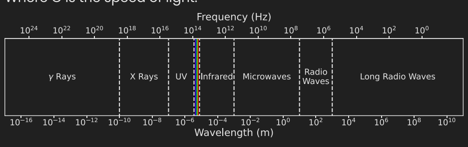
Colour Science Precis

for the CGI Artist

Electromagnetic Spectrum

The electromagnetic spectrum is the full range of all types of electromagnetic radiation, organised by frequency or wavelength.

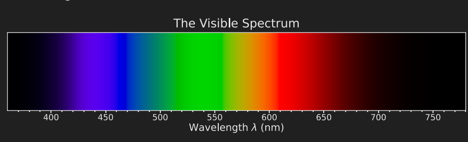
Wavelength (λ) is related to frequency (f) as follows: λ = C/f
Where C is the speed of light.



Light

Electromagnetic radiation that is considered from the point of view of its ability to excite the human visual system (HVS).

The visible spectrum approximately spans 360-780 nm in wavelength.



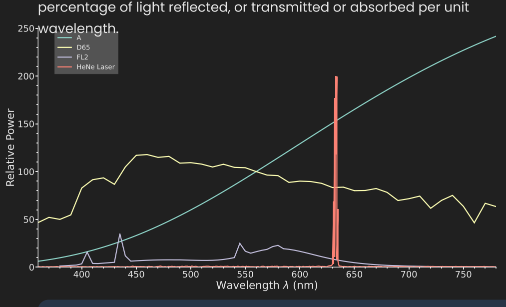
Colour

Characteristic of visual perception that can be described by attributes of hue, brightness (or lightness) and colourfulness (or saturation or chroma).

Even though colour is universally used to describe the stimuli that caused the sensation, e.g., the red pen, colour is not an intrinsic physical property of objects but the interpretation our brains make about a specific characteristic of objects. This delineation, whilst not critical, is important to remember when modelling objects appearance with computer-generated imagery (CGI).

Spectral Distribution

The radiant power emitted by a light source (or illuminant, i.e., **standardised table of values or mathematical function representing an ideal light source**) is characterised by a spectral distribution giving the power of the light per unit area per unit wavelength. The radiant power reflected, transmitted or absorbed by a surface is characterised by a spectral distribution giving the percentage of light reflected, or transmitted or absorbed per unit wavelength.



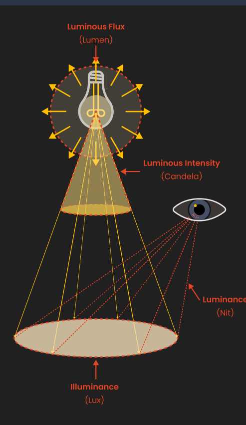
Radiometry & Photometry

Radiometry **is the measurement of quantities associated with electromagnetic radiation.**

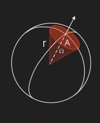
Photometry **is the measurement of electromagnetic radiation quantities relative to the HVS sensitivity to brightness, e.g., V(λ).**

	Omni-Directional	Directional
Total	Radiant Flux Φ_e ($Watt, W$)	Radiant Intensity $I_{e,\Omega}$ (W/sr)
	Luminous Flux Φ_v ($Lumen,\ lm = cd \cdot sr$)	Luminous Intensity I_v ($Candela,\ cd = lm/sr$)
Per Unit Area	Irradiance E_e (W/m^2)	Radiance $L_{e,\Omega}$ ($W/sr/m^2$)
	Illuminance E_v ($Lux,\ lx = lm/m^2$)	Luminance L_v ($Nit,\ nt = cd/m^2$)

1 watt of 555nm green light has a luminous flux of 683 lumens.



Solid Angle Ω (Steradian, sr) : Three dimensional angle, ratio of subtended area A on a sphere to radius r squared.



$$\Omega = \frac{A}{r^2}$$

Luminous Flux : Luminous energy per unit time.
Luminous Intensity : Luminous flux per unit solid angle.
Illuminance : Luminous flux incident on a surface.
Luminance : Luminous flux per unit solid angle per unit projected source area.

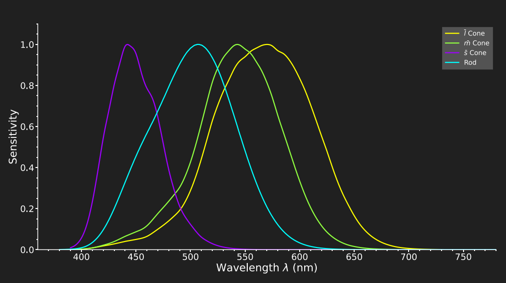
Human Visual System (HVS)

Photoreceptors

The HVS has two main classes of retinal photoreceptors:

Cone Cells : Responsible for photopic vision, *i.e.,* **vision under daytime illumination conditions**, and colour perception

Rod Cells : Responsible for scotopic vision, *i.e.,* **vision under dark illumination conditions**



Just-Noticeable Difference

The just-noticeable difference (JND) is the minimum change in stimulus intensity required to produce a detectable variation in sensory experience.

