



HAL
open science

Colorimetry for Computer Graphics designers

Charbel Tannous

► **To cite this version:**

Charbel Tannous. Colorimetry for Computer Graphics designers. Master. Technologie des médias, UBO Brest, France. 2017, pp.28. hal-04289513

HAL Id: hal-04289513

<https://hal.science/hal-04289513v1>

Submitted on 16 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Colorimetry for Computer Graphics designers

C. Tannous 

Université de Brest, Lab-STICC, CNRS-UMR 6285, F-29200 Brest, FRANCE

(Dated: [November 16, 2023](#))

Computer Graphics used in Digital Cinema, Video and Image Synthesis requires deep understanding of Colorimetry and the interaction between light sources illuminating scene elements and their perception by an observer.

PACS numbers: 42.66.Si,42.72.-g,85.60.Jb

Keywords: Visual perception,light sources,light-emitting diode

Contents

I. Introduction	1
II. Perceptual properties of the human eye	3
A. Adaptation to darkness	4
B. Glare	6
C. Comparison of eye and ear perceptual properties	6
III. CIE Chromaticity Coordinates	10
A. From CIE Chromaticity Coordinates to RGB components	13
B. Gamut in analog and digital technologies	13
C. From Color to Gray	14
D. From Gray to Color: B&W film colorization	15
IV. Light sources for Cinema projectors	15
A. Luminous efficacy of Black-Body radiation sources	16
B. Luminous efficacy of Lasers and LEDs	17
C. Luminous efficacy of Xenon arc lamps	18
V. Display technologies	21
A. Analog display technology	21
B. Digital display technologies	22
VI. Reflectance distribution functions (RDF)	23
A. Varieties of scene element properties	23
B. Directional, Conical and Hemispherical RDF	25
A. Radiometric and Photometric units	26
References	27

I. INTRODUCTION

Computer Graphics and Color rendering quality in Cinema, Video and Image synthesis are associated with the nature of lighting, interaction between light and the various elements in a given scene such as humans, textiles, animals, insects, surrounding objects like walls, furniture, foliage, trees...the final judge being human eye perception of an observer.

Thus it must be realized that one must understand the ways we create and calibrate light sources, their interaction with scene elements that could be human skin, various surroundings that could be made of wood, plastic, metal... understand the reflection processes by all these objects and finally get to the eye perception process.

Computer Graphics and Color rendering are also useful in post-processing, restoration and remastering of films, Videos and Images.

Color Science really started with Gustav Kirchhoff (1–3) who used to watch blacksmiths in his village and observe the color change of small holes in heated metals during their processing.

He noticed a pattern of color change as the metal is being heated according to a typical sequence from red to orange, yellow, white and finally to blue.

He also noticed that color change did not depend on the nature of the metal but on the size of the cavity.

Kirchhoff wrote his observations in a paper (1) titled *On the relation between the radiating and absorbing powers of different bodies for light and heat*, in the Philosophical Magazine in 1860.

It is intriguing that J. C. Maxwell (4) wrote the same year and in the same Journal, a paper titled *On the theory of compound colors and the relations of the colors of the spectrum* explaining his trichromatic theory inspired from Thomas Young. However, it took some time until 1931 for serious calibration of Color to begin, when the CIE undertook a series of pioneering measurements called Color Matching experiments in order to calibrate rigorously color and its human perception.

CIE is *Commission Internationale de l'Eclairage* or International Organization for Lighting based in Vienna (Austria) and previously in Paris. It sets standards for light, sources of light and colors and is responsible of the metrology of lighting akin to the NIST (National Institute of Standards and Technology) in the USA.

The CIE decided to select a number of "standard" observers to make a comparison between a color of a given wavelength λ and a superposition of three selected monochromatic sources called RGB primaries that correspond to red at 645.2 nm, green at 526.3 nm and blue at 444.4 nm. The weight of each of the three colors to perform the match was recorded. The observations were done at a fixed distance of 50 cm with two possibilities for the eye angle opening (defined by the observation diameter value) of 2° and 10° .

From the metrology point of view, the SI system of units is based on seven entities: the meter, the kilogram, the second, the ampere, the kelvin, the mole and the candela as the unit of luminous intensity (Lumen is candela per unit solid angle).

