cannot be created by addition of the primary lights**, but they can only be produced by subtraction of light values.

In the experiments, subtraction does not mean using negative light intensities, but to **add a base colour to the target colour**. This process desaturates the colours and since the mix of colours is linear, then **adding to the target is equal than subtracting from the light mixture** that creates the second colour in the experiments.

We normally represent colour with an equation:

$$C = rR + gG + bB$$

Now when we add one of the primaries to the stimulus (colour; the thing we are matching) itself, we can write this equation:

$$C + rR = gG + bB$$

The new colour, $C + rR$, can now be matched by an additive mixture of the other two. Now we can rearrange this equation to make:

$$C = -rR + gG + bB$$

In other words, matching the additive mixture of the original stimulus C and some red with some green and blue, means that – if it were possible – we could match the original stimulus C with the same amount of green and blue and a negative amount of the red.

For example, to generate violet requires adding a green light to the target, thus generating a negative green value.

There is no (visible) colour basis that can generate all visible colours. However, it is possible to define theoretical basis that, although are too saturated to be visible, it can create all the colours.

This is the basic rationale for creating the CIE XYZ model that is presented later.

CIE RGB colour matching functions

CIE RGB colour matching functions

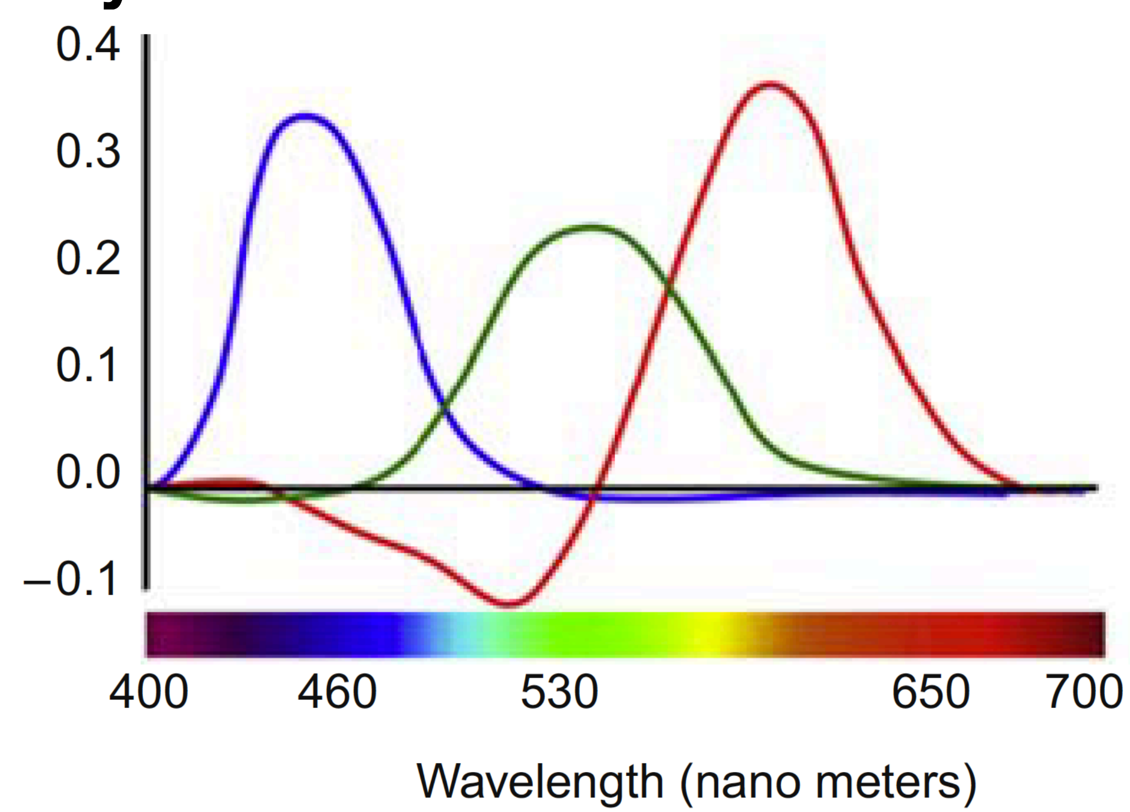
It is impractical to perform colour matching experiments to obtain the components of all the visible colours, but the experiments were limited to a finite set of colours.

Thus, the colour description should provide a rule that can be used to infer the components of **any** possible colour according to the results obtained in the (limited) matching experiments.

The mechanism that permits the determination of the components of any colour is based on the *colour matching functions*.

The colour matching functions are illustrated in CIE RGB image on the right and they **define the intensity values of the base colours that produce any monochromatic colour with a normalised intensity**.
The functions give three values that represent the components of the colour generated by a single wavelength and with unit intensity.

For example, to create the same colour as a single light at 580 nm, you combine three base colours with intensities 0.24, 0.11 and 0.001.

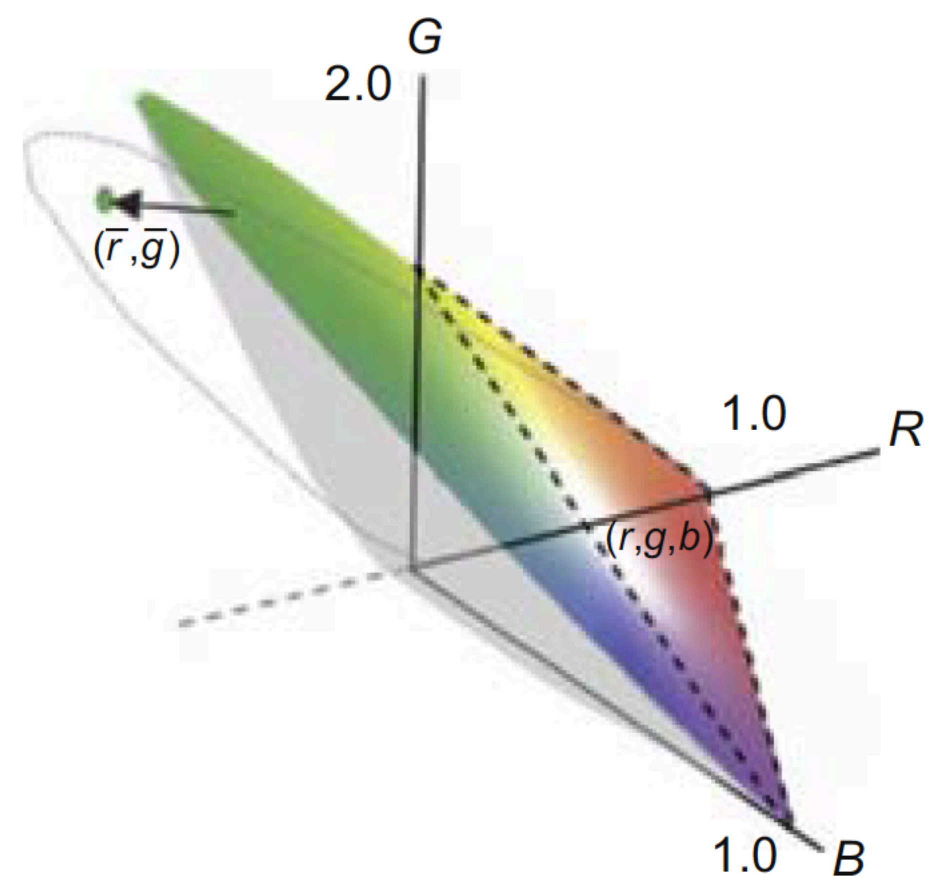


CIE RGB chromaticity diagram and chromaticity co-ordinates

The CIE RGB model characterises colours by three components, thus the graph of the full set of colours is a three-dimensional volume.

As colours increase in distance from the origin, their brightness increases and more colours become visible forming a conical shaped volume.

In the figure, the base colours coincide with the corners of the triangle drawn with black dashed lines.
Thus, the triangular pyramid defined by this triangle contains the colours that can be created by addition.



You obtain the plane visible in figure using formula given in the next slide.

CIE RGB chromaticity diagram and chromaticity co-ordinates

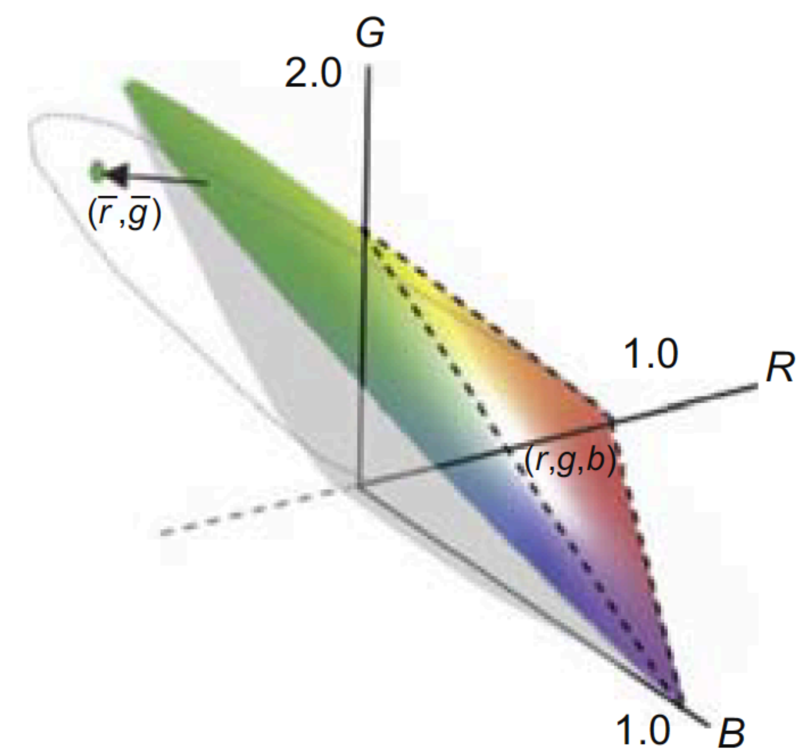
In general, the visualisation and interpretation of colours using three-dimensional representations is complicated, thus colour properties are sometimes visualised using two-dimensional graphs. The most common way to illustrate the CIE RGB colour space is to consider only the colour's chromaticity. That is, the luminous energy is eliminated by normalising against the total energy. The chromaticity co-ordinates are defined as:

$$r' = \frac{r}{r+g+b}, g' = \frac{g}{r+g+b}, b' = \frac{b}{r+g+b}.$$

Only two of the three normalised colours are independent and one value can be determined from the other two. For example, we can compute blue as

$$b' = 1 - r' - g'.$$

As such, **only two colours can be used to characterise the chromaticity of the colour** model and the visible colours can be visualised using a two-dimensional graph. The graph created by considering the colour's chromaticity is called the chromaticity diagram.



CIE RGB chromaticity diagram and chromaticity co-ordinates

The chromaticity diagram

Any point in the colour space is mapped into the chromaticity diagram by two transformations.

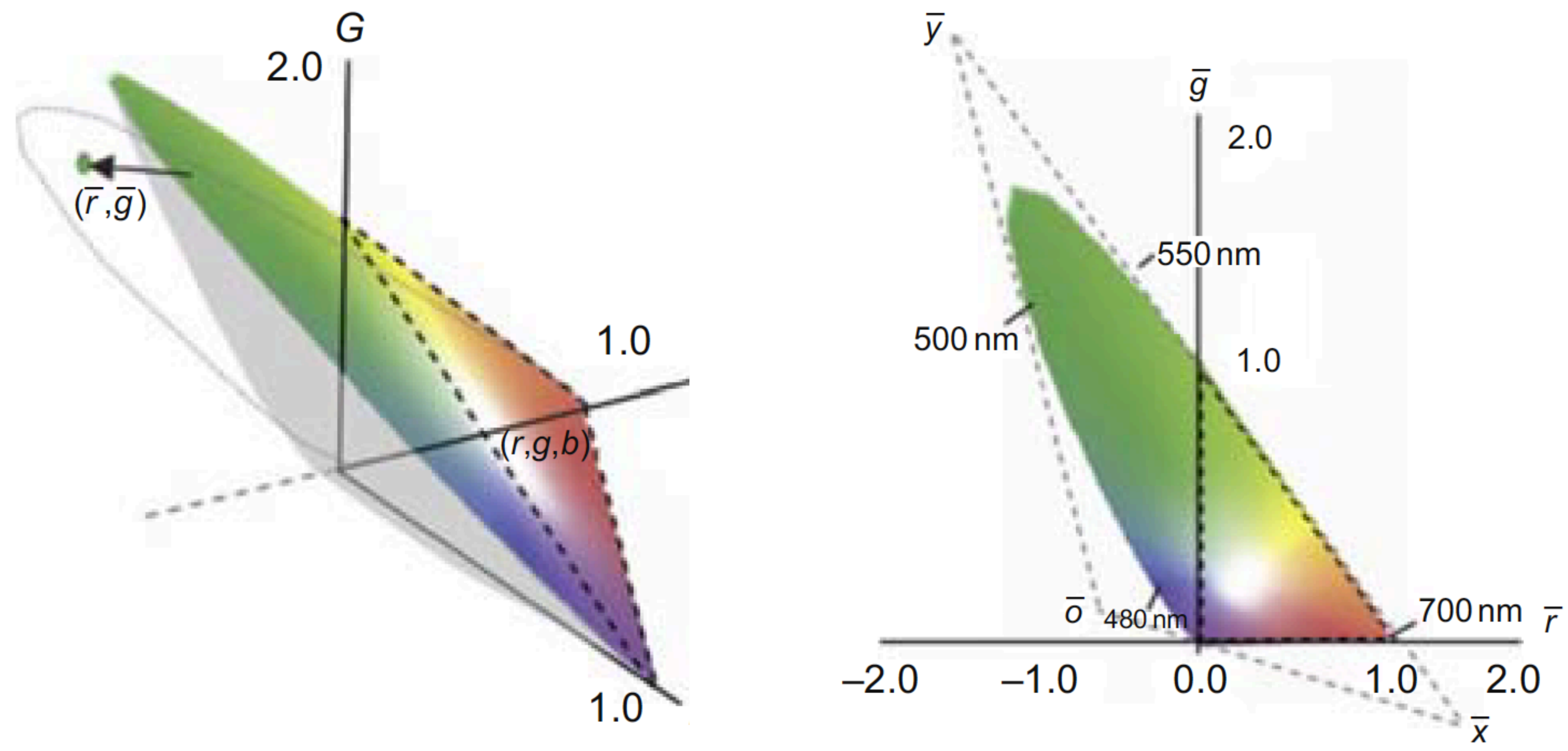
- First:
  Equations from previous slide maps the colours into the plane that contains the coloured shape in the figure. That is, by tracing radial lines from the origin to the plane. You can see from the transformation that any point in the same radial projection line will end up in the same point in the coloured shape in the figure. That is, points in the coloured shape in the figure characterise colours independent of their luminous energy

- Second:
  The points are orthogonally projected into the plane RG. That is, the b' coordinate is eliminated or set to zero. In the figure, the border of the area resulting from the projection is shown by the gray curve in the RG plane. This area is known as **chromaticity diagram**.

In consequence, points in the chromaticity diagram characterise colours independent of their luminous energy. For example, the colours with chromaticity coordinates $[0.5,0.5,0.5]$ and $[1,1,1]$ are shown as the same point $[1/3,1/3]$ in the diagram. This point represents both white and grey since they have the same chromaticity, but the first one is a less bright version of the second one. Since the chromaticity cannot show white and grey for the same point, it is coloured by the normalised colour $[r', g', b']$.

CIE RGB colour model (on the left) and CIE RGB chromaticity diagram (on the right).

Notice "negative" part for green reflecting our greater sensitivity to this colour.



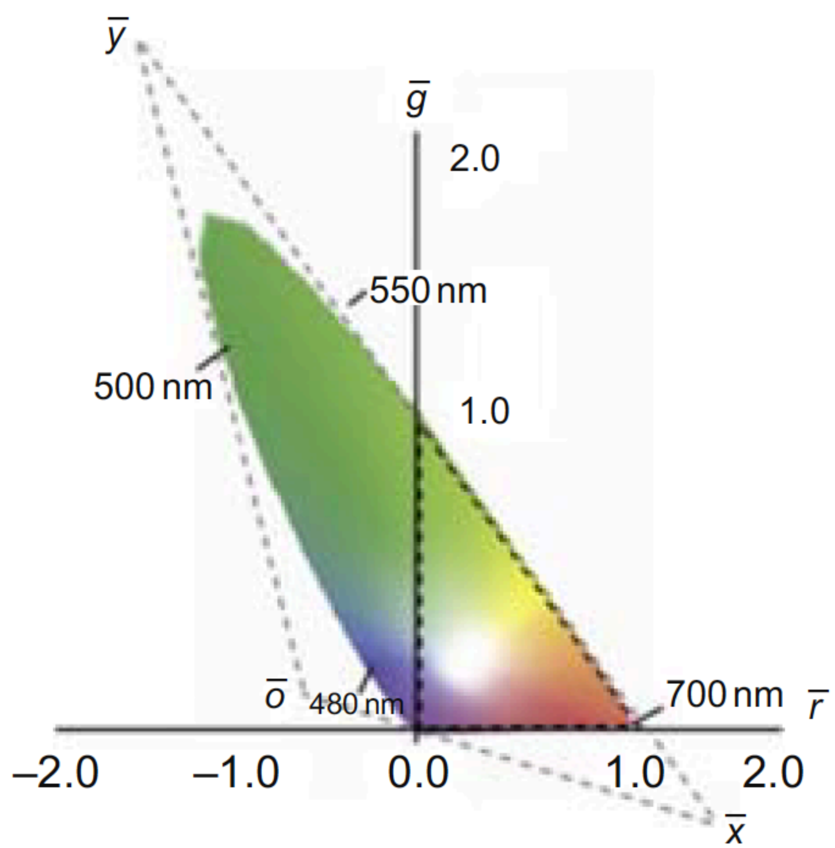
CIE RGB chromaticity diagram and chromaticity co-ordinates

The visible spectrum of colours outlines a horseshoeshaped region in the chromaticity diagram. The red and green components of each colour are determined by the position of the colours in the axes in the graph whilst the amount of blue is determined based on them.

The top curved rim delineating the visible colours is formed by colours with a single-frequency component. This line is called the **spectral line**, and it represents lights from 400 to 700 nm.

The spectral line defines the border of the horseshoe-shaped region since these colours are the limit of the human eye's perception.

The straight line of the horseshoe region is called the **purple line** and **is not formed by single wavelength colours** but each point in this line is formed by mixing the two monochromatic lights at 400 and 700 nm.



CIE XYZ colour model

Cons of CIE RGB model

The CIE RGB model has several undesirable properties.

- First, its colour matching functions contain negative values. Negative colours do not fit well with the concept of producing colours by adding base colours and they introduce sign computations.

- Secondly, the colour components are not normalised, for example, a colour created by a light with a single frequency at 410 nm are $[0.03, -0.007, 0.22]$. A better colour description should have all the components bounded to range from zero to one.