The Fechner principle, also known as Fechner's law, states that the intensity of a sensation increases proportionally to the logarithm of the stimulus intensity.

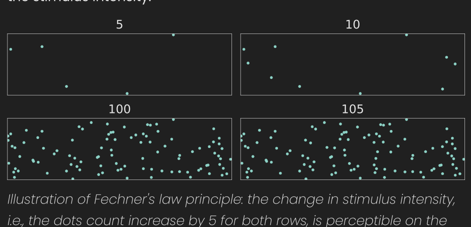


Illustration of Fechner's law principle: the change in stimulus intensity, i.e., the dots count increase by 5 for both rows, is perceptible on the top row but barely noticeable on the bottom row where the stimulus intensity was high to start with.

Dynamic Range

Dynamic range is the ratio between the maximum and minimum measurable light quantity in a scene.

In the context of motion pictures and games, dynamic range is expressed in photographic stops. Exposure value (EV) in stops is calculated as the log² of the test luminance (Y) relative to a reference luminance level (Y_r), i.e., twice the luminance is a one stop difference; four times the luminance is two stops; and so forth:

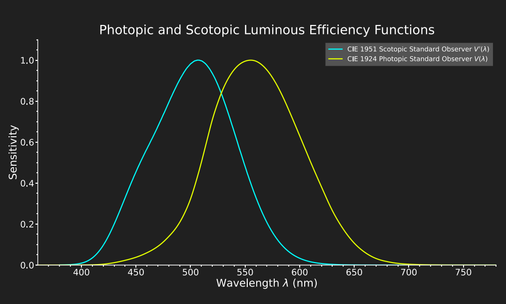
$$EV = log_2\left(\frac{Y}{Y_r}\right)$$

The HVS simultaneous or steady-state dynamic range spans over ~12 stops with an adaptation range of ~33 stops; the upper detection threshold rises with a brighter environment.

Object	Luminance (cd/m²)	Relative Exposure (EV)
Sun	1,600,000,000	23.9
Incandescent lamp (filament)	23,000,000	17.8
White paper in sunlight	10,000	6.6
Blue Sky	5000	5.6
Dolby Pulsar HDR reference monitor	4000	5.3
HDR reference monitor	1000	3.3
White paper in office lighting (500 lux)	160	0.7
Standard Television Reference Monitor	**100**	**0**
Preferred values for indoor lighting	50 - 500	-1.0 - 2.3
Digital Cinema Projector	48	-1.1
White paper in candlelight (5 lux)	1	-6.6
Night vision (rods in the retina)	0.01	-13.3

Luminous Efficiency Functions

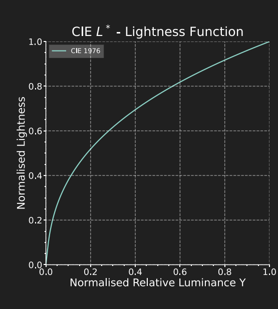
The luminous efficiency function V′(λ) and V(λ) model the wavelength-dependent sensitivity of the HVS to light and are used to calculate the luminous flux of a light source (or illuminant).



Perceived Brightness

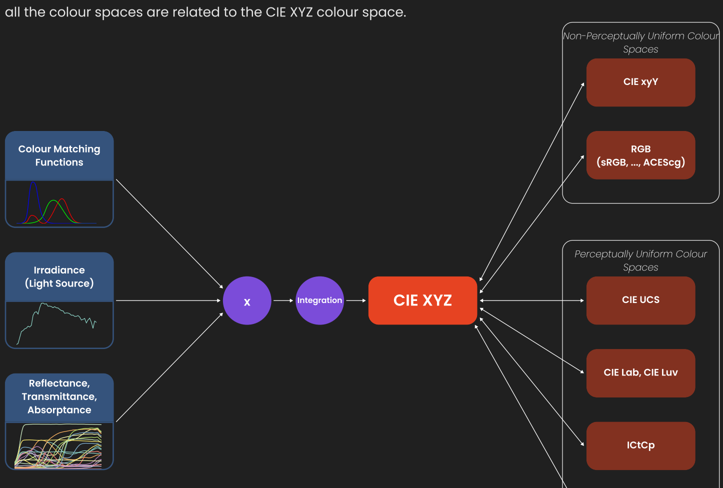
The HVS perceived brightness has a non-linear relationship with the physical intensity of light. It can better discriminate the brightness variation of light when its intensity is low.