Prior to 1979, the SI system of units defines the candela as follows:

A pure sample of Platinum at its melting temperature ($T=2042$ K) emits exactly 60 candelas/cm²/sr along the normal to the sample (per unit surface, in cm² and per unit solid angle, in sr or steradian).

This definition of the candela persisted until 2018, when a major paradigm shift occurred in the metrology world. Instead of relying on force and mass measurements on the basis of calibration and comparison, seven constants were selected to be the basis of the SI system redefining all other metrological quantities. These seven quantities were selected for stability and high accuracy (see Table 1). This paradigm provides new definitions of the kilogram, the kelvin, the mole, and the ampere with some consequences to some fundamental constants.

Defining constant	Symbol	Numerical value	Unit
Hyperfine transition frequency of Cesium	$\Delta\nu_{Cs}$	9 192 631 770	Hz
Speed of light in vacuum	c	299 792 458	m.s ⁻¹
Planck constant	h	$6.626\ 070\ 15 \times 10^{-34}$	J.s
Elementary charge	e	$1.602\ 176\ 634 \times 10^{-19}$	C
Boltzmann constant	k_B	$1.380\ 649 \times 10^{-23}$	J.K ⁻¹
Avogadro constant	N_A	$6.022\ 140\ 76 \times 10^{23}$	mol ⁻¹
Luminous efficacy	K_{cd}	683	lm . W ⁻¹

Table1: The seven defining constants of the SI and the seven corresponding units they define. J is Joule, W is Watt, lm is Lumen and K_{cd} refers to the Candela efficacy which is equal to the photopic standard value 683 lm/Watt (lumens/Watt) previously adopted by the SI (5) system, also called the "Mechanical equivalent of the Lumen".

Computer Graphics and Color rendering might be of interest for Engineers, Arts students or even Physicists realizing

that, in fact, Quantum Physics and Statistical Physics interpreted Kirchoff observations as a photon gas in a cavity obeying Planck radiation law (2; 3) with a thermal average spectral energy density $E(\lambda)$ of the Bose-Einstein form (the chemical potential is zero since the number of photons is not fixed):

$$E(\lambda) = \frac{8\pi hc}{\lambda^5} \frac{1}{\left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1 \right]} \quad (1)$$

λ is the wavelength, h is Planck constant, c is velocity of light in vacuum, k_B is Boltzmann constant and T the temperature.

This law is derived in many Statistical Physics books and is usually enough for standard Physics curriculum. It represents the average spectral energy density of a Black-Body at temperature T .

Since a Black-Body (absorbs and) emits radiation, we need a Planck law equivalent for the *Emission Spectral Power Density*. Henceforth, the latter is called, for short, Emission Power Spectrum (EPS).

$E(\lambda)$ the photon average spectral energy density has units of Energy/Volume/Wavelength, whereas EPS functions $P(\lambda)$ and $P_B(\lambda)$ (Black-Body) have units of Power/Surface/Wavelength since they correspond to photons emitted at the source surface. The term "spectral density" originates from the fact we are working per unit wavelength.

Drawing analogy from electric charge current density \mathbf{J} ($\mathbf{J} = \rho\mathbf{v}$ with ρ the charge density and \mathbf{v} the velocity), we multiply the average spectral energy density by the velocity of light c and divide by 4π , the whole space solid angle, in order to obtain a power current density.

Thus results the Planck distribution for the EPS function depending on wavelength λ , temperature T and unit solid angle:

$$P_B(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{\left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1 \right]} \quad (2)$$

where $K_{cd} = 683 \text{ lm/Watt}$ (lumens/Watt) the standard value adopted by the SI (5) system called the "Mechanical equivalent of the Lumen".

In the scotopic case, $K'_m = 1700 \text{ lm/Watt}$ is the standard value adopted by the SI (5) system as a counterpart to the photopic K_{cd} .

A possible definition of K'_m is obtained from $K'_m = 683 V(\lambda_{max})/V'(\lambda_{max})$ stemming from the fact photopic and scotopic curves intersect approximately at $\lambda_{max}=555 \text{ nm}$ (more precisely, they intersect at 555.80 nm). That yields $K'_m = 1660 \text{ lm/W}$ close to the standard value.

Physics students are exposed to Black-Body radiation in undergraduate Quantum Physics or in Graduate/Undergraduate Statistical Physics without any clue regarding its significance as to the fundamental role it plays in the development of light source calibration, development and of lighting in general.