- All the base colours have a contribution to the brightness of a colour. That is, the perceived brightness is changed by modifying any component. A more useful description should concentrate the brightness on a single component such that the perception of a colour can be related to the definition of chromaticity and brightness.

The CIE XYZ model was developed to become a universal reference system that overcomes these unwanted properties.

CIE XYZ colour model

The basis of the CIE XYZ model is denoted by the triplet $[X, Y, Z]$ and its components are denoted as $[x, y, z]$. Thus, for this model you have:

$$C = xX + yY + zZ$$

and the chromaticity coordinates are defined as:

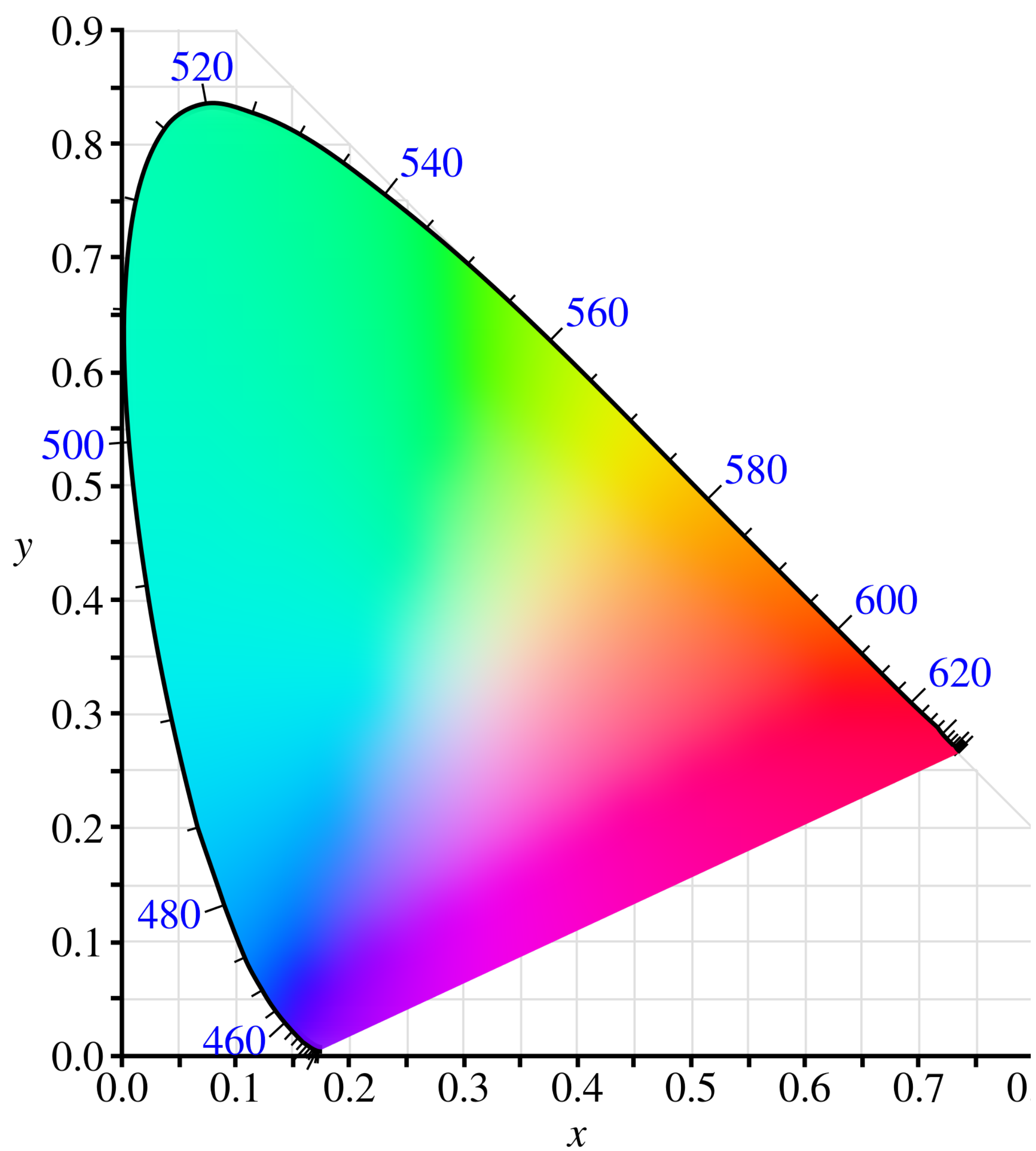
$$x' = \frac{x}{x+y+z},\ y' = \frac{y}{x+y+z} \text{ and } z' = \frac{z}{x+y+z}.$$

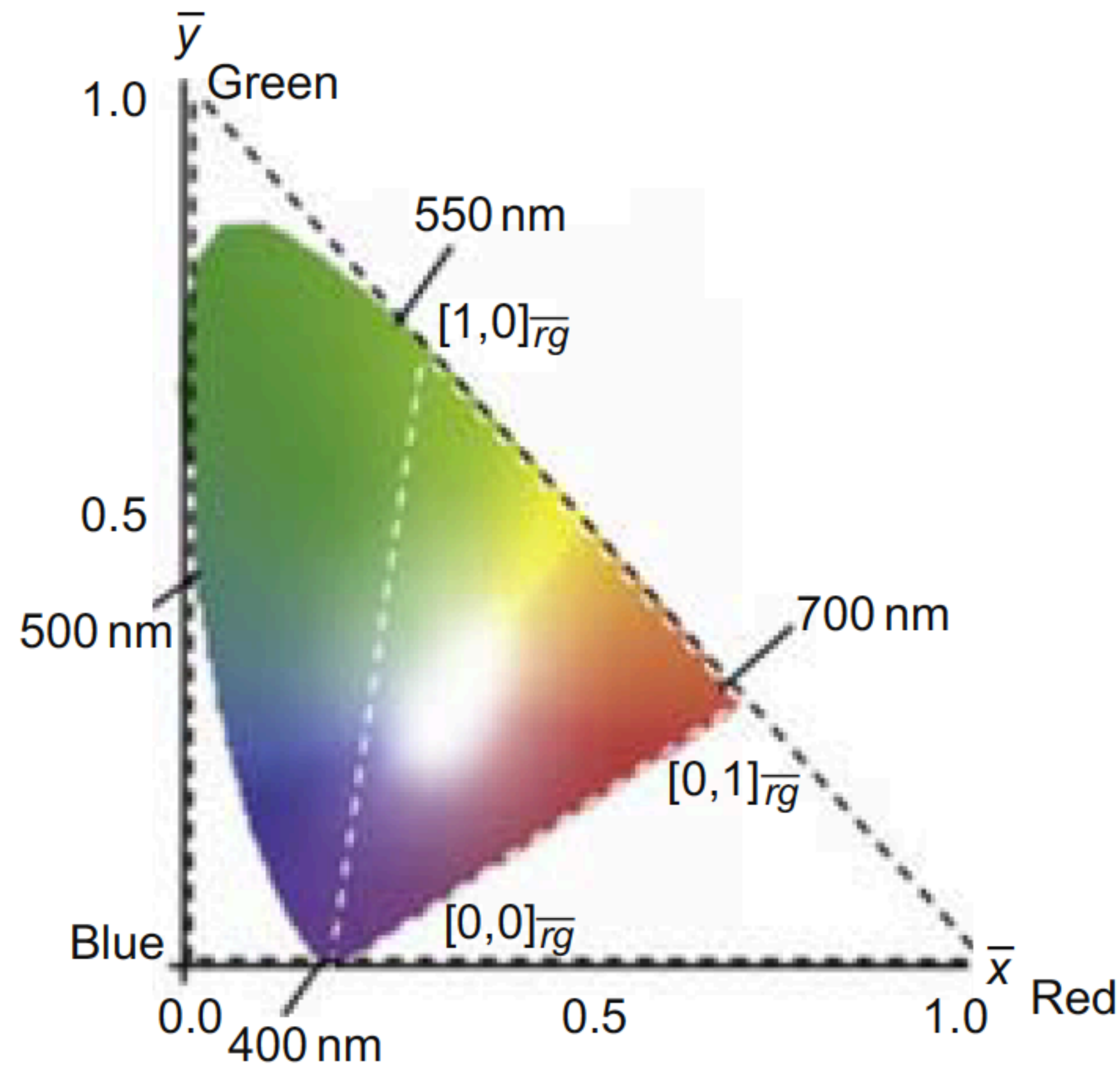
Similarly, we have that:

$$z' = 1 - x' - y'$$

CIE XYZ colour model

At difference of the CIE RGB, the colour components in the XYZ colour model are not defined directly by matching colour experiments, but they are obtained from the components of the CIE RGB model by a linear transformation.

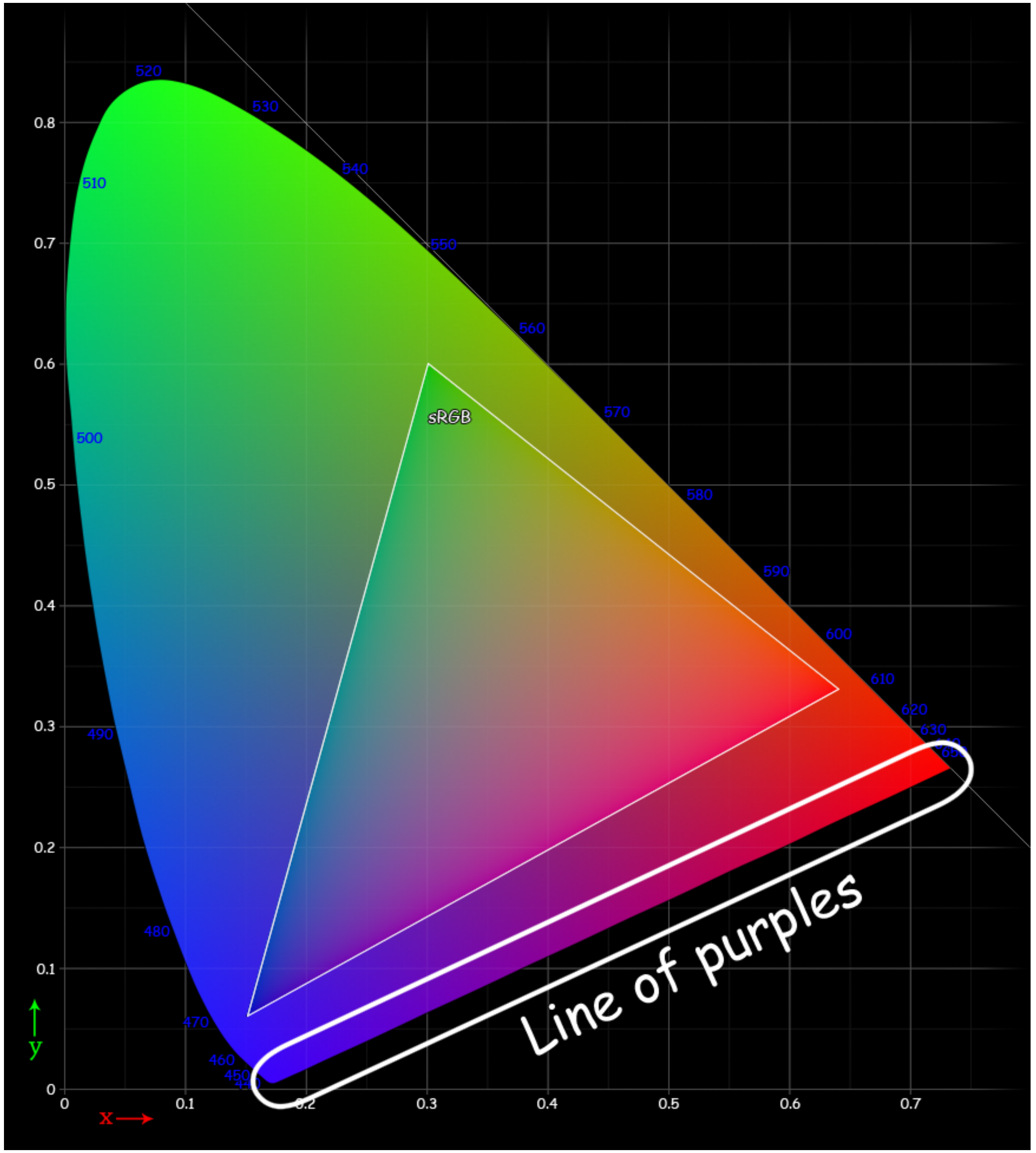




XYZ chromaticity diagram

Line of purples

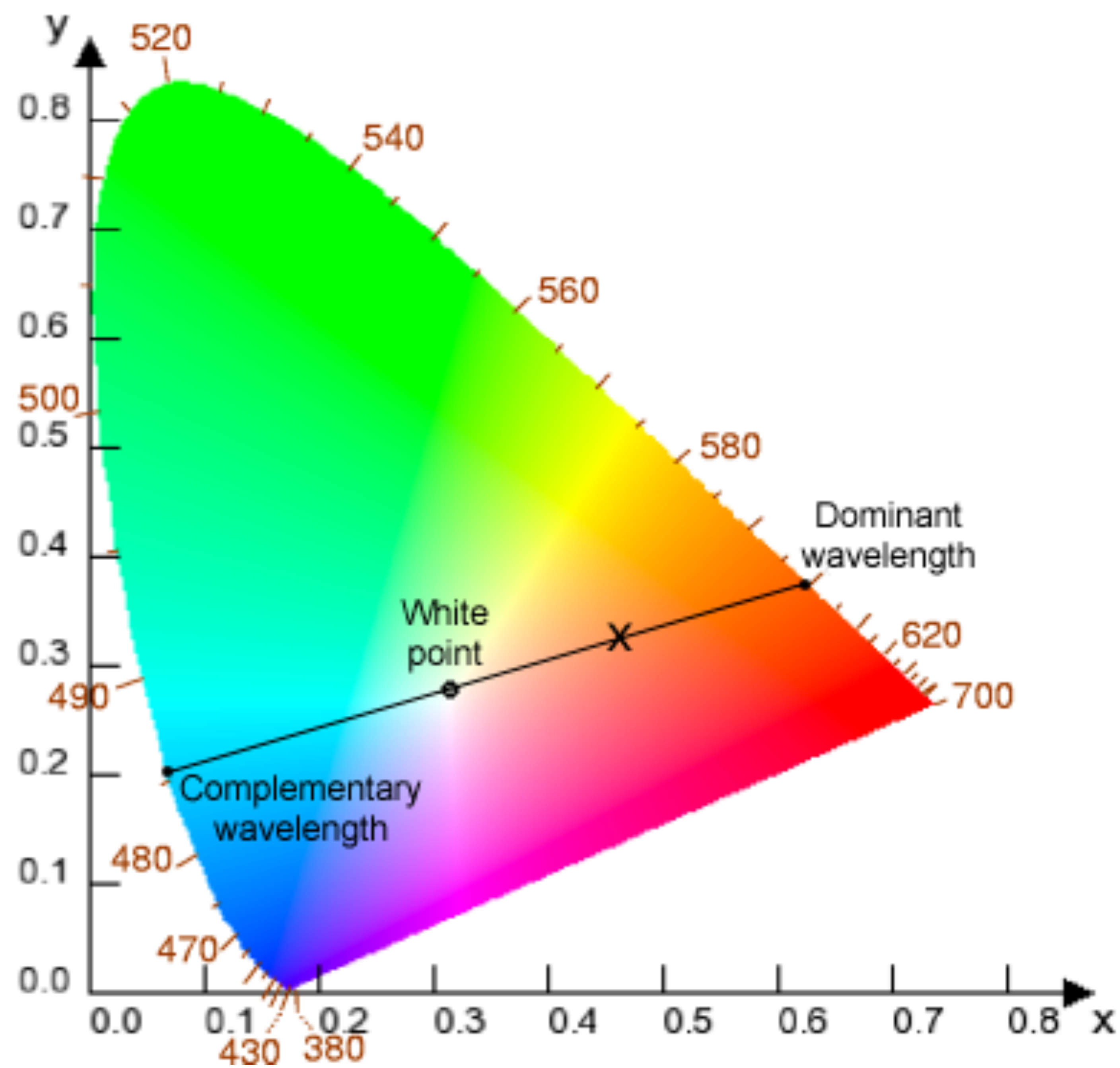
In color theory, the line of purples or purple boundary is the locus on the edge of the chromaticity diagram formed between extreme spectral red and violet. Except for these endpoints of the line, colors on the line are non-spectral (no monochromatic light source can generate them). Rather, every color on the line is a unique mixture in a ratio of fully saturated red and fully saturated violet, the two spectral color endpoints of visibility on the spectrum of pure hues. Colors on the line and spectral colors are the only ones that are fully saturated in the sense that, for any point on the line, no other possible color being a mixture of red and violet is more saturated than it.