CIE L characterises the perceptual response to relative luminance.*



Colour Spaces

A colour space is defined as **the geometric representation of colour in space**. In CIE colorimetry, all the colour spaces are related to the CIE XYZ colour space.



Spectral Domain	Tristimulus Domain
Radiometry	Photometry

CIE XYZ

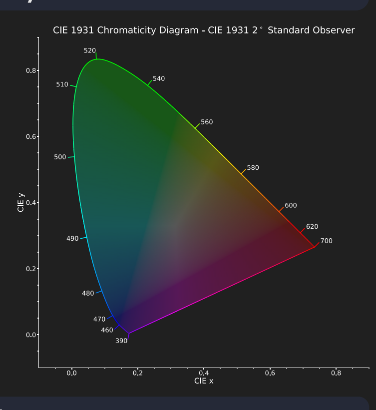
Spectral radiant energy is converted into CIE XYZ tristimulus values, i.e., three dimensional geometric representation, by integrating the result of the product of the reflectance, transmittance or absorptance spectral distribution of a sample and the spectral power distribution of a light source (or illuminant) with the colour matching functions, i.e., linear combination of the cone cells sensitivities.

CIE xyY

The CIE xyY colour space is a projective transformation along the luminance axis (Y) of the CIE XYZ colour space that separates the luminance axis (Y) from chrominance plane (x and y axes).

The CIE 1931 Chromaticity Diagram is a visualisation all the colours seen by the CIE 1931 2° Standard Observer, i.e., **standardised average human observer sensitivity for a 2° field of view**, on the CIE xyY colour space chrominance plane.

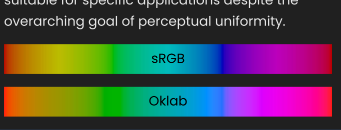
The curved edge forming the horseshoe shape is known as the Spectral Locus and is composed of physically realisable monochromatic, i.e., one wavelength, colours. The line that closes the horseshoe shape is known as the line of purples.



Perceptually Uniform Colour Spaces

The CIE xyY colour space's representation of colour distances does not correlate with perceptual differences. This discrepancy has led to the development of alternative colour spaces aimed at achieving perceptual uniformity, where ideally, a one-unit change would have a consistent perceptual impact in any direction.

However, no colour space has yet achieved complete uniformity across all perceptual attributes such as lightness, chroma, and hue. Different perceptually uniform colour spaces prioritise certain attributes at the expense of others, therefore, making them more suitable for specific applications despite the overarching goal of perceptual uniformity.



- **CIE UCS** : Used to represent the correlated colour temperature of light sources (or illuminants)
- **CIE Lab** : Current CIE recommendation
- **CIE Luv**: Adopted simultaneously with CIE Lab and used for the CIE 1976 UCS chromaticity diagram
- **IPT** : Excellent hue uniformity, used in gamut mapping applications
- **ICtCp** : Used for HDR imaging
- **Oklab** : Good perceptual uniformity for graphics applications, used by Cascading Style Sheets (CSS)

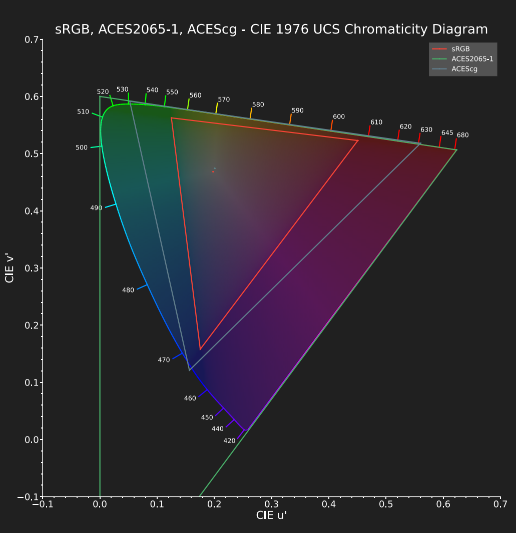
One objective for a perceptual uniform colourspace is the measure of colour differences, i.e., ΔE. The CIE recommends using the CIE 2000 colour difference formula which improves on measuring euclidean distances in CIE Lab.