The underlying basis of lighting progress is the existence of Haitz law (6) that is similar to Moore law of Electronics evolution. Haitz law (6) states that "For a given wavelength, the amount of light generated by LEDs increases by a factor of 20 and the cost per lumen (unit of perceived light) decreases by a factor of 10, every period of ten years".

Light production by a radiation source is described by a luminous efficacy ratio η_L as the product $\eta_C \times \eta_P$ where:

- η_C is the conversion efficacy ratio that is number of photons produced (having any wavelength) over input energy (usually electrical but it could also be mechanical, thermal or chemical...).
- η_P is the light perception (or Photometric) Efficacy Ratio (PER). It is the ratio of number of photons perceived by the human eye (photon wavelength in the visible spectrum) to the total number of photons (Note that some authors call it η_S , the spectral efficacy).

II. PERCEPTUAL PROPERTIES OF THE HUMAN EYE

Light sensed by the human eye is given by averaging over wavelength, $P_B(\lambda)$ with the eye sensitivity function called $V(\lambda)$ by the CIE.

This function depicted in fig. 1 peaks at 559 nm (Yellow-Green) wavelength, close to the maximum sensitivity of the human eye at 555 nm. The analytical expressions (7) for daylight and dark sensitivities $V(\lambda), V'(\lambda)$ differ slightly from tabulated values provided by the CIE. Daylight sensitivity is $V(\lambda) = 1.019 \exp(-285 [(\frac{\lambda}{1000}) - 0.559]^2)$ (also called photopic) with λ expressed in nm.

Dark sensitivity $V'(\lambda)$ (scotopic) is shifted with respect to $V(\lambda)$ by 45 nm to shorter wavelengths and peaks at 510 nm (Purkinje shift). Presently this wavelength is estimated to be 507 nm where $V'(\lambda)$ has its maximum.

Analytically (7) $V'(\lambda) = 0.992 \exp(-321.9 [(\frac{\lambda}{1000}) - 0.503]^2)$. Both analytic expressions are obtained (7) from a non-linear least-square fit to Gaussian functions. They are useful in the case of continuous spectral distribution and show less than 1% error with Black-Body sources from 1500 to 20,000 K. Nevertheless, they must be used with caution in the case of narrow-band or line sources (7).

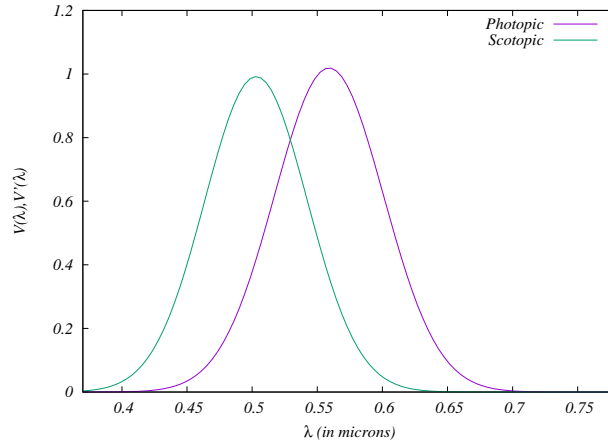


Fig.1: $V(\lambda)$ function (8) giving the eye sensitivity versus wavelength in daylight (photopic) and $V'(\lambda)$ in the dark (scotopic). They are shifted one with respect to the other by 45 nm, the Purkinje shift.

The conversion from Radiometry (covering all wavelengths, i.e. $\lambda \in [0, \infty]$) to Photometry (covering the visible interval, i.e. $\lambda \in [380\text{nm}, 780\text{nm}]$) is carried out by multiplying the total power per unit surface (in Watts/m²) perceived by eye:

$$\int_0^{\infty} P_B(\lambda)V(\lambda)d\lambda \quad (3)$$

by the "Mechanical equivalent of the Lumen" K_{cd} such that:

$$\text{Perceived light} = K_{cd} \int_0^{\infty} P_B(\lambda)V(\lambda)d\lambda \quad (4)$$

It is important to notice that we are carrying the integration over all positive frequencies and not the visible spectrum (wavelength interval [380 nm, 780 nm]) since we are dealing with radiation energy ($\lambda \in [0, \infty]$) and counting on $V(\lambda)$ to quantify perception.