XYZ chromaticity diagram

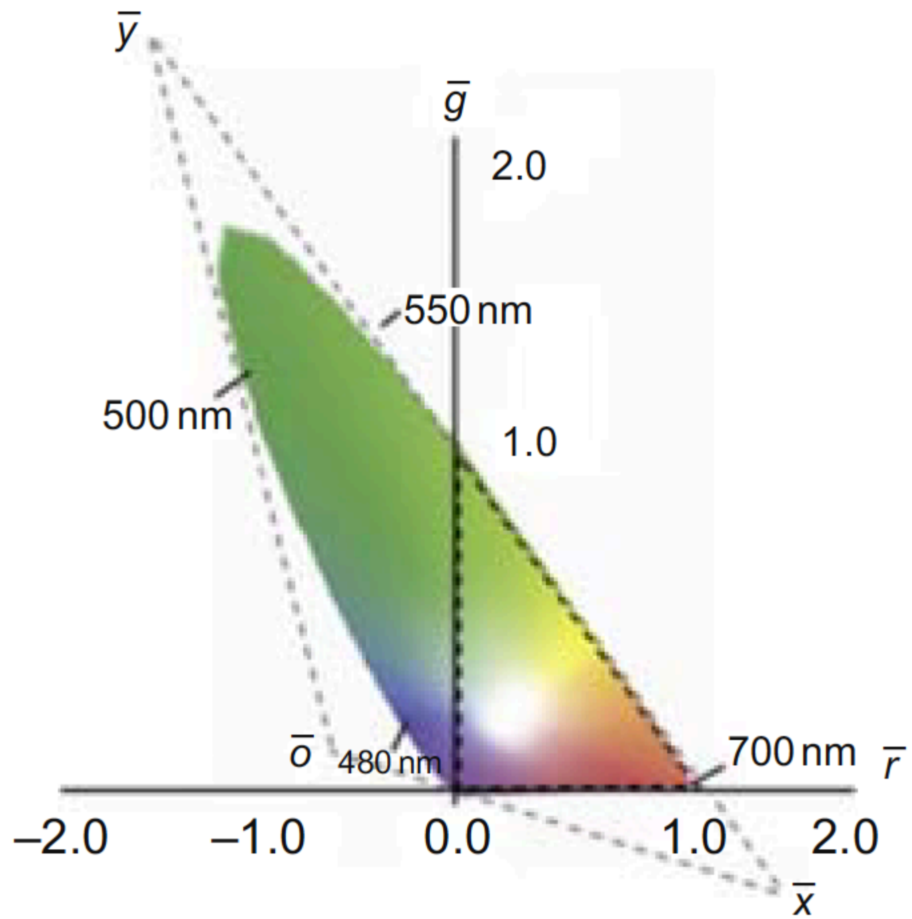
Dominant wavelength

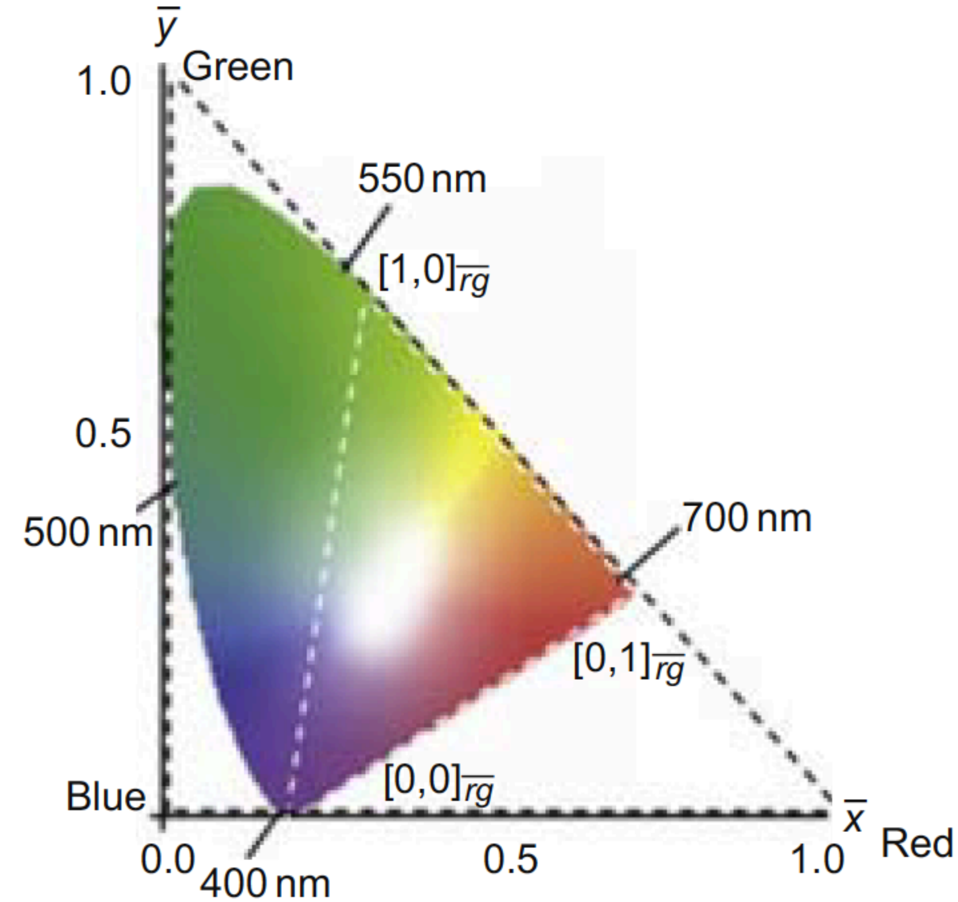
On the CIE color coordinate space, a straight line drawn between the point for a given color and the point for the color of the illuminant can be extrapolated out so that it intersects the perimeter of the space in two points. The point of intersection nearer to the color in question reveals the dominant wavelength of the color as the wavelength of the pure spectral color at that intersection point. The point of intersection on the opposite side of the color space gives the complementary wavelength, which when added to the color in question in the right proportion will yield the color of the illuminant.



XYZ chromaticity diagram

CIE RGB chromaticity diagram vs. XYZ chromaticity diagram





The CIE RGB and CIE XYZ models represent **all** the colours that **can be perceived by the human eye** by combining three monochromatic lights (nonvisible for the XYZ model).

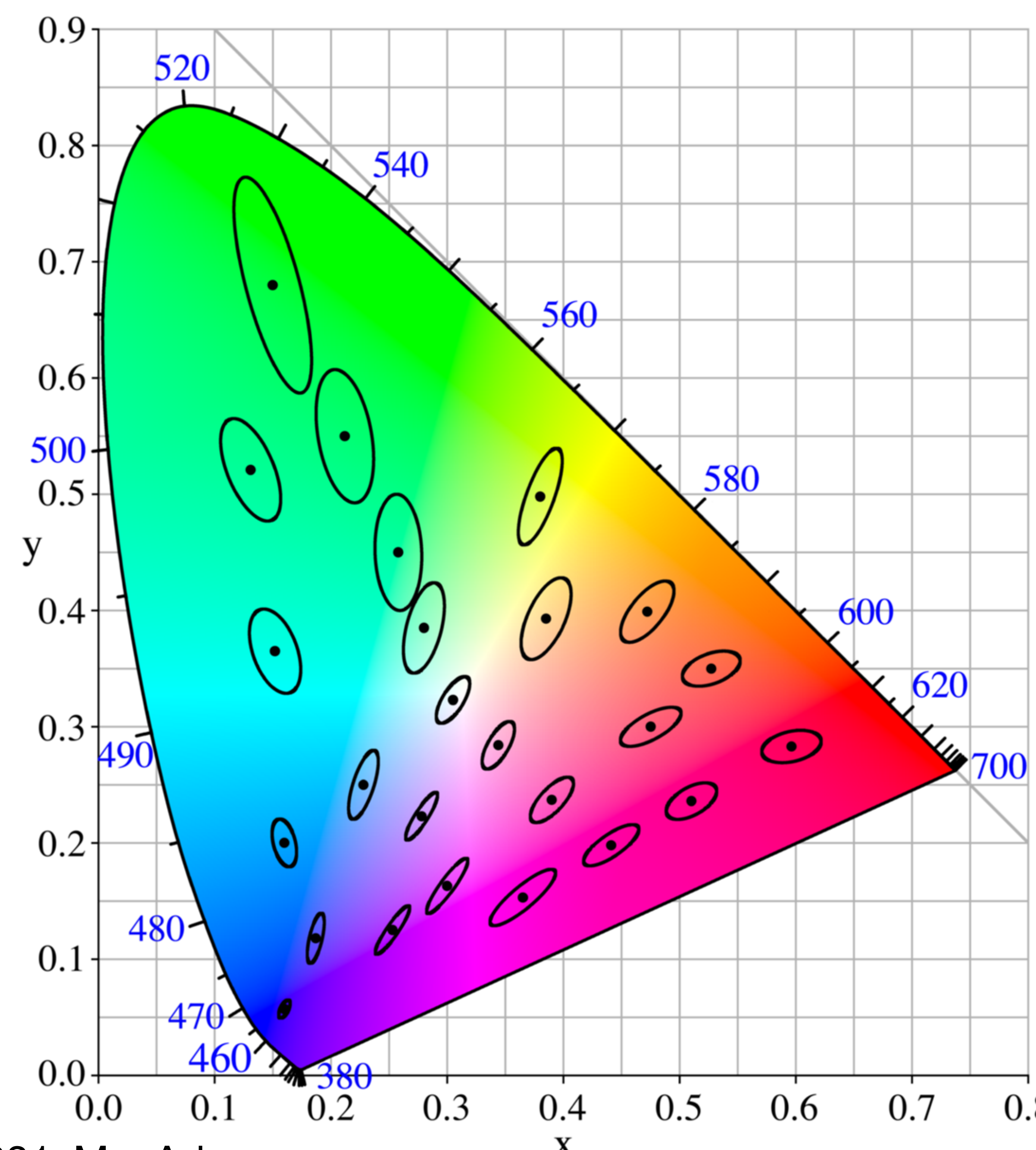
Uniform colour spaces: CIE LUV and CIE LAB

Cons of CIE XYZ model

The XYZ model is very useful for visualising the colours we can perceive and their relationships.

However, it **lacks uniformity or perceptual linearity**. That is, the perceived difference between two colours is not directly related to the distance of the colours as represented in the chromaticity diagram. The nonuniformity of the XYZ system is generally illustrated by using the MacAdam ellipses on the right image.

These ellipses were obtained by experiments using matching colours. In the experiments, observers were asked to adjust the colour components of one colour until it matches a fixed colour from the chromaticity diagram. The centre of the ellipse is given by the fixed colour and their area encompasses the matching colours by the observers.



https://commons.wikimedia.org/wiki/File:CIExy1931_MacAdam.png

Uniform colour spaces: CIE LUV and CIE LAB

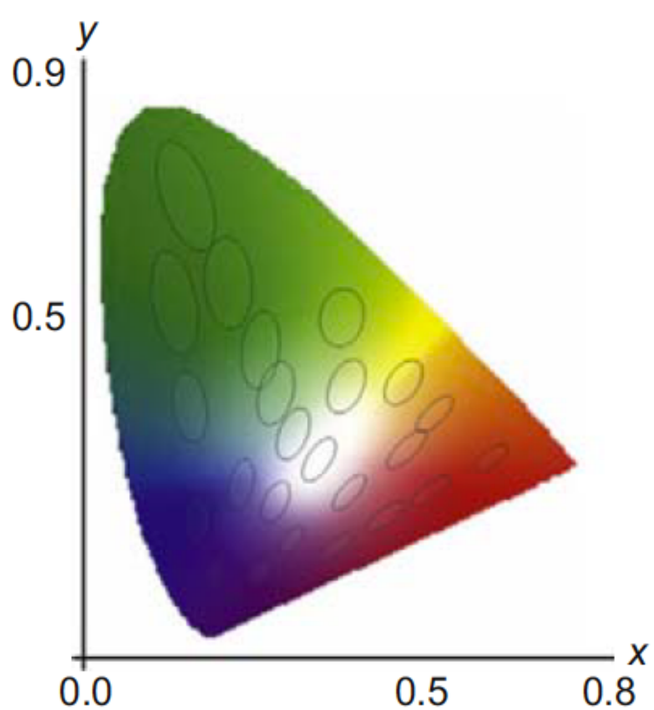
The MacAdam experiments showed that our ability to distinguish between colours is not the same for all colours, thus distances in the chromaticity diagram are not a good measure of colour differences. Ideally, observed differences should be delineated by circles with the same radius such that a given distance between colours has the same meaning independent of the position in the diagram.

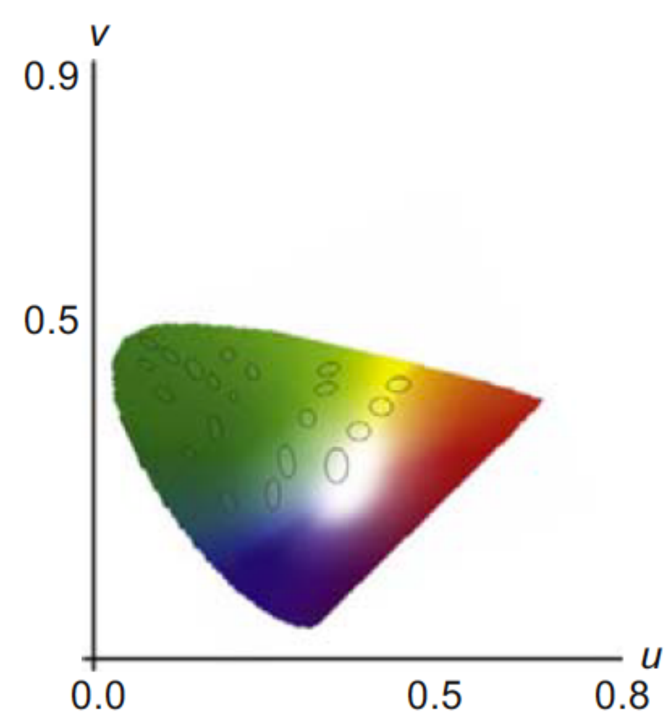
Uniform colour spaces: CIE LUV and CIE LAB

In 1976, the CIE provided two standards for these uniform spaces. They are known as the CIE LUV and the CIE LAB colour models. The basic concept of these models is to transform the colour components of the XYZ colours so that perceptual differences in the chromaticity diagram are more uniform.

The definition of the CIE LUV model is based on the following equation that transforms the colour components of the XYZ model

- $u = \dfrac{4x}{x + 15y + 3z}, v = \dfrac{9y}{x + 15y + 3z};$
- $u = \dfrac{4x'}{-2x' + 12y' + 3}, v = \dfrac{9y'}{-2x' + 12y' + 3}.$





Both forms are equivalent, but one is expressed using colour components and the other by using chromaticity co-ordinates. In both cases, the transformation distorts the co-ordinates to form a colour space with better perceptual linearity than the XYZ colour model.

Final word

It is important to understand that the colours in the LUV, LAB, and XYZ models are the same and they represent the colours we can perceive.

These transformations just define mappings between co-ordinates. That is, they change the way we name or locate each colour in a coordinate space.

What is important is how coordinates of different colours are related to each other. That is, each colour model arranges or positions the colours differently in a co-ordinate space, so the special relationships between colours have specific properties.

Additive and subtractive colour models

RGB and CMY

The CIE RGB and XYZ models represent all the colours that can be perceived by the human eye by combining three monochromatic lights (in case of the XYZ model, these lights are nonvisible but it doesn't matter).

Although they have important theoretical significance, they are not adequate for modelling practical colour reproduction and capture systems such as photography, printers, scanners, cameras, and displays.

The RGB colour models use base colours containing strong components close to the red, green and blue wavelengths. The base colours in these models are denoted as $[R, G, B]$ and their components as $[r, g, b]$. Other reproduction systems, such as inkjet and laser printers **use base colours close to the complementary of RGB**. That is, **cyan** (greenish-blue), **yellow** and **magenta** (purplish-red).

These models are called CMY and their base colours and components are denoted as $[C, M, Y]$ and $[c, m, y]$, respectively. **The motivation** to have several RGB and CMY colour models is to **characterise the physical properties of different reproduction systems**.

RGB and CMY

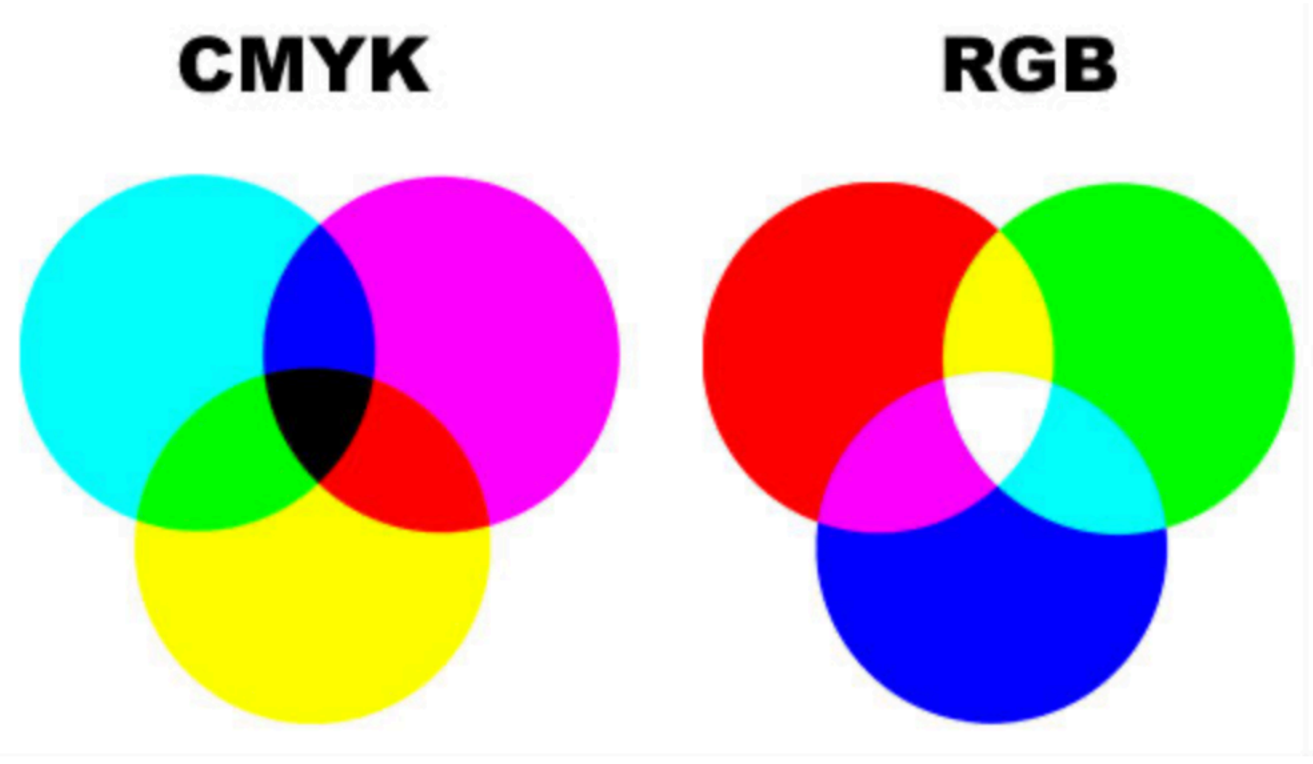
The RGB and CMY colour models differ in the way in which the colours are created; RGB is an **additive** model whilst CMY is **subtractive**. The additive or subtractive nature of the models is determined by the physical mechanism used in the reproduction system.

RGB and CMY

In the RGB, the base colours are generated by small light-emitting components such as fluorescent phosphors, diodes or semiconductors. These components are positioned very close to each other, so **its light is combined and perceived as a single colour**. Thus, the creation from colours stems from black and it adds the intensities of the base colours.

In CMY, the base colours are colourants that are applied on a white surface. **This colours act as filters between the white surface and the eye producing a change in our perception.** That is, colours are subtracted from white.

For example, **to create green, we need to filter all the colours but green, thus we should apply the complementary or opposing colour to green: magenta**.



RGB and CMY

CMY has been extended to CMYK model by adding black to the base colours. The use of black has two practical motivations.