RGB Colour Space

An additive RGB colour space, related to the CIE XYZ colour space by a matrix transformation, is fully specified by three components:

Primaries

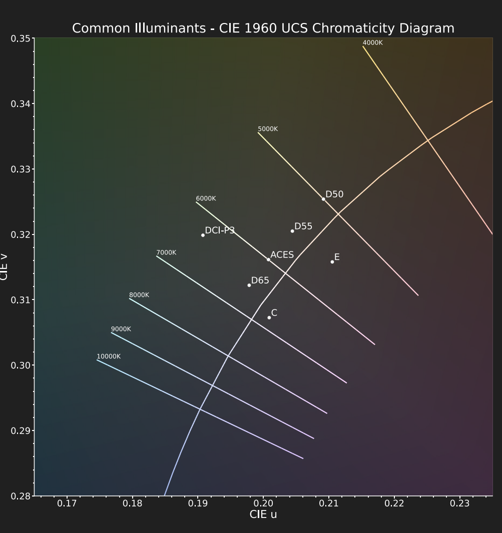
Colour primaries, typically specified as chromaticity coordinates, along with the device's dynamic range, define an RGB colour space's colour gamut, or the range of colours it can reproduce. Although RGB gamuts span a three-dimensional volume, they are frequently depicted as two-dimensional triangles on chromaticity diagrams for visual simplicity. Despite a preference for using uniform colour space representations, e.g., CIE 1976 UCS Chromaticity Diagram, the non-uniform CIE 1931 Chromaticity Diagram remains a common choice for these illustrations.



Whitepoint

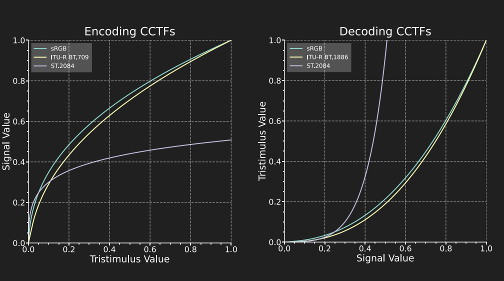
The whitepoint of a RGB colour space is the reference point that represents the colour perceived as pure white. It is obtained with full emission of the red, green and blue components.

Colours lying on the neutral axis line passing through the whitepoint and the origin of the RGB colour space gamut, irrespective of their luminance, are achromatic.



Colour Component Transfer Functions

Colour Component Transfer Functions (CCTFs) are mathematical functions applied to the individual, e.g., R, G, and B, colour channels of a colour space.



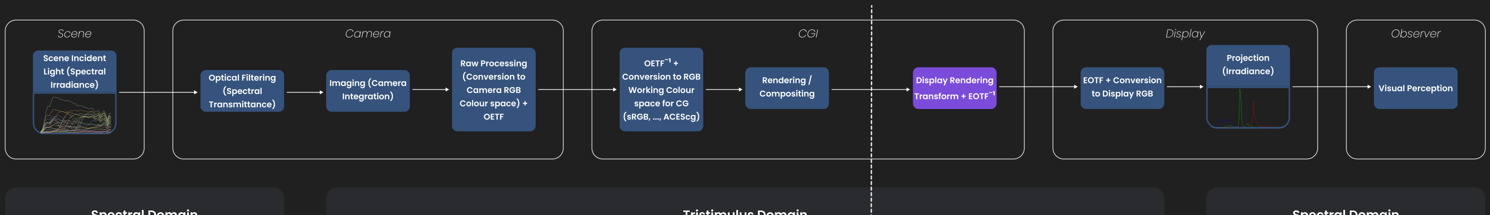
Encoding CCTFs, e.g., Opto-Electronic Transfer Function (OETFs) used by digital cameras, convert RGB scene relative luminance to non-linear R'G'B' code values. Non-linear encoding is used for storage and bandwidth optimisation and to improve perceptual uniformity by leveraging the non-linearity of the HVS.

The primes in R'G'B' denotes the non linearity of the encoded values.

Decoding CCTFs, e.g., Electro-Optical Transfer Function (EOTFs) used by displays, TVs or projectors, on the other hand, convert non-linear R'G'B' code values back to RGB scene relative luminance.

It describes how, for example, a display, such as a TV or a projector, responds to an incoming electrical signal and converts it back into light.

Colour Imaging System - Scene Irradiance to Display Light

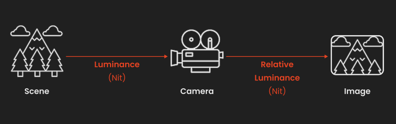


Spectral Domain	Tristimulus Domain	Spectral Domain
Radiometry	Photometry	

⟵ **Scene-Referred Image State** | **Output-Referred Image State** ⟶

Imaging Quantities

ISO 12232-2019 defines the relationship between the luminance of a scene and the digital camera focal plane exposure, i.e., time-integrated illuminance in lux-seconds. The image captured by a digital camera is typically described in terms of relative luminance. When using a RGB renderer, e.g., Arnold or Renderman, the rendered image is also represented using relative luminance.