Thus one can draw absolute photopic $K_{cd}V(\lambda)$ and scotopic $K'_m V'(\lambda)$ functions versus wavelength as displayed in fig. 2.

A. Adaptation to darkness

The phenomenon of retinal adaptation is important for understanding how viewers perceive movies in cinema theaters or in home cinemas and belongs to sensory physiology and one fundamental aspect is adaptation of the eye to dim lights.

Data on dark adaptation of eye show that on entering a dark environment after a stay in the outside daylight, the eye at once begins to increase in sensitivity. This increase appears at first to be slow; but after five minutes, the increase

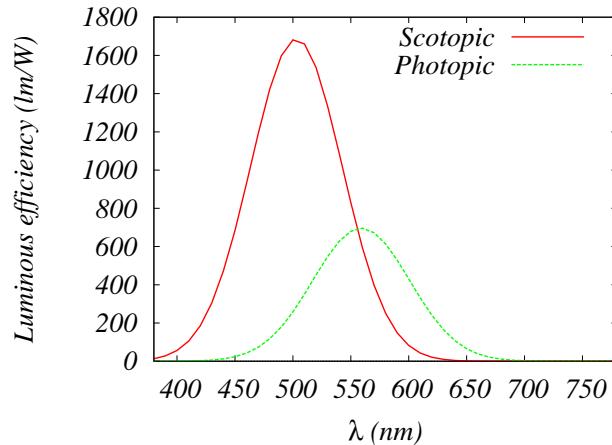


Fig.2: Absolute photopic $K_{cd}V(\lambda)$ and scotopic $K'_m V'(\lambda)$ eye sensitivity functions in lm/W versus wavelength (8). The curves intersect at $\lambda_{max} = 555$ nm.

becomes quite fast, the eye acquiring a sensitivity several hundred times its initial value. After 30 minutes stay in dark the sensitivity still increases, but more slowly than before; and after 45 minutes or an hour a maximum value is reached.

The final sensitivity varies slightly with different people, however the fully adapted condition of the eye is easily 5,000 to 10,000 times more sensitive than at the beginning.

It is believed that the rate of adaptation is greatest at first, as displayed in Table 2 with sensitivity showing three parts: an initial slow phase, an intermediate rapid one, and a final phase ending in a maximum.

Time is given by formula $t = k \ln(I)$ with t in minutes I is light intensity and k is a constant measured between 0.01 and 0.02 by several researchers (see Table 2).

Time (minutes)	Sensitivity	Intensity	ln(intensity)
0	38.7	25,840.0	4.41
2	99.7	10,030.0	4.00
5	398.7	2,506.0	3.40
8.5	1,065.0	934.6	2.97
12	3,420.0	292.4	2.47
20	16,870.0	59.9	1.78
31	30,780.0	32.5	1.51
39.5	45,270.0	22.1	1.34
45	54,080.0	18.5	1.27
72	54,080.0	18.5	1.27

Table2: Early experimental data on Dark Adaptation of the Eye. Adapted from Hecht (9)

Eye adaptation is triggered by retinal photochemical and physiological adjustment as well as variation of pupil diameter. Thus it can finally handle luminance levels over the $[10^{-6} \text{ cd/m}^2\text{-}10^5 \text{ cd/m}^2]$ interval with almost flat visual performance response between 100 cd/m^2 and $10,000 \text{ cd/m}^2$.

Adaptation time strongly depends on luminance levels at the beginning and end of the process.

fig. 3 describes schematically dark adaptation process beginning at a 100 cd/m^2 luminance. When luminance varies up to a 10:1 ratio adaptation runs almost instantly without interrupting visual performance. Complete adaptation might take between 30 to 60 minutes.

In sharp contrast, during light adaptation retinal sensitivity is reduced to a fifth of its original value to later on adjusting to the new surrounding light with the entire process lasting a few minutes.