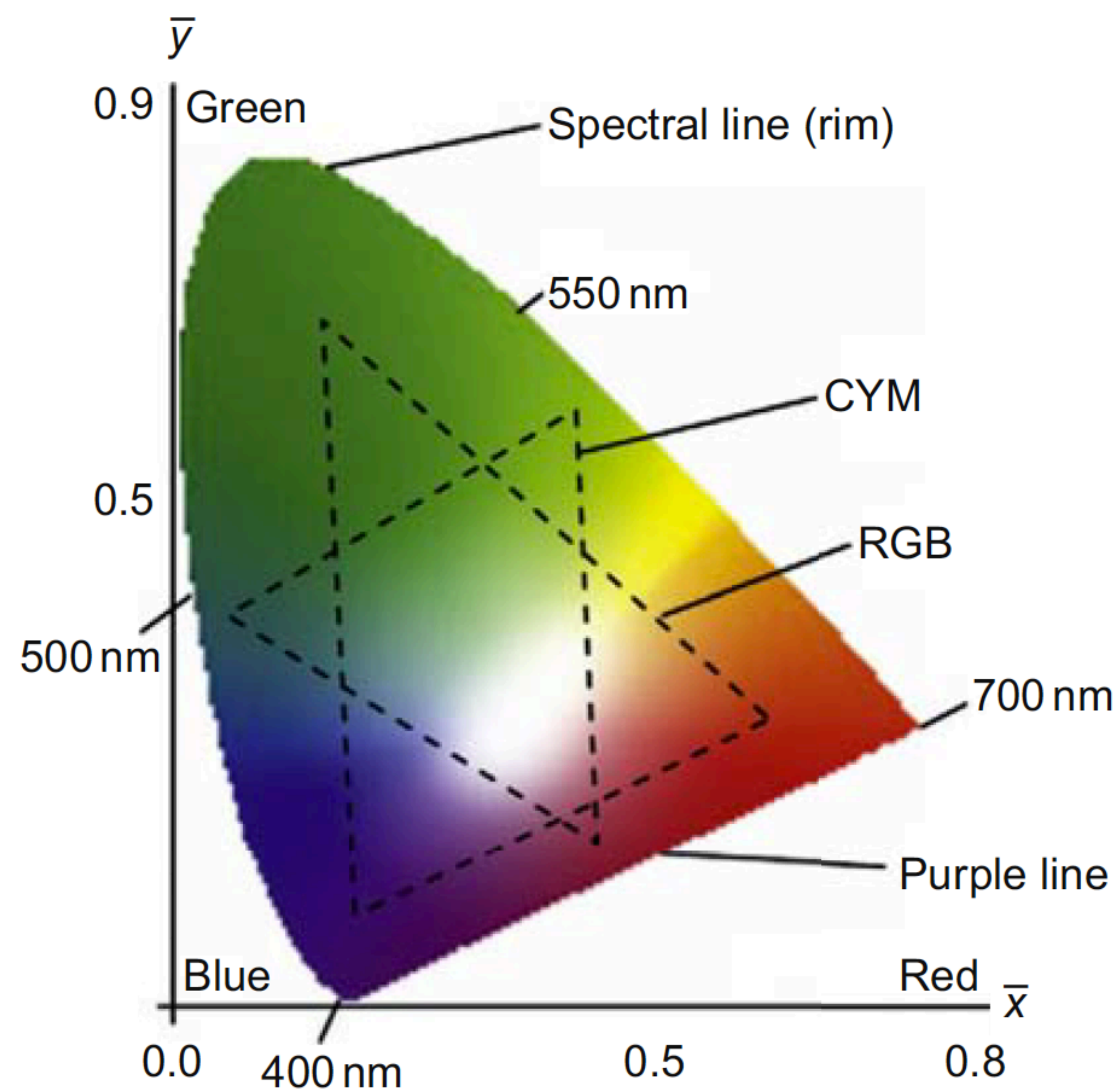
- First, in a reproduction system, it is cheaper to include a black than use CMY to generate black.
- Secondly, using three different colours produces less detail and shade than using a single colour.

This is particularly important if we consider that a great amount of printing material is in black and white.

RGB and CMY

Since RGB and CMY models are relevant for reproduction systems, in addition to the additive and subtractive properties, it is very important to determine which colours are included in the colour model. This is called the gamut and it is generally described using a triangle in the chromaticity diagram.

The triangles' vertices are defined by the base colours of typical RGB and CMY models. Since colours are linearly combined, each triangle contains all the colours that can be obtained by the base colours. That is, the gamut.



RGB and CMY

RGB to/from CMY

[CMYK:1-CMYK:2]

Luminance and chrominance colour models

Luminance and chrominance colour models

Why new model?

As you know, the RGB colour models define base colours according to practical physical properties of reproduction systems. Thus, the brightness of each colour depends on ALL components.

However, in some applications, like video transmission, it is **more convenient to have a separate single component to represent the perceived brightness**. From a historical perspective, perhaps the most relevant models that use a component to represent brightness are the YUV and YIQ.

In the early development of television systems, it was important to have the brightness in a single component for two main reasons:

- First, the system was compatible with the old black and white televisions that contained a single luminance component; the added colour data can be transmitted separately from the brightness.

- Secondly, the transmission bandwidth can be effectively reduced by dropping the bandwidth of the components having the chromaticity; since the human eye is more sensitive to luminance, the reduction in chromaticity produces less degradation in the images that when using the RGB model. Thus, transmission errors are less noticeable by the human eye.

Currently, the data reduction achieved with this colour models is not only important for transmission and storing but also for video processing. For processing, a separate luminance can be used to apply techniques based on grey level values as well of techniques that are independent of the luminosity.

Luminance and chrominance colour models

The UV representation of chrominance was chosen over straight R and B signals because $U = B - Y$ and $V = R - Y$ are **color difference signals**. In other words, the U and V signals tell the television to shift the color of a certain spot (CRT displays do not have discrete pixels) without altering its brightness. Or the U and V signals tell the monitor to make one color brighter at the cost of the other and by how much it should be shifted. The higher (or the lower when negative) the U and V values are, the more saturated (colorful) the spot gets. The closer the U and V values get to zero, the lesser it shifts the color meaning that the red, green and blue lights will be more equally bright, producing a greyer spot. This is the benefit of using color difference signals, i.e. instead of telling how much red there is to a color, it tells by how much it is more red than green or blue. In turn this meant that when the U and V signals would be zero or absent, it would just display a greyscale image.

Luminance and chrominance colour models

YUV and YIQ

The YUV and YIQ colour models are specified by the NTSC and PAL television broadcasting standards. The difference between both colour models is that the YIQ has a rotation of $33°$ in the colour components. The rotation defines the I axis to have colours between orange and blue and the Q axis to have colours between purple and green. Since the human eye is more sensitive to changes in the I axis than to the colours in the Q component, then the signal transmission can use more bandwidth for I than for Q to create colours that are clearly distinguished.

Luminance and chrominance colour models

The primary advantage of luma/chroma systems such as Y′UV, and its relatives Y′IQ and YDbDr, is that they remain compatible with black and white analog television. The Y′ channel saves all the data recorded by black and white cameras, so it produces a signal suitable for reception on old monochrome displays. In this case, the U and V are simply discarded. If displaying color, all three channels are used, and the original RGB information can be decoded.

Another advantage of Y′UV is that some of the information can be discarded in order to reduce bandwidth. The human eye has fairly little spatial sensitivity to color: the accuracy of the brightness information of the luminance channel has far more impact on the image detail discerned than that of the other two. Understanding this human shortcoming, standards such as NTSC and PAL reduce the bandwidth of the chrominance channels considerably.

YUV provide an intuitive representation of intensity, but chrominance only represents the difference to white at same luminance, thus the colour ranges are not very intuitive.

Luminance and chrominance colour models

It is very important to notice that transformations between RGB colour models and luminance and chrominance models do not change the colour base, but they only rearrange the colours to give a different meaning to each component. Thus, the base colours of luminance and chrominance models are given by the RGB standards. For example, YIQ uses the NTSC RGB base colours. These are called the RGB base or primaries of the YIQ colour model. That means that the luminance and chrominance models are defined from RGB base colours, and this is the reason why sometimes luminance and chrominance are considered as a way of encoding RGB data rather than a colour model per se.

Luminance and chrominance colour models

Luminance and gamma correction

The transformation from RGB to YUV is defined by considering the y component as the perceived intensity of the colour.

If you consider the contribution that each component has to luminosity, then y will be approximately given by:

$$y = 0.18r + 0.79g + 0.02b$$

In the YUV and YIQ models, this equation is not directly used to represent brightness, but it is modified to incorporate a nonlinear transformation that minimises the perceived changes in intensity.

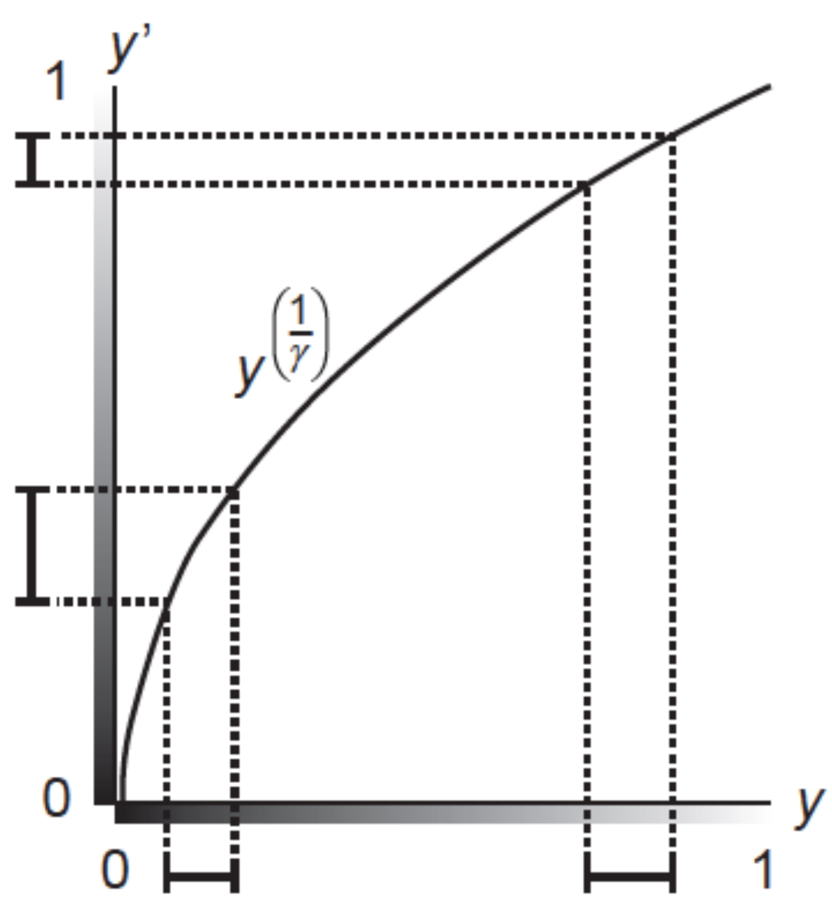
Since the human eye distinguishes more clearly variations in intensity at low luminance than when the luminance is high, then **an efficient coding of the brightness can be achieved if more bandwidth is used to represent dark values than bright values**.

Coding and decoding luminance is called gamma encoding or gamma correction.

Luminance and chrominance colour models

Luminance and gamma correction

In the transformations used in gamma correction the horizontal axis of the graph represents the luminance y and the vertical axis represents the *luma*. The *luma* is generally denoted as y', and it is the value used to represent brightness in the YUV and YIQ colour models. Accordingly, some texts use the notation Y'UV and YUV to distinguishing models using gamma corrected values.



Luminance and chrominance colour models

Luminance and gamma correction

YUV and YIQ standards defines a gamma value as $\gamma = 2.2$, so

$$y' = \Gamma(y) = y^{\frac{1}{\gamma}} = y^{\frac{1}{2.2}} = y^{0.45}.$$

Since the RGB components in television sets were produced by three independent electron beans, then the encoding cannot apply the transformation to combine luminance, but each component is separately gamma corrected.

That is, the luma is defined as the sum of gamma corrected RGB components. Thus, by gamma correcting:

$$y = 0.18r + 0.79g + 0.02b$$

you obtain a formula for gamma corrected luminosity:

$$y' = 0.299r' + 0.587g' + 0.114b'$$

The prime symbol in this equation is used to indicate gamma corrected values. That is, $r' = \Gamma(r)$, $g' = \Gamma(g)$ and $b' = \Gamma(b)$. These values have a range between zero and one.

There is an alternative definition of luma that was developed according to current displays used for HDTV technology. This definition is given by:

$$y' = 0.212r' + 0.715g' + 0.072b'.$$

Luminance and chrominance colour models

RGB-YUV Conversion

Different formulas are effect of different standards: compare

https://en.wikipedia.org/wiki/YUV

Section: Conversion to/from RGB

Luminance and chrominance colour models

Understanding YUV data formats

[Other:8]

Additive perceptual colour models

Perceptual colour models

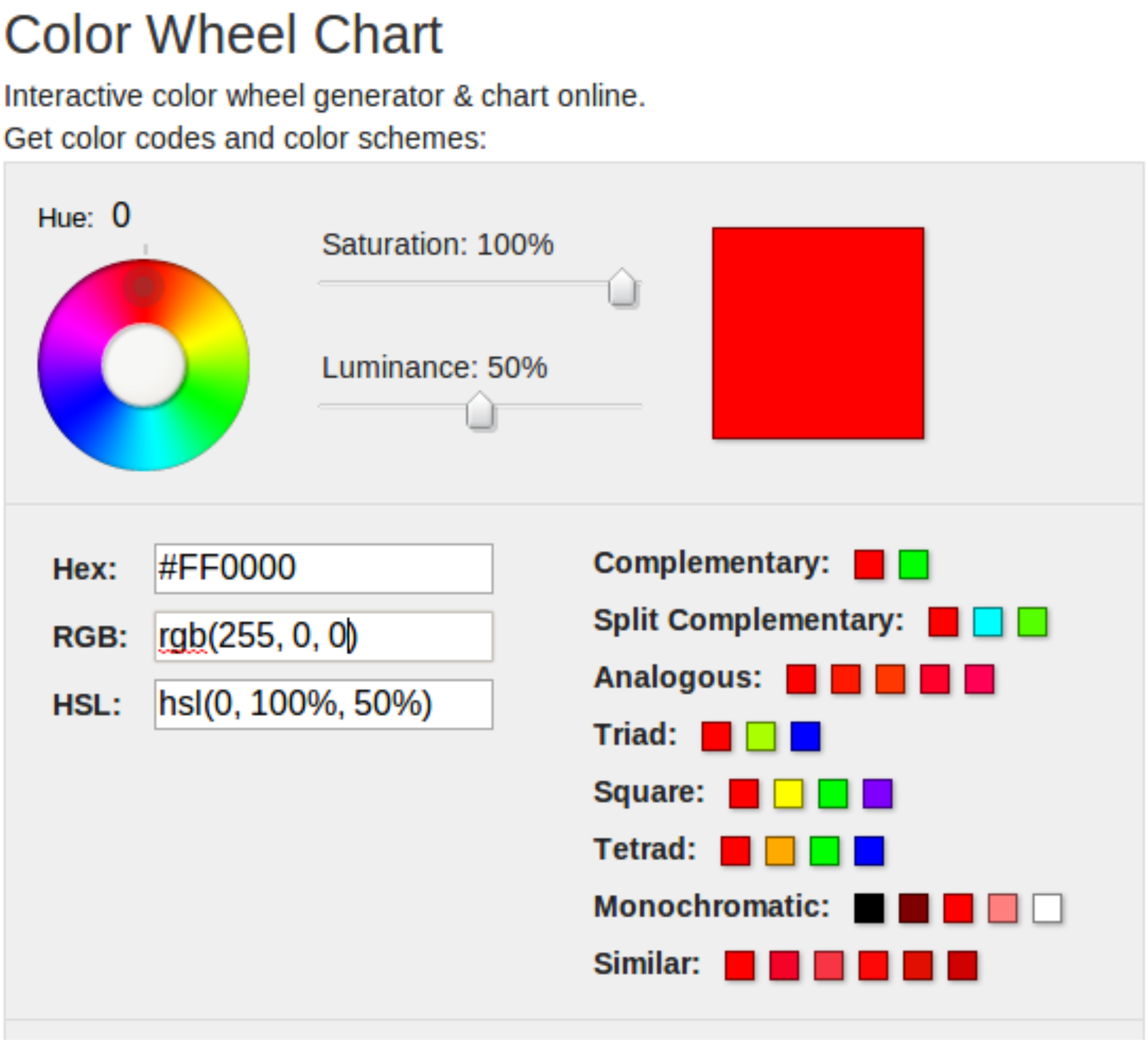
As mentioned earlier, RGB colour models are aimed at representing colours created in reproduction systems. Thus, the combination of RGB components can be not intuitive to human interpretation. That is, it is difficult to determine the precise values that should have colour components that create a particular colour. Even when using the visualisation of the RGB colour cube, the interpretation of colours is not simple since perceptual properties such as the colour brightness vary indistinctly along the RGB axes.

YUV provide an intuitive representation of intensity, but chrominance only represents the difference to white at same luminance, thus the colour ranges are not very intuitive. **Perceptual colour models are created by a transformation that rearranges the colours defined by the RGB colour model such that their components are easy to interpret.** This is achieved by relating components to colours' characteristics such as hue, brightness or saturation. Thus, tasks such as colour picking and colour adjustments can be performed using colour properties having an intuitive meaning.

Perceptual colour models

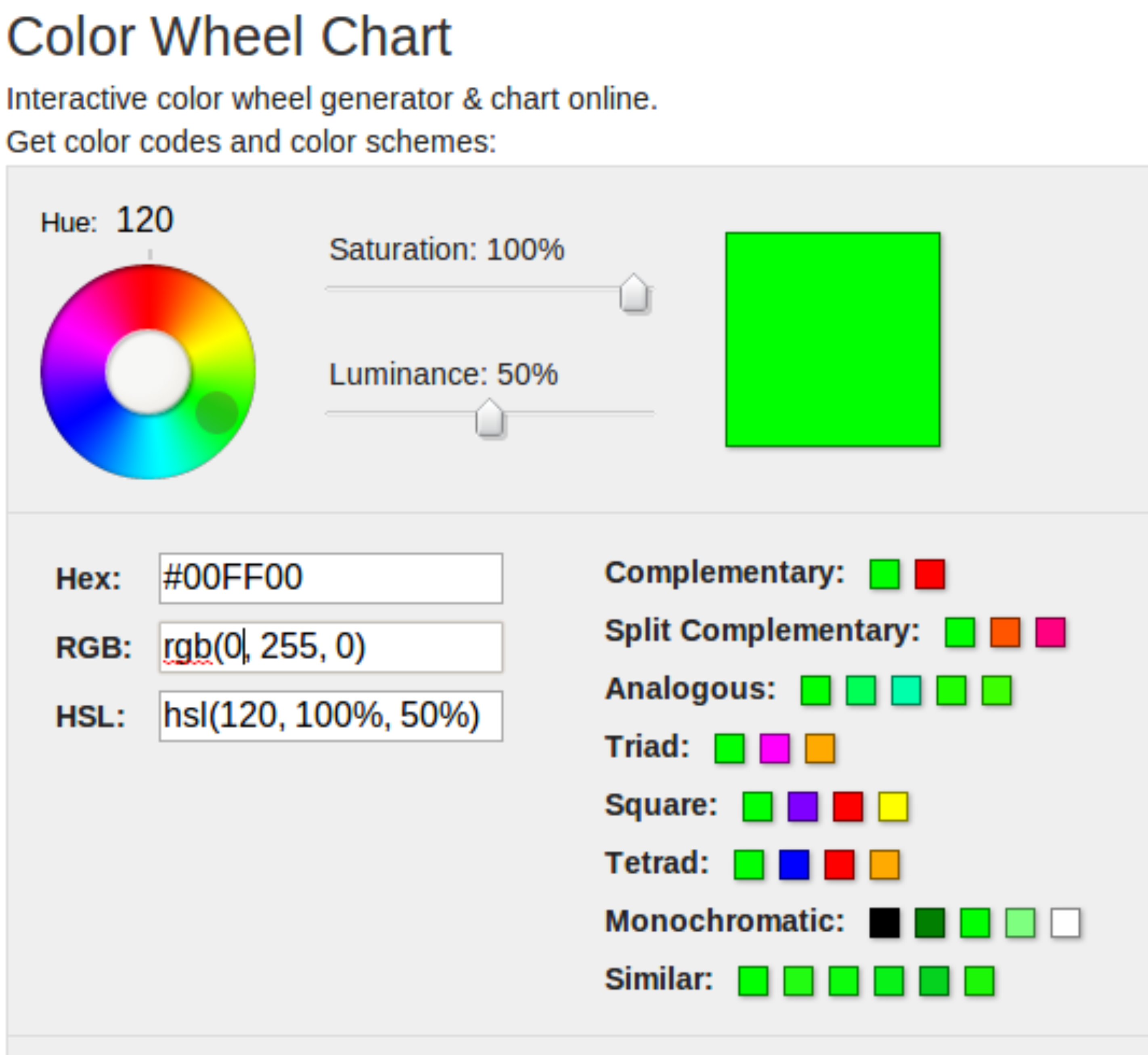
Terminology and practical meaning: hue, brightness and saturation

The hue is what distinguishes, for example, green from blue, and is common to various shades of red.