A digital camera is however not truly colorimetric: It sensitivities are not linear combination of the cone cells sensitivities, mostly for performance reasons, i.e., it does not satisfy the Maxwell-Ives criterion.

Accordingly, it is debatable to discuss about illuminance and luminance, but for simplicity, the precis uses those quantities.

Mapping Between Image States

The two main image states and the mapping between those, are defined by ISO 22028-1 as follows:

Scene-Referred Image State

Image state associated with image data that represents estimates of the colour space coordinates of the elements of a scene.

A scene-referred image does not store the scene radiance, but estimates of its colorimetry for a given observer. It has been converted from the radiometric spectral domain to the photometric tristimulus domain by integration with the camera colour filters or by virtue of being rendered directly into a RGB colour space for CGI.

Additivity and linearity are maintained: A doubling of scene exposure produces a doubling of image relative luminance.

Output-Referred Image State

Image state associated with image data that represents the colour space coordinates of the elements of an image that has undergone colour-rendering appropriate for a specified real or virtual output device and viewing conditions.

This ISO definition specifies the state of an image upon having been processed to be printed or viewed on a display. Due to the non-linear nature of colour-rendering, additivity and linearity are not maintained: A doubling of scene exposure does not produce a doubling of image relative luminance.

Colour Rendering

Mapping of image data representing the colour space coordinates of the elements of a scene to output-referred image data representing the colour space coordinates of the elements of a reproduction.

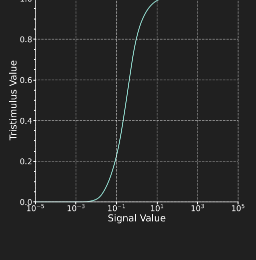
This ISO definition describes the conversion between the two main image states. In CGI, colour rendering is performed by the Display Rendering Transform (DRT).

Display Rendering Transform

The Display Rendering Transform (DRT) converts the image from a scene-referred state to an output-referred state.

Colour rendering is necessary because display devices, often, cannot reproduce the entire scene dynamic range and colorimetry. The viewing conditions are also different between the scene capture and imagery exhibition. The DRT ensures that the displayed image retains the intended artistic look and feel, despite the technical limitations of the display devices and the surround differences.

The DRT involves tone mapping and colour space mapping. Tone mapping transforms the image's relative luminance to fit it within the display's dynamic range, expanding mid-tones, compressing shadows and highlights, and altering contrast to achieve a pleasing result. Colour space mapping ensures that the colours in the image are represented accurately on the target display device, taking into account the device's specific primaries, whitepoint, and EOTF.



The luminance mapping of a DRT has the shape of a sigmoid curve, commonly referred to as a "S-Curve".

The left figure abscissa is using a Log 10 scale.

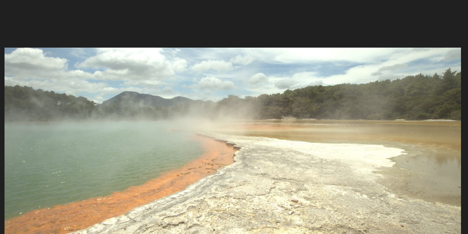
Numerous DRT have been engineered, each offering unique aesthetics and look.

Some involve colour rendering in RGB colour space using per-channel processing. Some colour correction operators process images similarly, e.g., Adobe Photoshop Curves, however, this generate undesirable colour clumping at the corners of the RGB colour space.

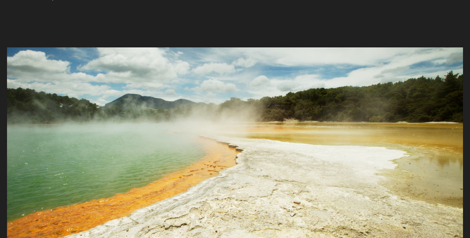
Perceptual uniform colour spaces (and colour appearance models) have been used in the design of DRT where the achromatic axis, e.g., lightness, is processed separately from the chromatic one.

ARRI's K1S1 and Reveal, RED's IPP2, ACES 's Output Transforms, Blender's Filmic and AgX, and FilmLight's T-Cam are common DRTs used in the industry.

The maximum pixel value is mapped to the display peak luminance producing a low-contrast, uncolourful and unpleasing image.



Linearly mapping the dynamic range of the scene colour estimates to that of the display produces an image with poor aesthetics. It lacks contrast, colourfulness, and the highlights are clipped.



The colour-rendered image with the DRT applied is appealing, exhibiting more contrast, colourfulness and highlights details.