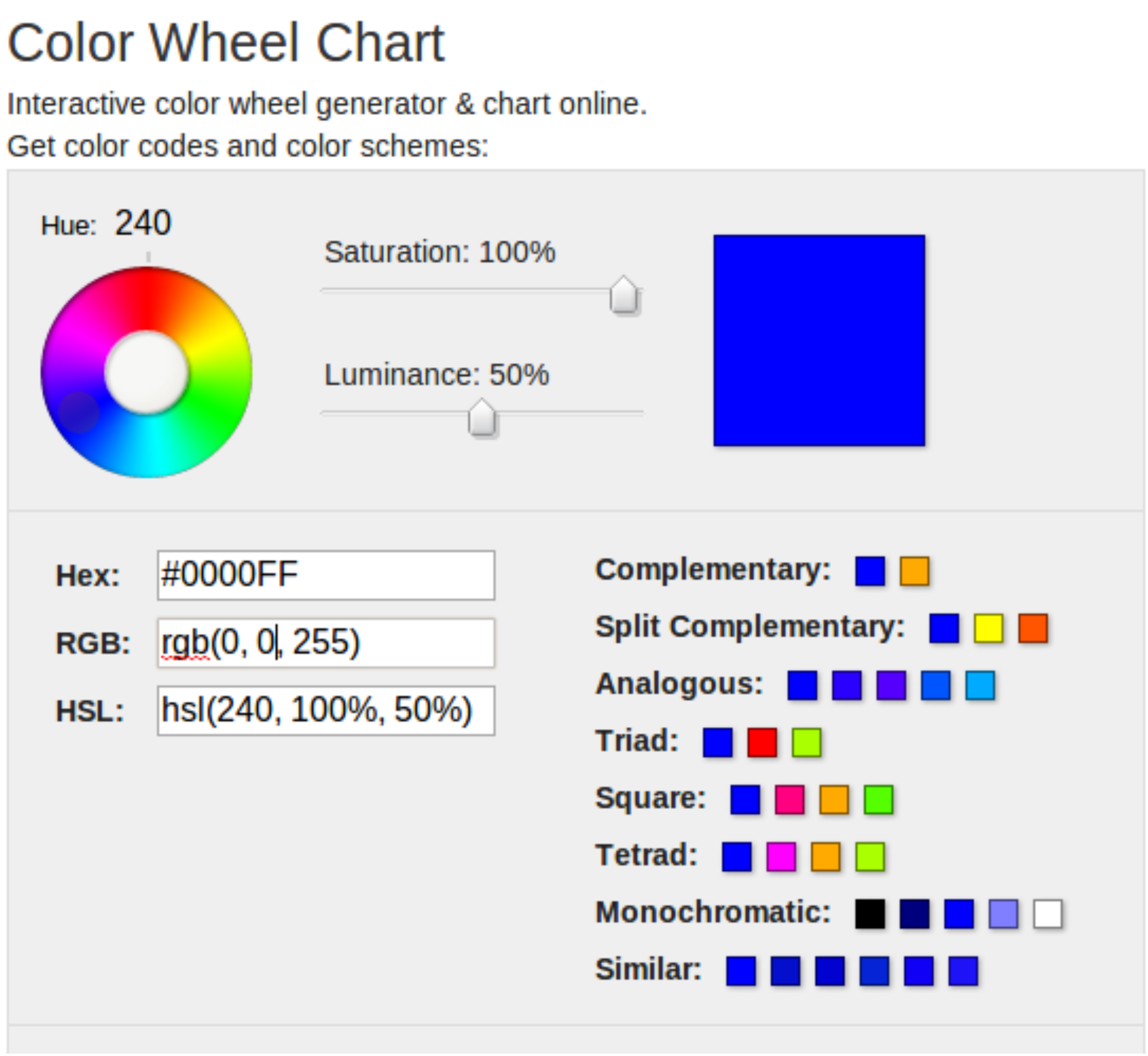
Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation



Perceptual colour models

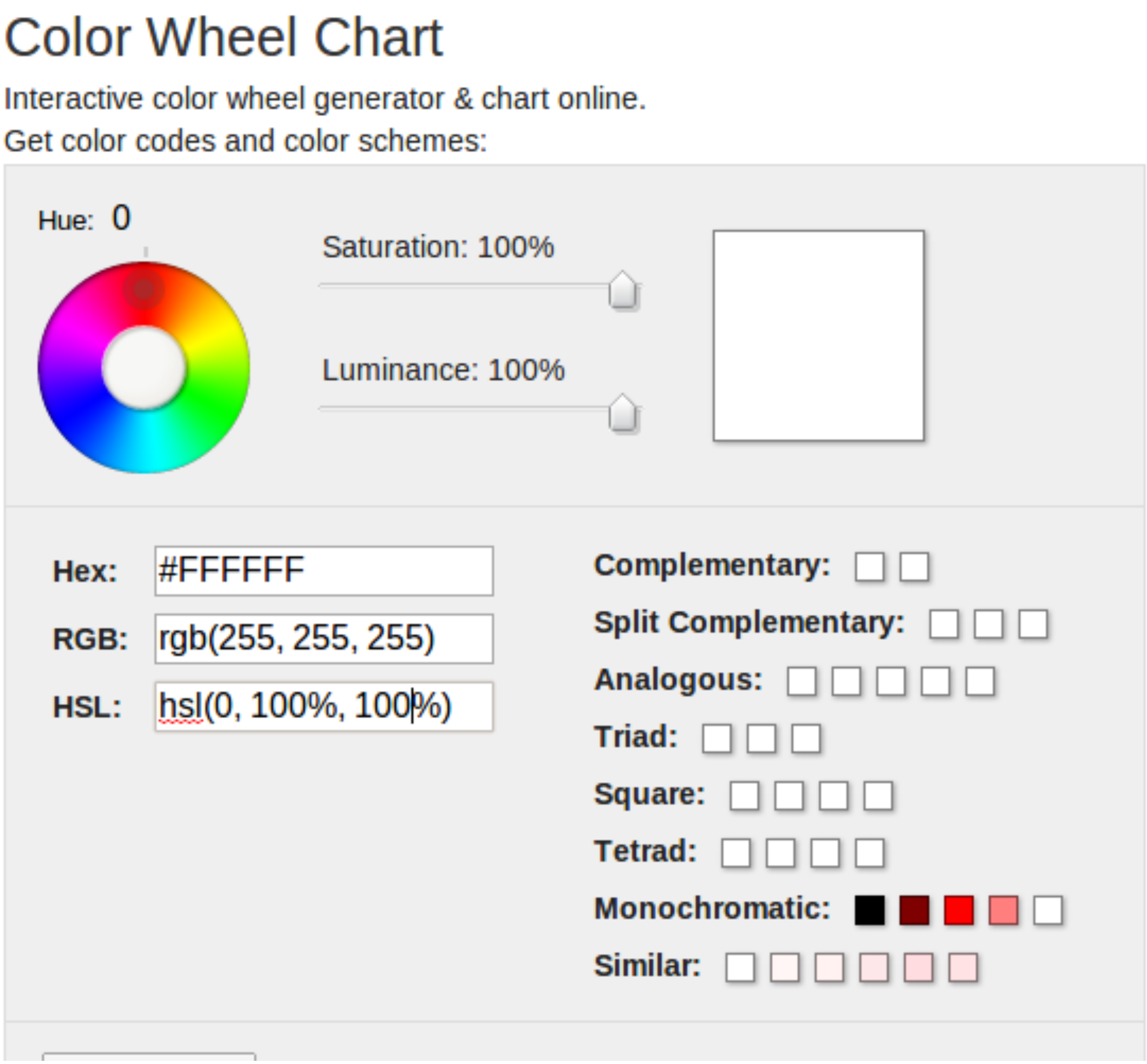
Terminology and practical meaning: hue, brightness and saturation



Perceptual colour models

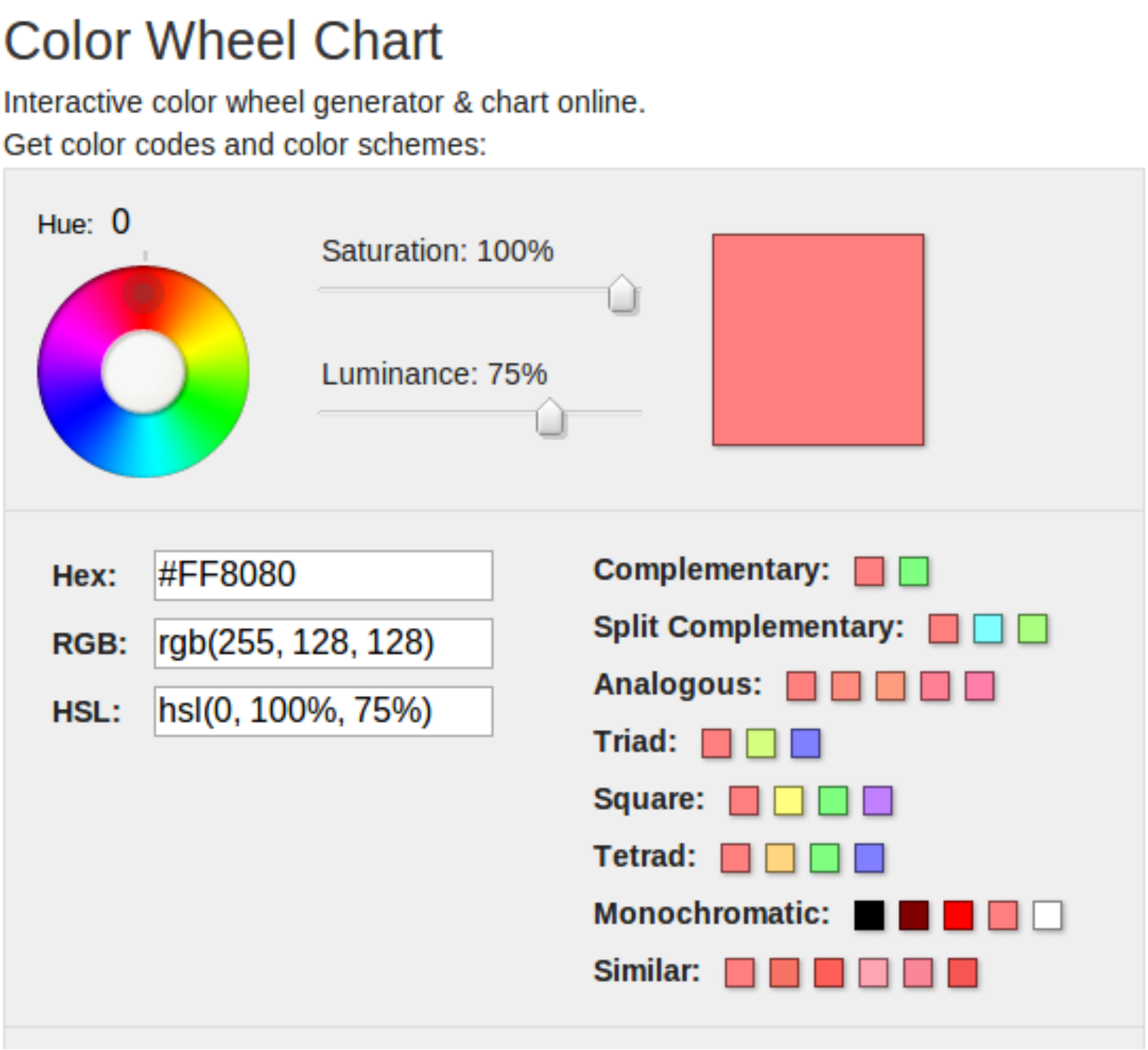
Terminology and practical meaning: hue, brightness and saturation

The brightness determines the degree of similarity to the color white (for light shades) or black (for dark shades).



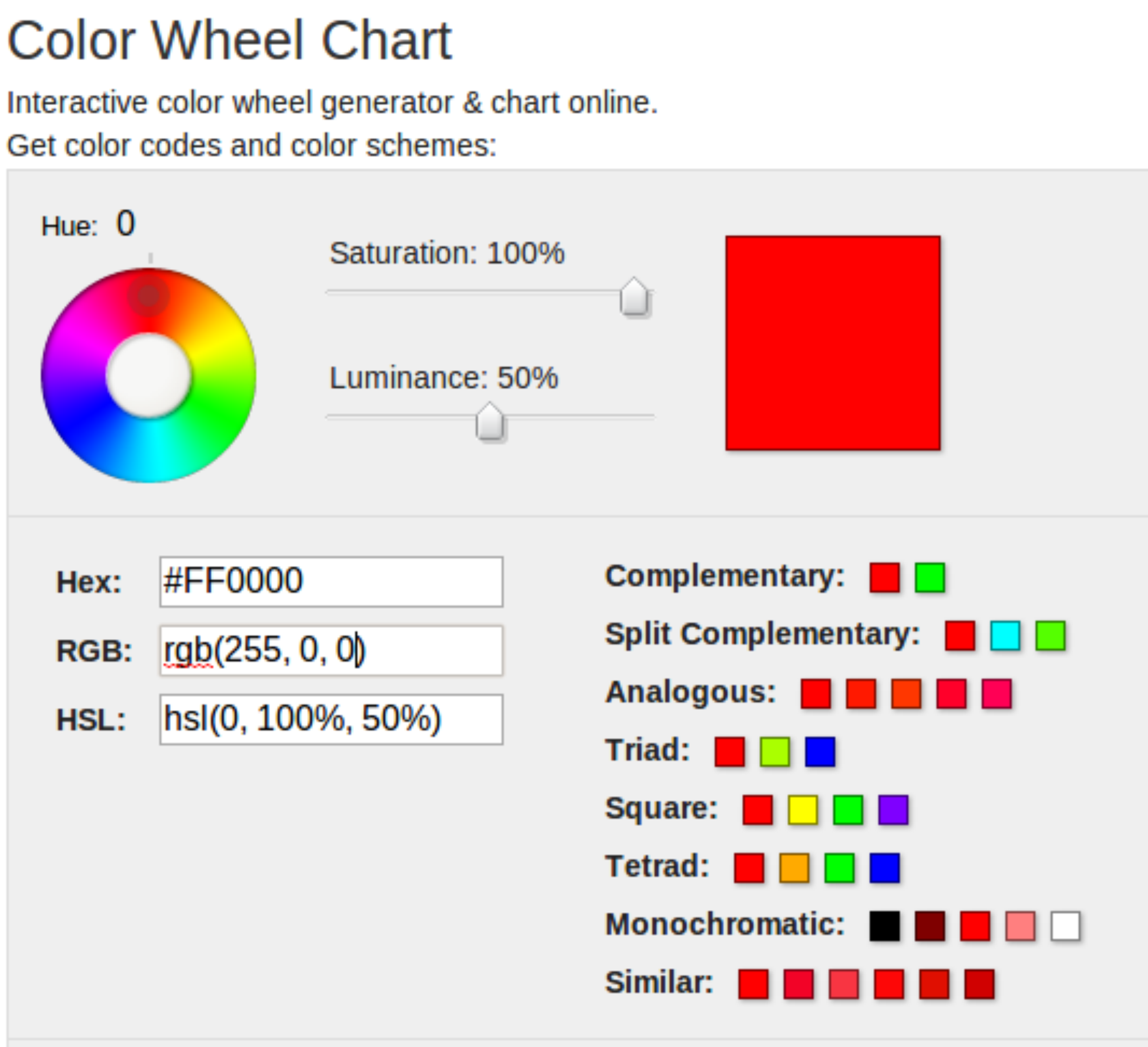
Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation



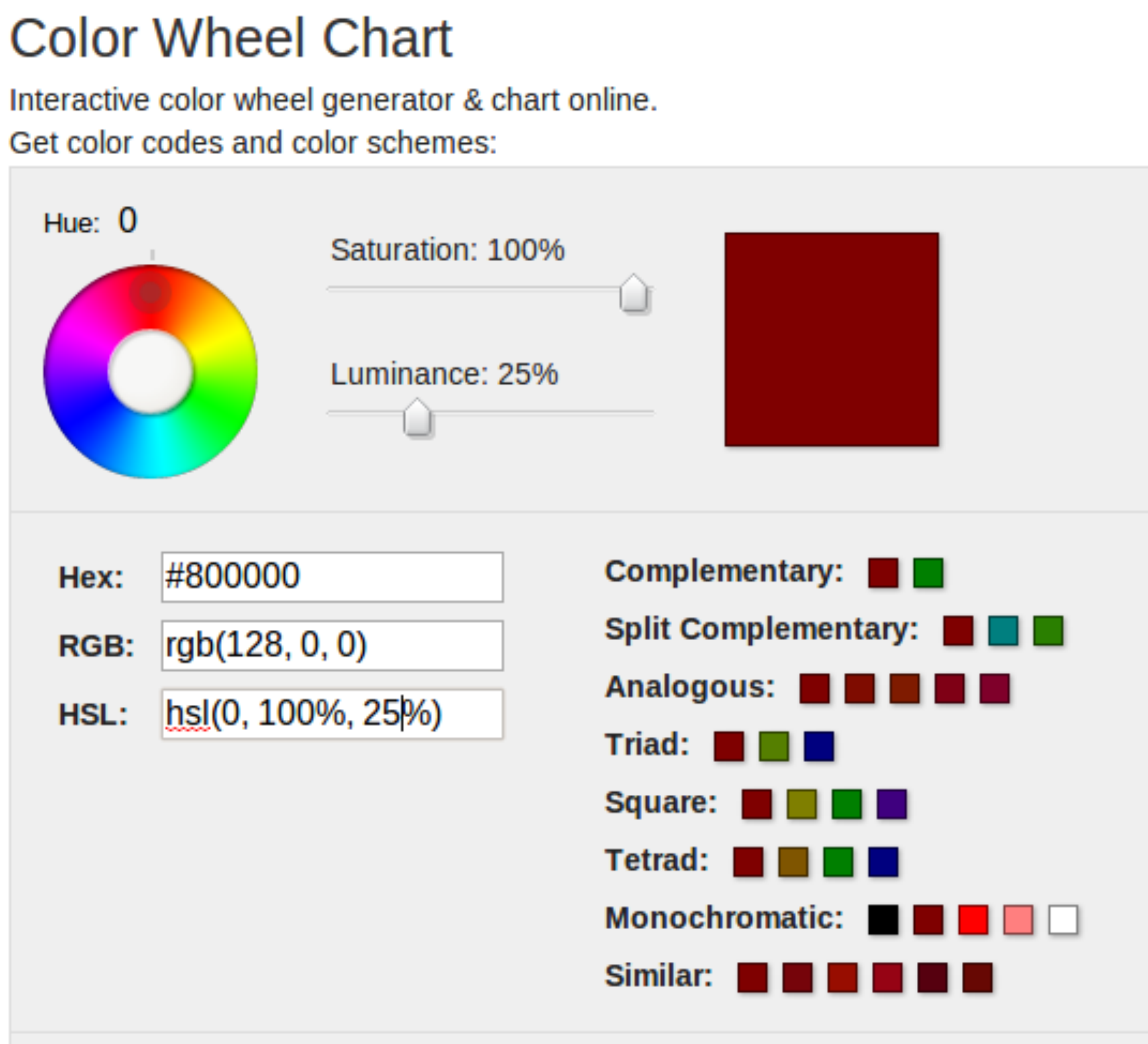
Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation



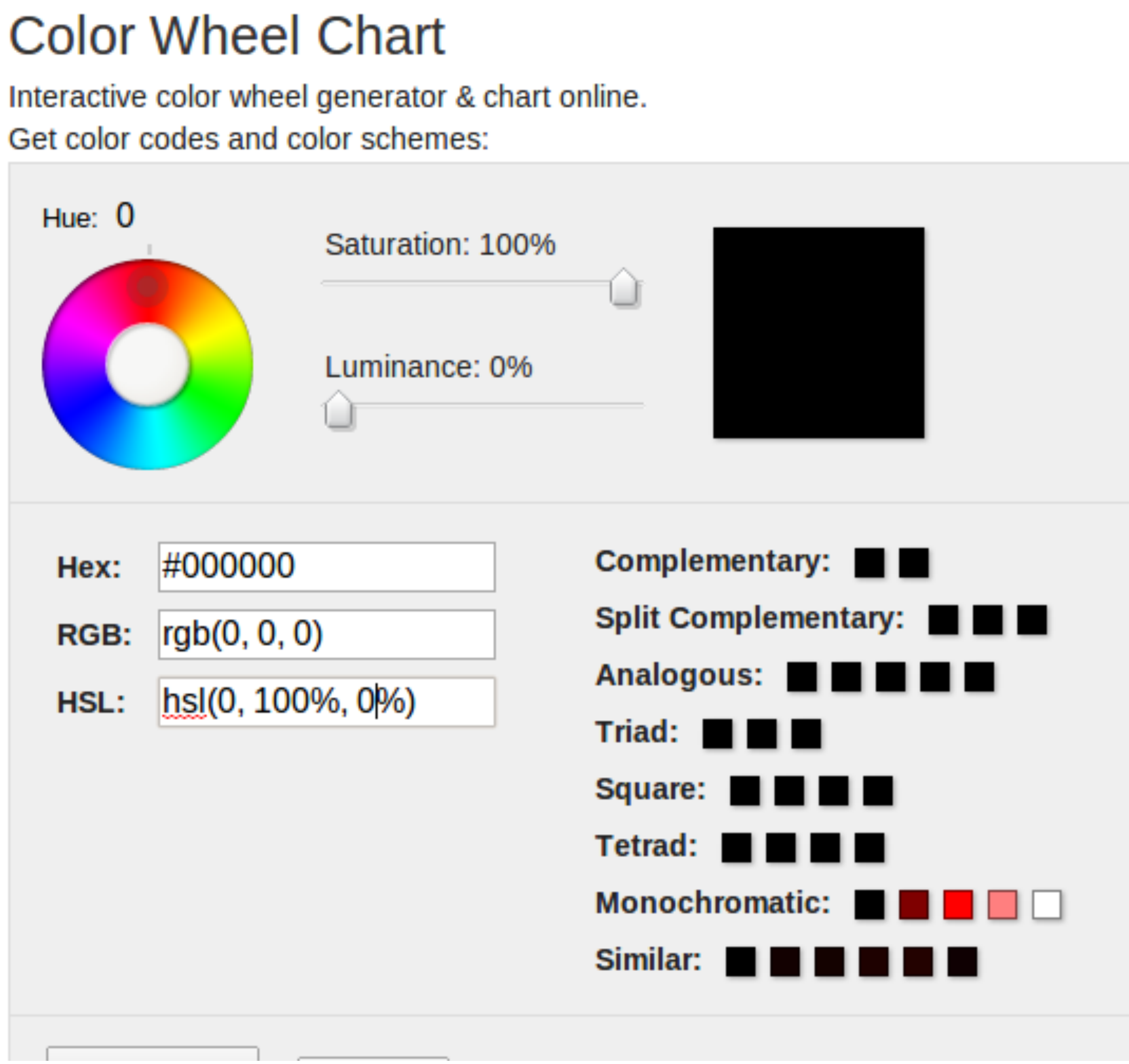
Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation



Perceptual colour models

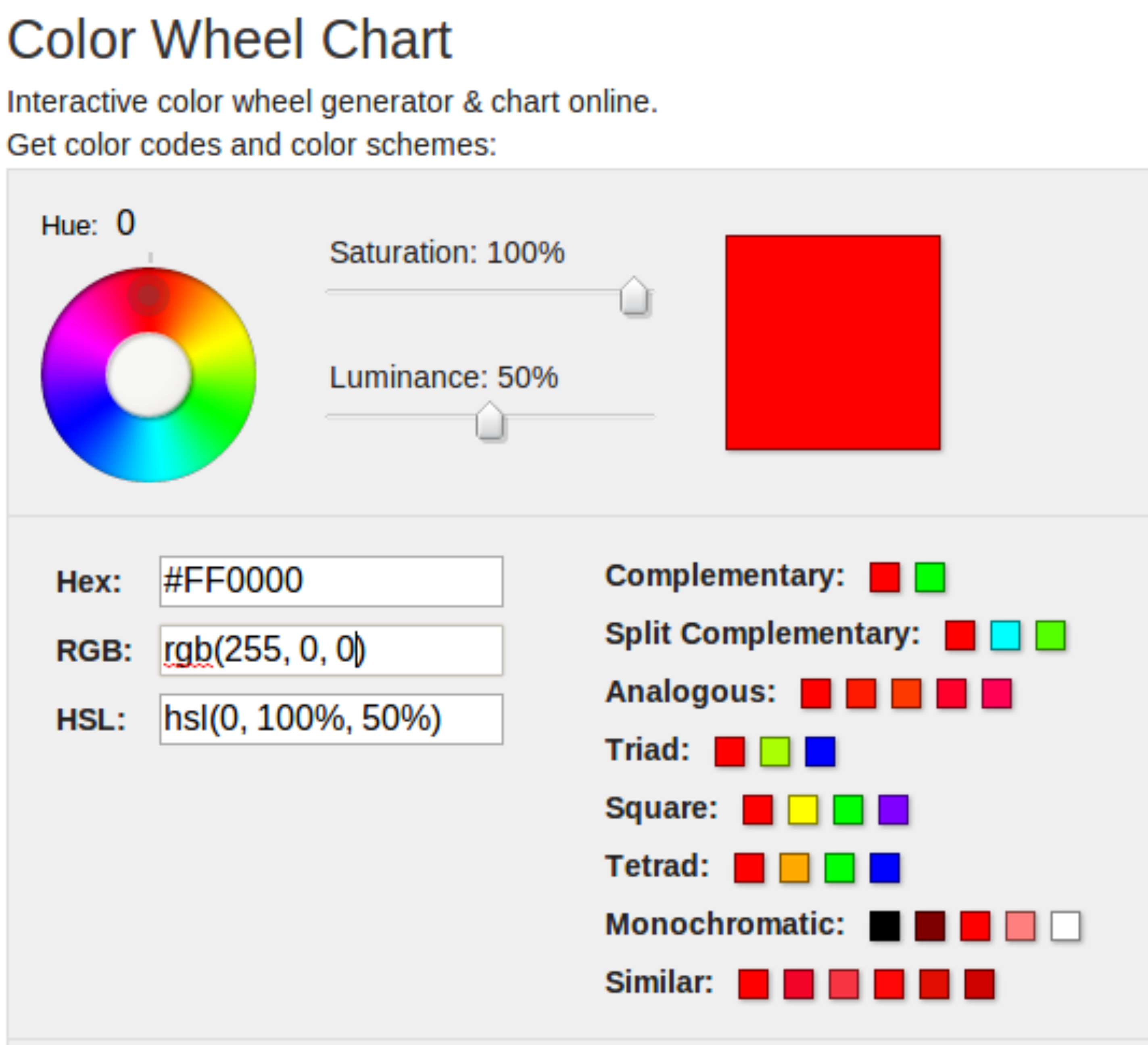
Terminology and practical meaning: hue, brightness and saturation



Perceptual colour models

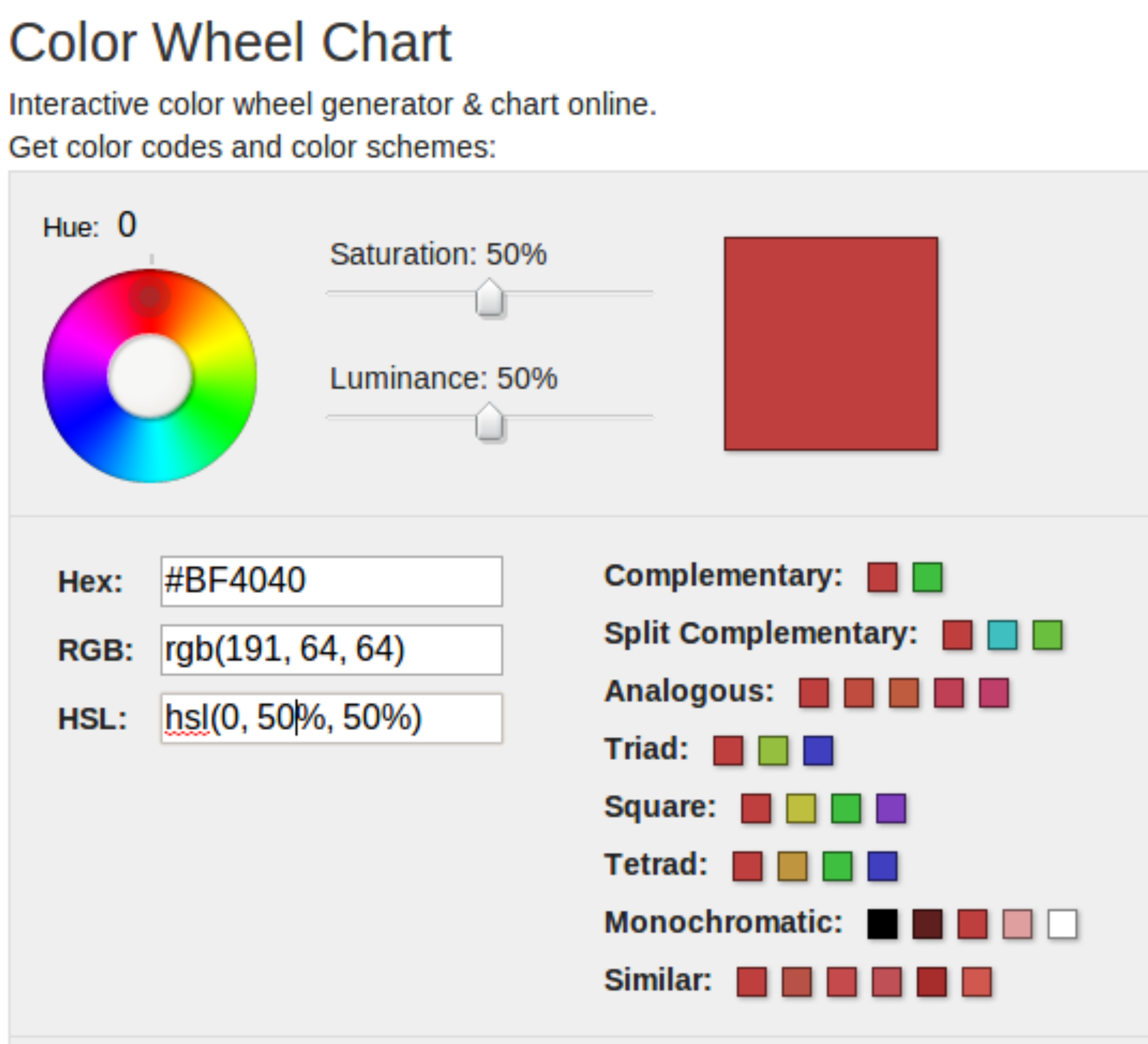
Terminology and practical meaning: hue, brightness and saturation

With the same hue and brightness, some shades seem more saturated (cleaner) to us, and others less.



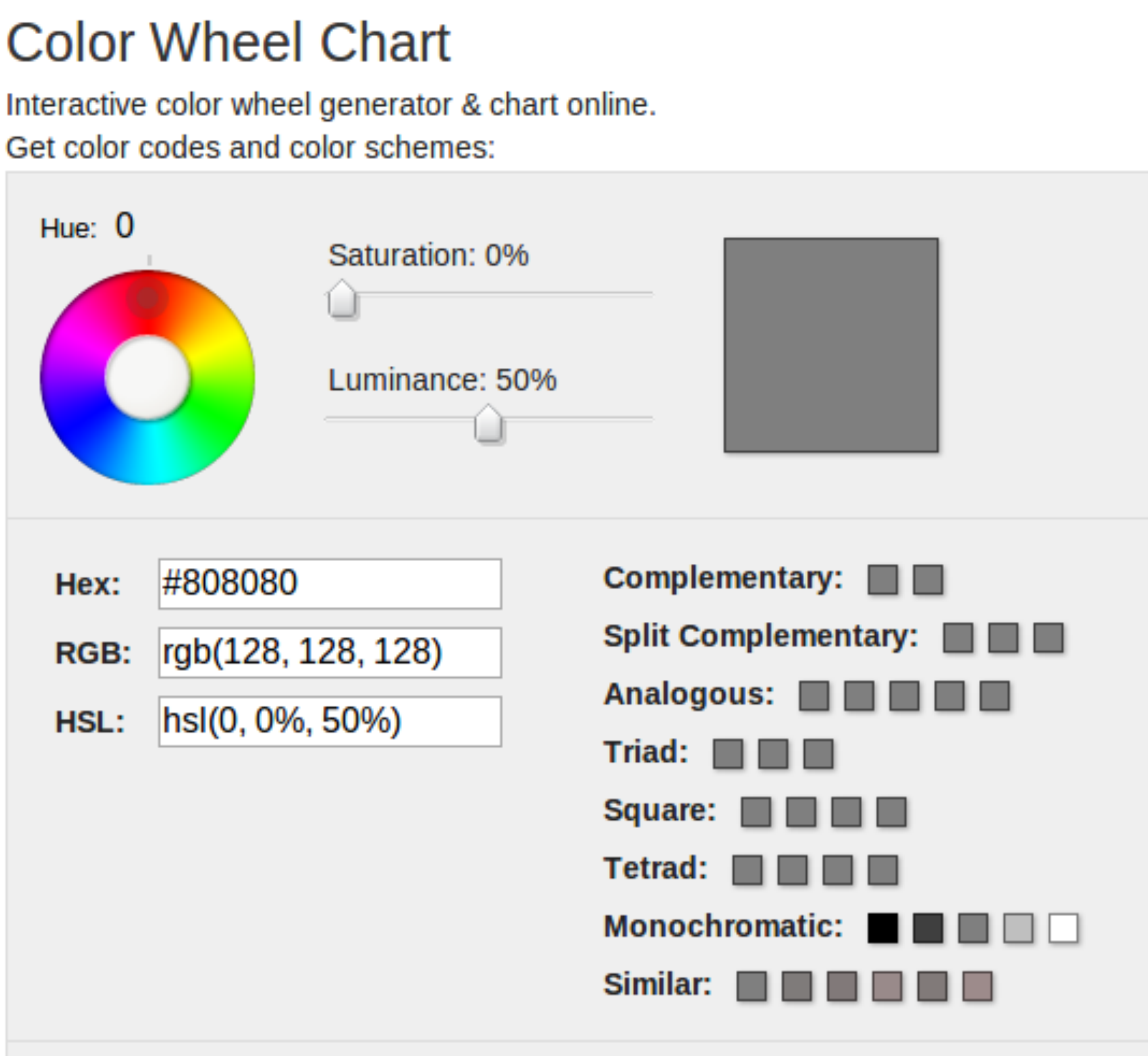
Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation



Perceptual colour models

Terminology and practical meaning: hue, brightness and saturation

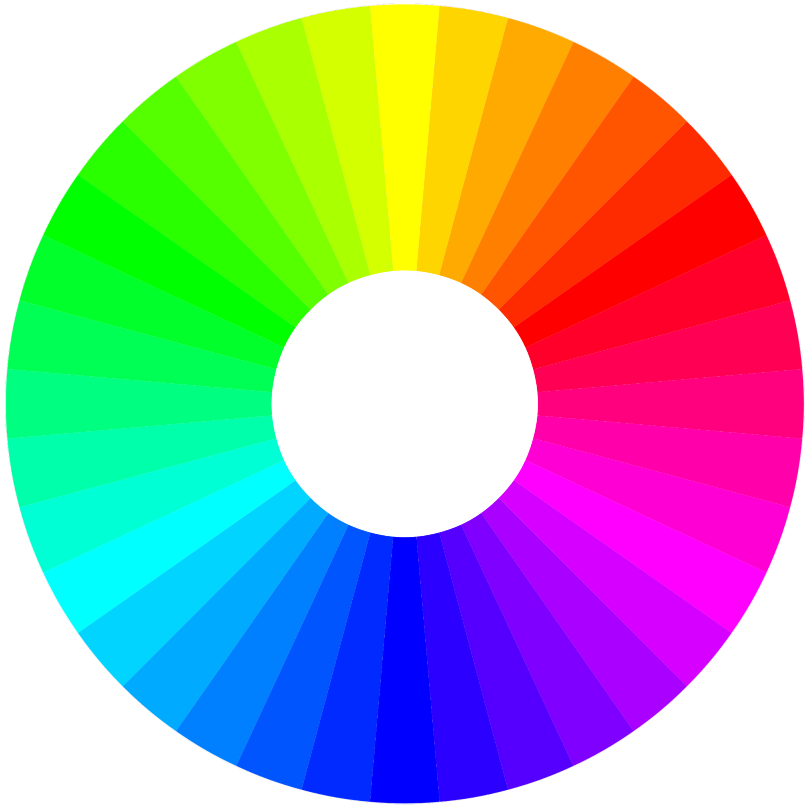


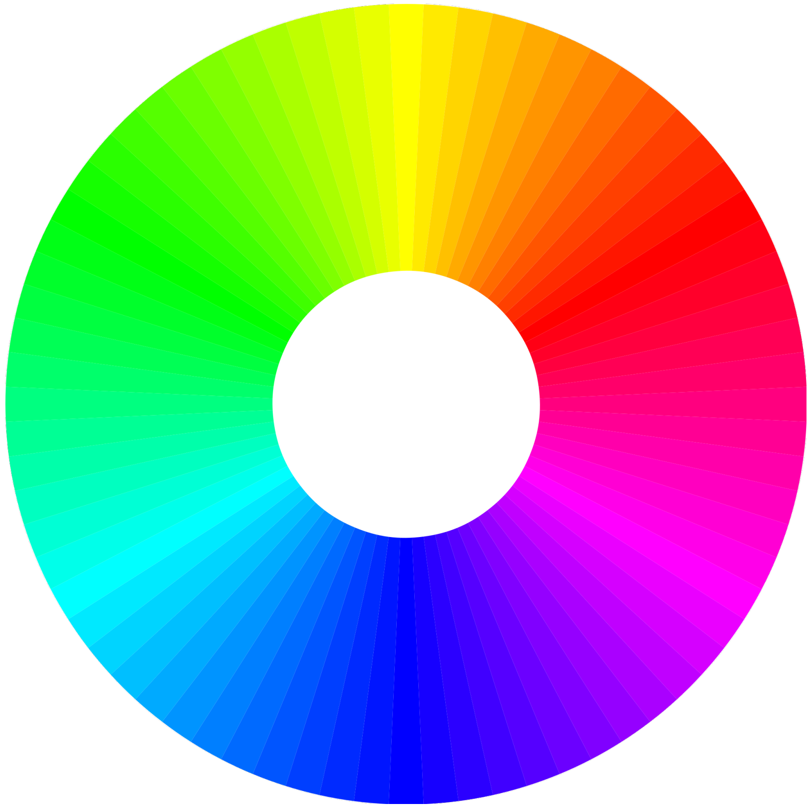
Perceptual colour models

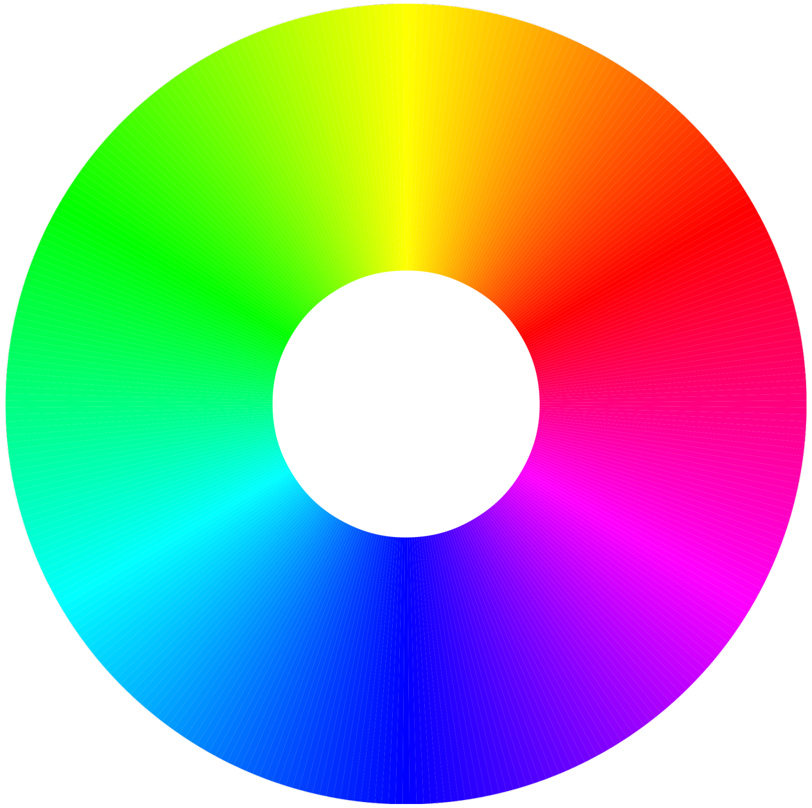
Hue

All colors on this color wheel should appear to have the same lightness and the same saturation, differing only by hue.

Color circle, intensity 54%, saturation about 70%





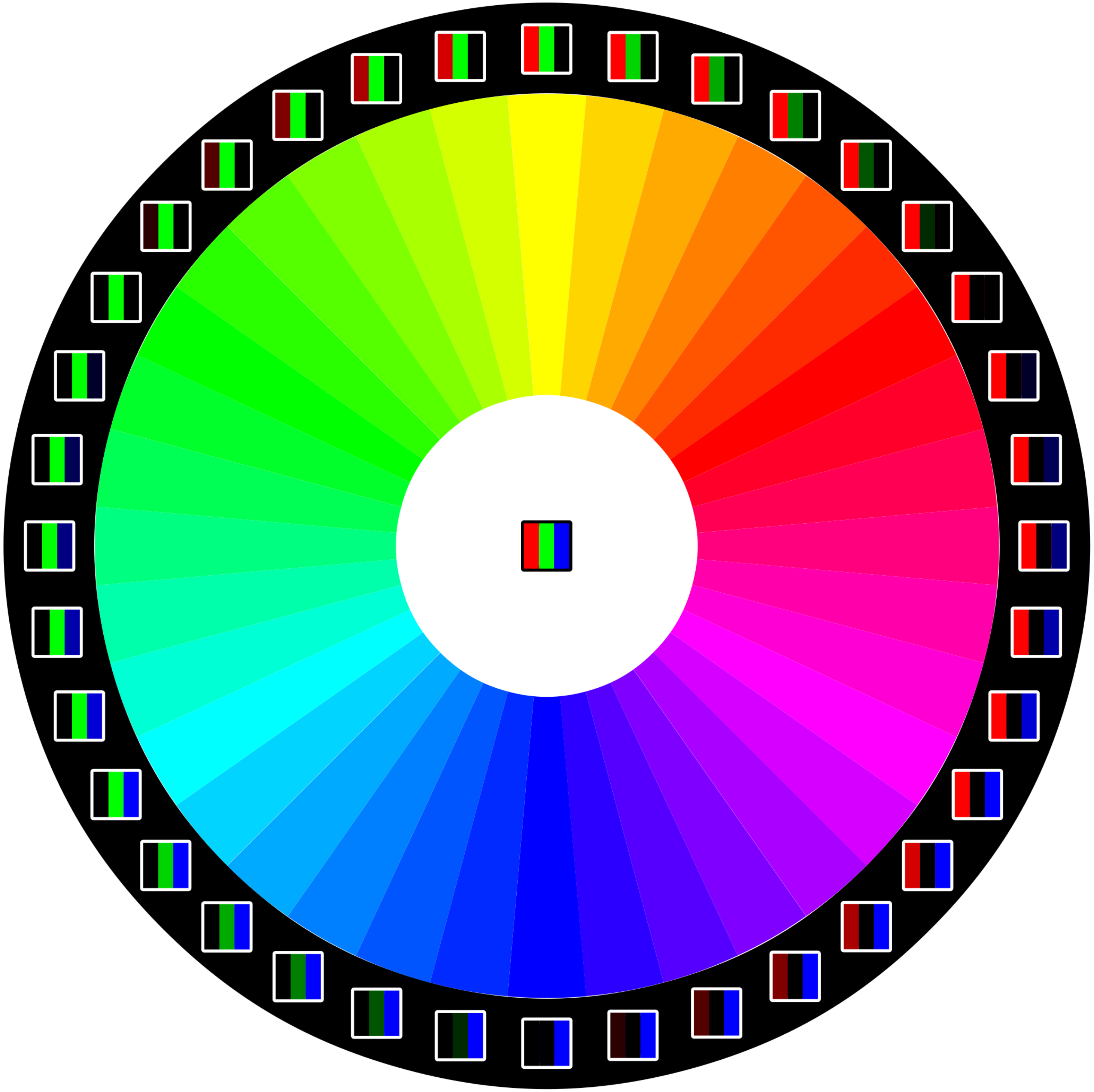


https://en.wikipedia.org/wiki/File:Colors-i54-ring.png

https://en.wikipedia.org/wiki/File:RGB_color_wheel_24.svg

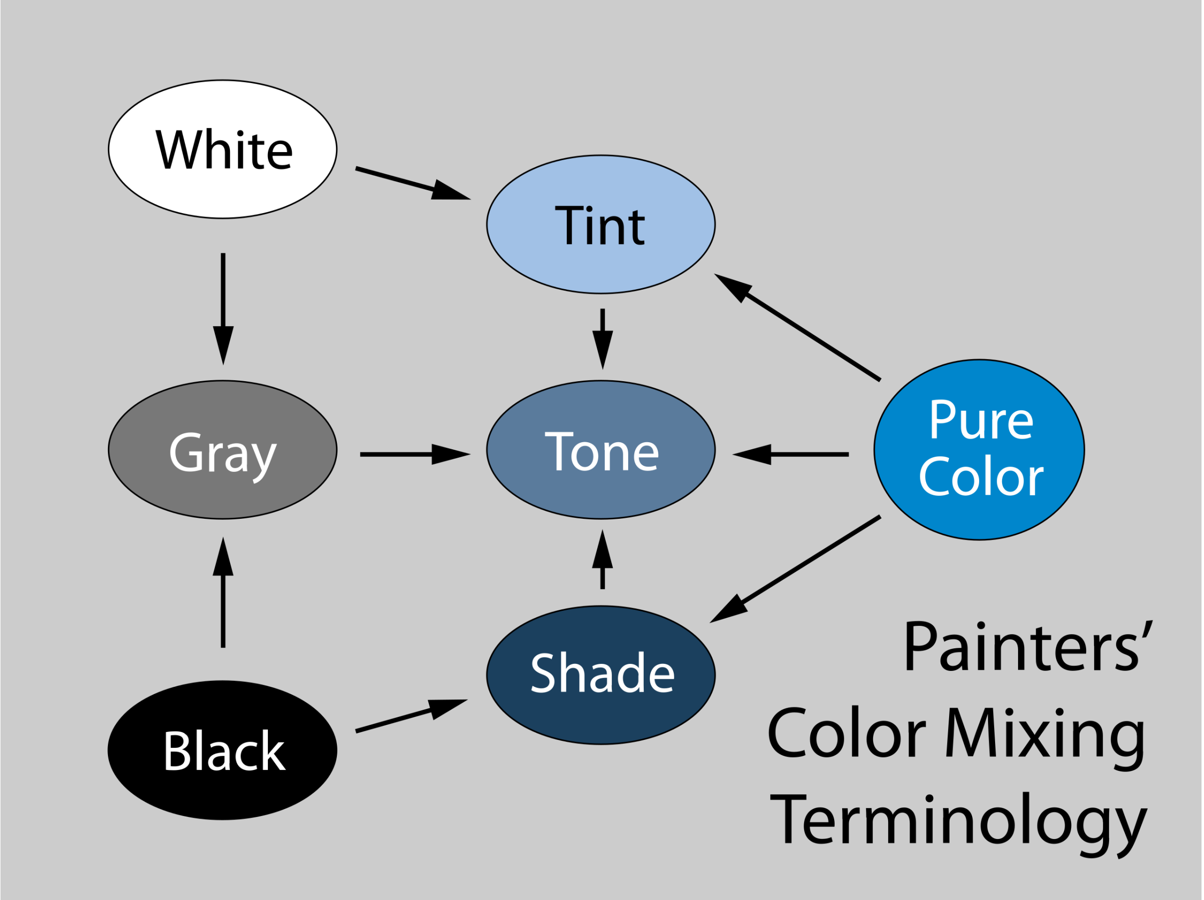
Perceptual colour models

Hue



Perceptual colour models

Terminology and practical meaning: tint, shade and tone



In color theory,

- a *tint* is a mixture of a color with white, which increases lightness,
- a *shade* is a mixture with black, which increases darkness.
- a *tone* is produced either by mixing a color with gray, or by both tinting and shading.

Both tinting and shading processes affect the resulting color mixture's relative saturation.

Mixing a color with any neutral color (including black, gray, and white) **reduces the chroma, or colorfulness, while the hue** (the relative mixture of red, green, blue, etc. depending on the colorspace) **remains unchanged**.

Perceptual colour models

The HSV and HSL colour models

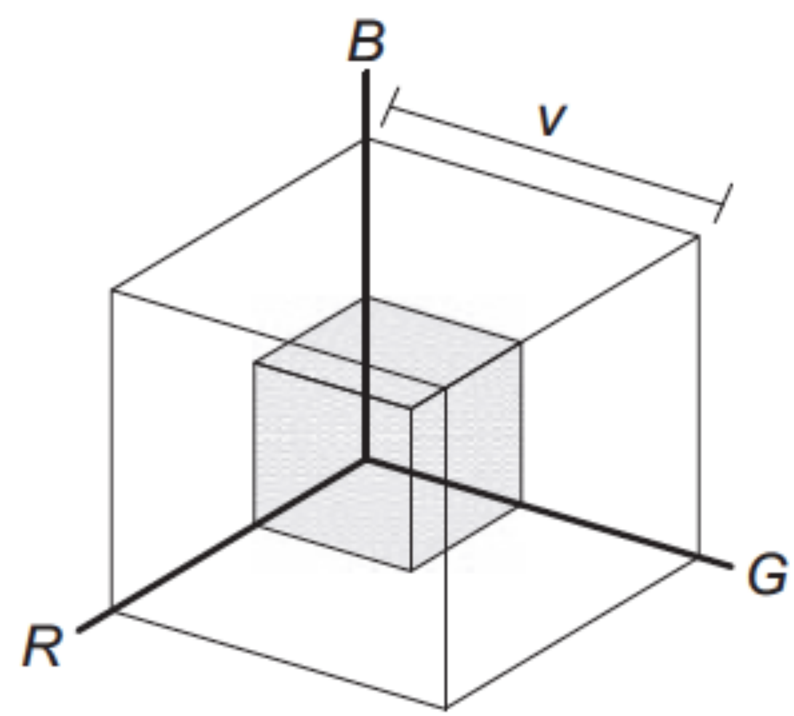
There are many perceptual colour models, but perhaps the most common are the HSV (Hue, Saturation, Value) and the HSL (Hue, Lightness, Saturation). The HSV is also referred to as HSI (Hue, Saturation, Intensity) or as the HSB (Hue, Saturation, Brightness).

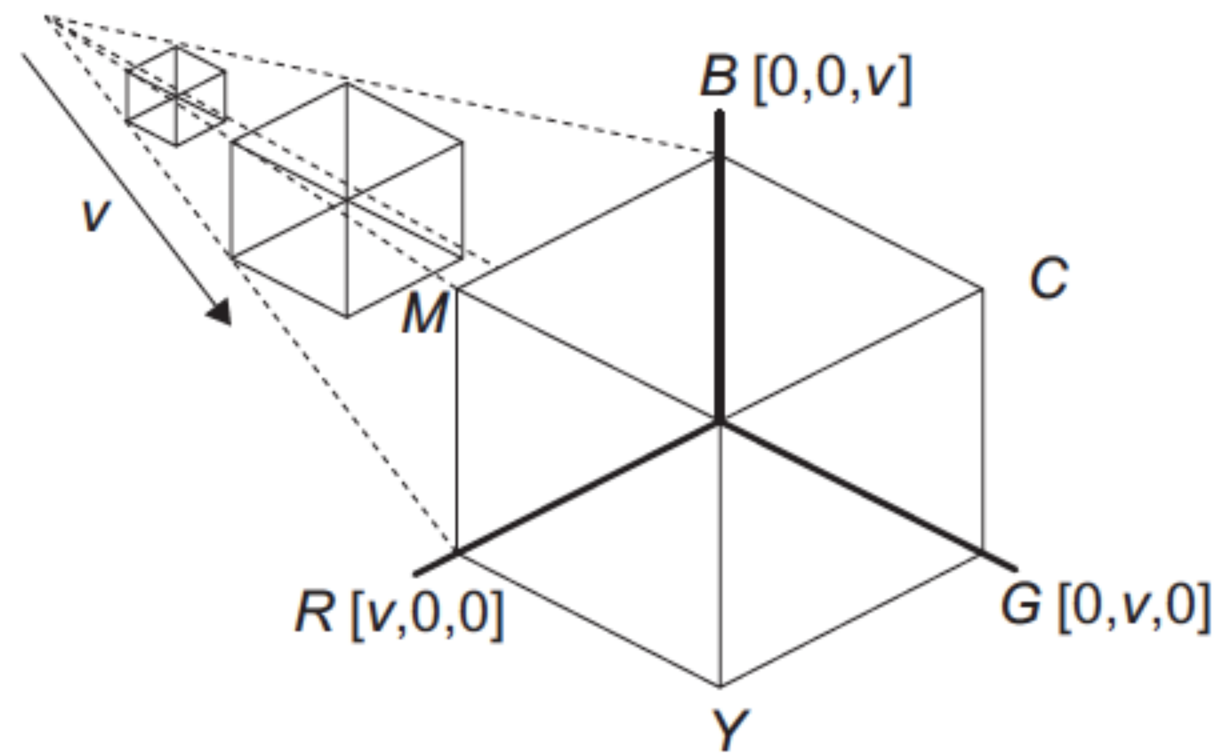
HSV and HSL use two components to define the hue and saturation of a colour but they use different concepts to define the component that represents the brightness.

Perceptual colour models

The hexagonal model: HSV

In this model three faces of three-dimensional RGB cube are projected into two-dimensional plane.





Three of the vertices of the hexagon are defined by the RGB axis and they have co-ordinates $[v,0,0]$, $[0,v,0]$ and $[0,0,v]$. The other three vertices define yellow, cyan and magenta, given by $[vv,0]$, $[0,v, v]$ and $[v,0,v]$.

Perceptual colour models

Value in the hexagonal model: HSV

In this model, the RGB colour cube is organised by considering a collection of sub-cubes formed by changing the coordinates of the components from zero to the maxima possible co-ordinate value. The quantity defining the size of the sub-cubes is called the *value* which generally ranges from 0 to 1. A value of 0 defines a sub-cube enclosing a single colour (i.e. black) and a value of 1 encompasses the whole RGB cube. The sub-cubes **do not contain all the colours they can enclose, but they only include the colours in the three faces that are visible from the point defining the white corner of the RGB colour cube and looking towards the origin**. In figure presented on previous slide these are the shaded faces of the smaller sub-cube. As such, each colour in the RGB colour cube is uniquely included in a sub-cube and the value that defines the sub-cube for any chosen colour can be determined by computing the maxima of its co-ordinates.

That is, a colour $[r, g, b]$ is included in the cube defined by a value given by $v = \max(r, g, b)$. According to this definition, the value in the HSV colour model is related to the distance from black. Fully saturated colours like red, green and yellow are in the same plane in the HSV colour space.

The colour is then defined as a position on a hexagonal plane around the lightness axis.

The size of the hexagon is given by v and consequently the set of hexagons for all the sub-cubes form a hexahedron with the peak in the location of black.

Perceptual colour models

Saturation in the hexagonal model: HSV

Since the centre of the hexagon defines grey levels, then the saturation s can be intuitively interpreted as the **normalised distance from the colour to the hexagon's centre**; when s is zero, the colour is grey, so it is desaturated. When the colour is saturated then s is unity and the colour lies in the border of the hexagon. In consequence, the computation of saturation can be easily done based on the geometry illustrated in previously presented figures.

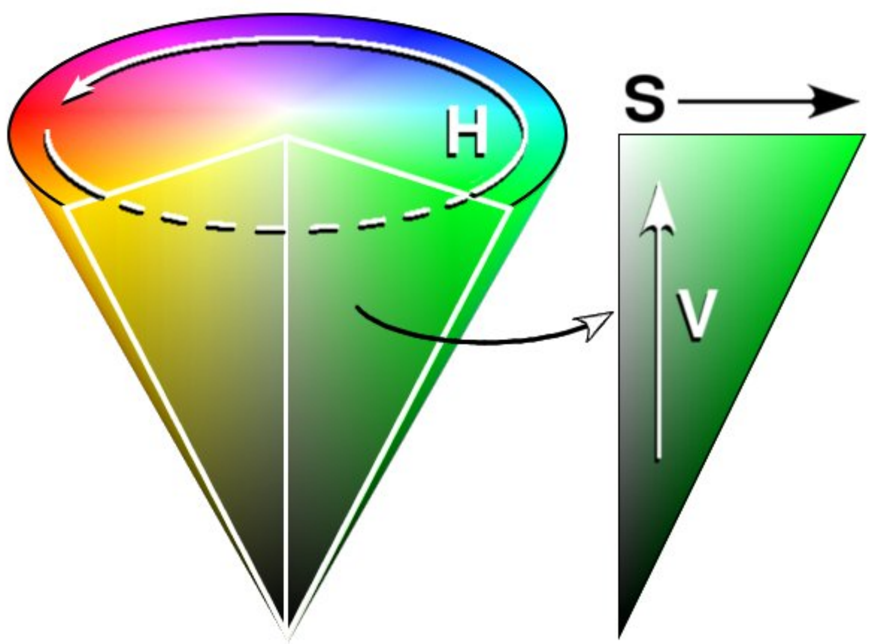
Perceptual colour models

Hue in the hexagonal model: HSV

The hue of a colour is intuitively interpreted by considering the geometry of the hexagon obtained by the sub-cube's projection. As such, the hue is considered as the angular value taking as reference the centre of the hexagon; by changing the angle, we change the colour from red, yellow, green, cyan blue and magenta. Naturally, the computation of the hue is also dependent on the part of the hexagon where the colour lies.

Perceptual colour models

Value, saturation and hue in the hexagonal model: HSV



Colors of value 1 in the HSV color space, with white (saturation 0) at the center and fully saturated colors at the edge. This circle is the top of the HSV circle/cylinder displayed above. All colors displayable on a screen are shades of these colors.

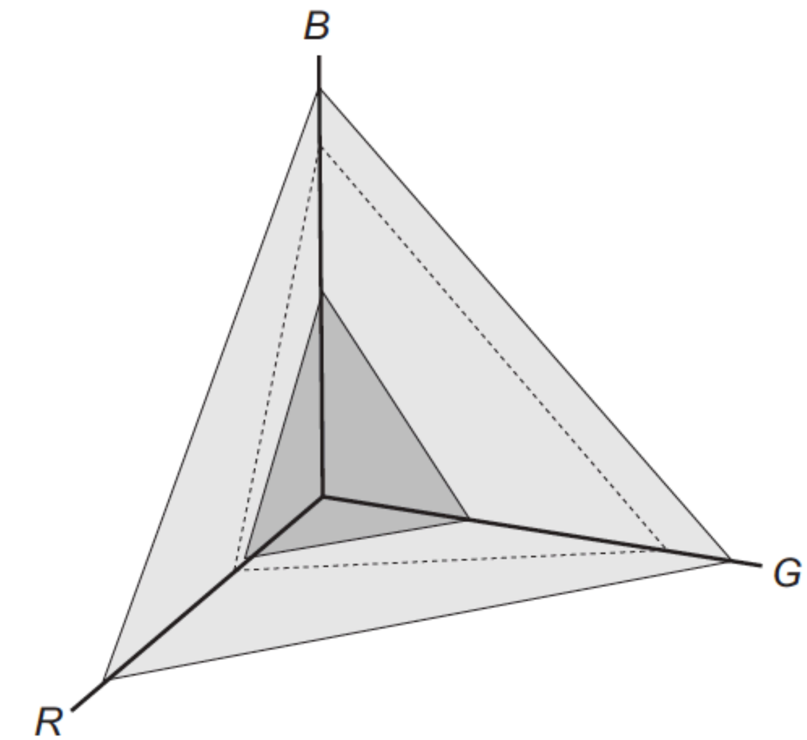
Perceptual colour models

RGB to/from HSV conversion

From [HSV:1-HSV:3]

Perceptual colour models

Saturation in the triangular model: HSL



In this model, the colours in the RGB cube are organised by a set of triangles formed by three points on the RGB axes.

Each triangle defines a plane that contains colours with the same lightness value. As the lightness increases, the triangle moves further away from the origin. The lightness in this model is defined by the value given by:

$$l = w_R r + w_G g + w_B b$$

where weights w_R, w_G and w_B are parameters of the colour model and they scale each of the axes. When the axes are scaled, the triangles' centre is biased towards a particular point. For example, if $w_R = 0.2$, $w_G = 0.4$ and $w_B = 0.4$, then the triangle intersects the R axis at the middle of the distance of the other axes, thus its centre will be biased towards the green and blue. This type of shift is illustrated by the dotted triangle in the diagram

In the triangle model, a colour is normalised to be independent of brightness by division by l:

$$r' = w_R \frac{r}{l},\ g' = w_G \frac{g}{l} \text{ and } b' = w_B \frac{b}{l}.$$

As such, a colour can be characterised by the **lightness** l and by its **hue** and **saturation** computed from normalised co-ordinates. This type of equation defines a central projection that maps the colours by tracing radial lines from the origin of the co-ordinate system. The projection uses radial lines to map the colours into the **normalised triangle** defined by the points $[1,0,0]$, $[0,1,0]$ and $[0,0,1]$.

Perceptual colour models

Hue in the triangular model: HSL

The hue of a colour is intuitively interpreted by considering the angular value in the normalised triangle by taking as reference the line joining the white point and the red colour.

Perceptual colour models

Saturation in the triangular model: HSL

Saturation is defined as the difference of a colour from grey. That is, it can be intuitively interpreted as the normalised distance from this colour to white. When the distance is zero the point represents a grey colour (shade of white) and when it is one it represents one of the colours in the perimeter of the triangle.

Perceptual colour models

Lightness in the triangular model: HSL

Each triangle defines a plane that contains colours with the same lightness value.

Perceptual colour models

RGB to/from HSL conversion

From [HSL:1-HSL:2]

Perceptual colour models

HSV vs. HSL

Both representations are mathematically cylindrical, but while **HSV** can be thought of conceptually as an **inverted cone of colors** (with a black point at the bottom, and fully-saturated colors around a circle at the top), **HSL** conceptually represents a **double-cone or sphere** (with white at the top, black at the bottom, and the fully-saturated colors around the edge of a horizontal cross-section with middle gray at its center).

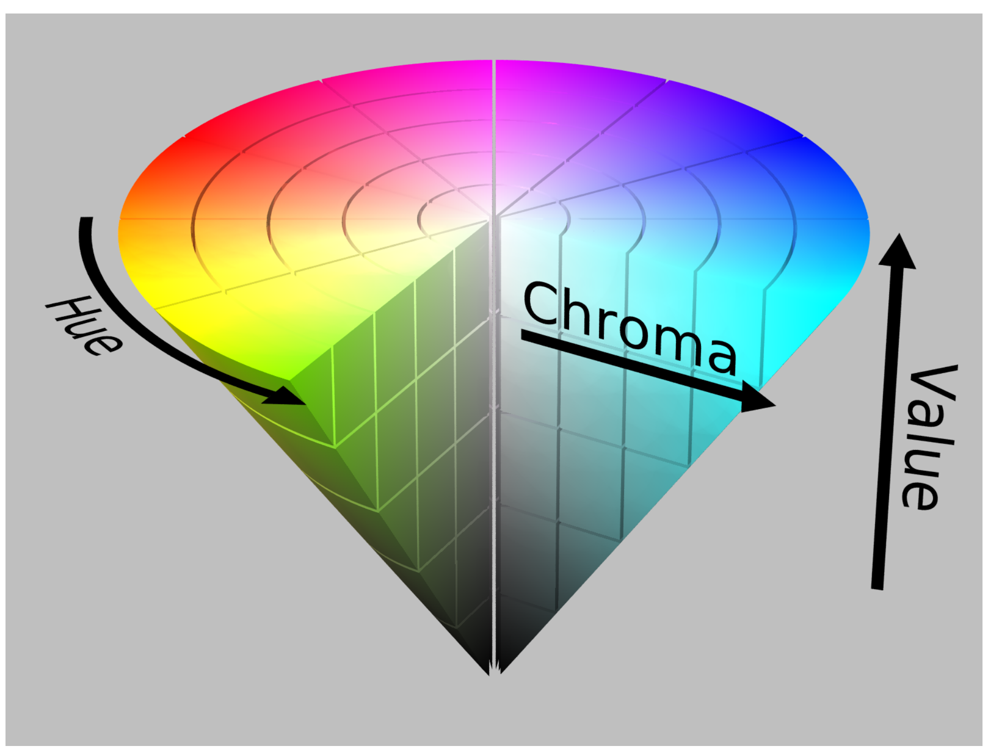
Both HSL and HSV describe colors as points in a cylinder whose:

- central axis ranges from black at the bottom to white at the top with neutral colors between them,
- where angle around the axis corresponds to “hue”,
- distance from the axis corresponds to “saturation”,
- and distance along the axis corresponds to “lightness”, “value”, or “brightness”.

Perceptual colour models

HSV vs. HSL

- In HSV, with V at maximum, saturation goes from saturated color to white (which may be considered counterintuitive).
- In HSL, the saturation component always goes from fully saturated color to the equivalent gray.
- In HSV, the V component only goes half way from black to white: from black to the chosen hue.
- The Lightness in HSL always spans the entire range from black through the chosen hue to white.



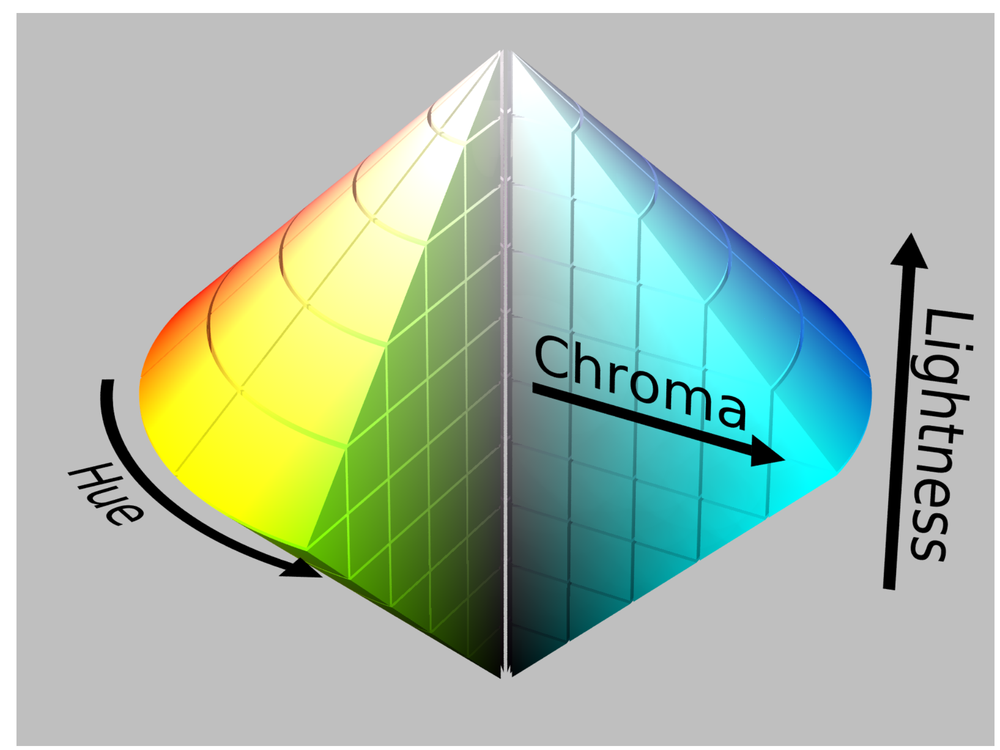
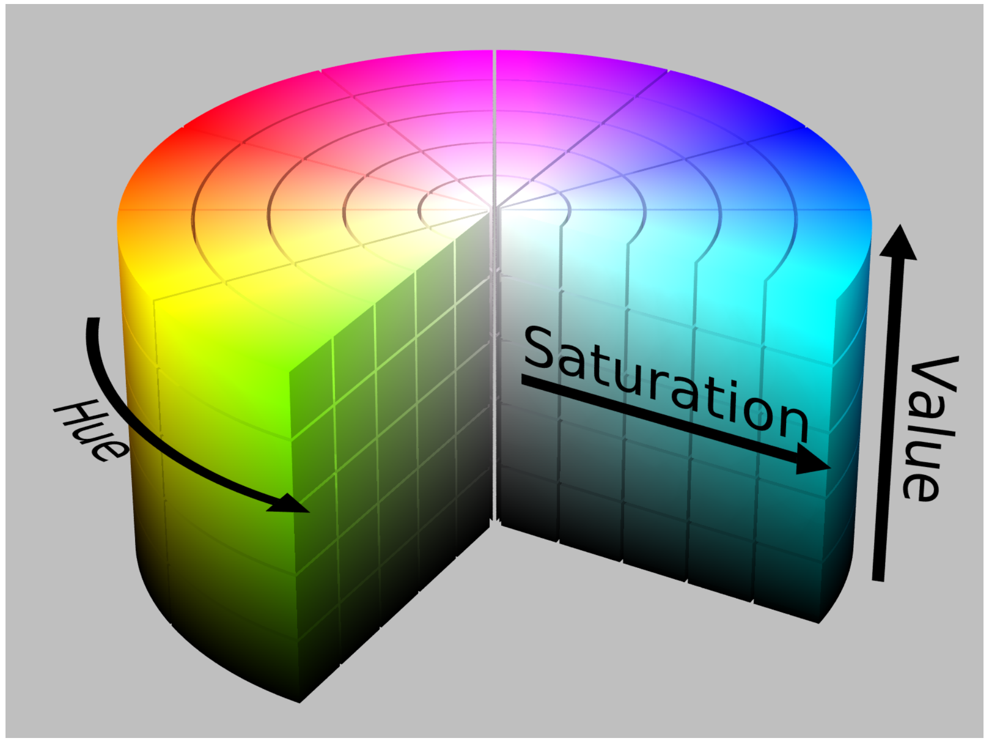


Image source: [Other:3]

Perceptual colour models

HSV vs. HSL

- In HSV, with V at maximum, saturation goes from saturated color to white (which may be considered counterintuitive).
- In HSL, the saturation component always goes from fully saturated color to the equivalent gray.
- In HSV, the V component only goes half way from black to white: from black to the chosen hue.
- The Lightness in HSL always spans the entire range from black through the chosen hue to white.



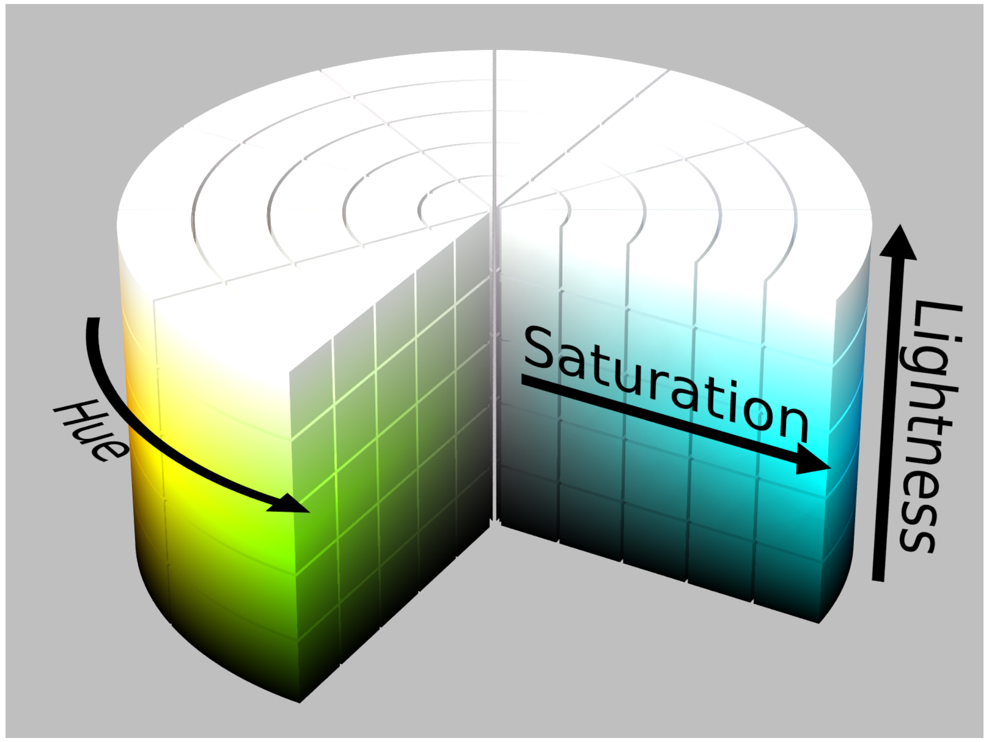


Image source: [Other:3]

Perceptual colour models

Chroma vs. saturation

Hue: is it red or blue or anything in between? If you consider spectrum of visible light, hue determines on which point of the spectrum the color roughly is.

Chroma:

It is a scale of **how much of a pure hue is present**. Consider a two sets of school uniforms. One new and one old. Though they are of the same colour you see less colour in the old one. That's chroma: intensity (measure) of the hue.

When decomposing a pixel value to components, it is possible to separate the quality of brightness or luminance (luma) of the pixel from its color contributors. These color contributors are called chroma components.

Saturation:

Saturation is comparison of chroma with a predetermined or a standard chroma (for example over the maximum chroma in the slice of the (bi)cone). Saturation is **relative intensity (measure) of a hue.**

How pure is the color (the hue). On the color space, pure hue can be mixed with white in different amounts. The less white, the more pure or saturated the hue.

Is the color purely, say, red, or is it muted down with some combination of gray? Totally saturated is red, totally unsaturated is gray (or white or black, depending on the lightness which in turn answers the question: is it closer to white, or closer to black?

See [Other:4-Other:5] for more explanations.

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