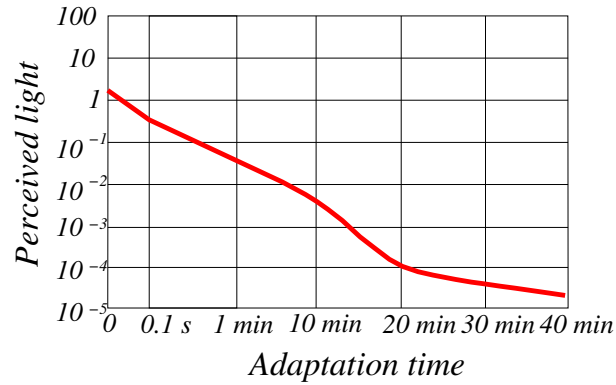


Fig.3: Time-dependent perceptual property of the eye. Dark adaptation in cd/m^2 is given versus time in minutes. Note that the time scale at intervals [0-0.1 sec], [0.1 sec-1 min] are different from the later intervals given in blocs of 10 minutes.

B. Glare

The eye responds differently as a person ages.

Lens loses its accommodation abilities with age and aqueous humour loses its elasticity becoming more rigid pulling on the retina across the membrane separating them.

In fig. 4, glare threshold is shown to decrease substantially with age.

Digital Cinema Initiative (DCI) limits upper threshold to $48 \text{ cd}/\text{m}^2$ the luminance of a white picture in the joint DCI/SMPTE (10; 11) (Society of Motion Picture and Television Engineers) report for at least two reasons:

- Eye increase of sensitivity in dim environments
- Glare threshold decrease with age

Lower threshold being limited to $10^{-4} \text{ cd}/\text{m}^2$ to account for eye sensitivity in dim environments, gives a quantification range of about 16 bits.

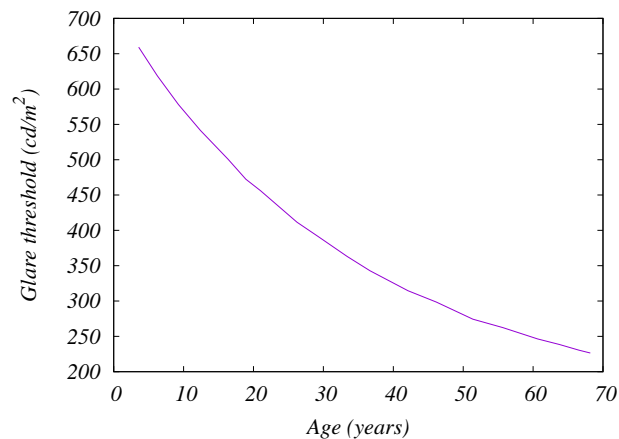


Fig.4: Time-dependent glare threshold of the eye as a function of age. Glare threshold is measured by exposition to a PC monitor. Glare threshold is in cd/m^2 .

C. Comparison of eye and ear perceptual properties

In Cinema there is a strong correlation between Image and Sound.

Cinema has been constantly improving Image quality from the color, aspect ratio, resolution, contrast... points of view in order to keep the audience impressed and attracted to theaters in order to counter the effect of presence of the television set in every home.

The progress of Cinema Image can be summarized along the lines:

- On the Color side, Cinema Image evolved from Black and White to a series of Color standards constantly improving their number, gamut, contrast...
- In terms of immersion level, it evolved from 2D, 3D, 4D, 7D-Hologram and recently to Virtual Reality
- In terms of Brightness: "Sufficiently bright" has been defined by Society of Motion Picture and Television Engineers (SMPTE) as belonging to $(41-75 \text{ cd/m}^2)$ interval, while accounting for the glare limit of 48 cd/m^2 in particular cases.
- In terms of spatial resolution: Conversion from (2K): 2048×858 to (4K): $4096 \times 1714 \text{ pixel}^2$
- In terms of aspect ratio: Table 3 shows several form factors ranging from 1.37:1 Academy to anamorphic form factor 2.39:1 complying with the Digital Cinema Distribution Master calling for a 2K or 4K format for distribution. Note that same scaling is used to make the Digital Cinema Distribution Master (DCDM) (12).

Format	Horizontal pixels	Vertical pixels	Camera Aspect Ratio	Projection Aspect Ratio
Academy	3656	2664	1.37	1.85
Cinemascope	3656	3112	1.175	2.39
Full Aperture	4096	3112	1.32	2.39
DCDM-4K	3996	2160	1.85	1.85
DCDM-4K	4096	1716	2.39	2.39

Table3: Scanned Resolutions and Aspect Ratios for common 35 mm Film Formats, compared to the 4K Image Structure for the Digital Cinema Distribution Master, DCDM. Adapted from Kennel (12)

Progress of Sound quality is also impressive (see Table 4) and the best example is the large production of movie musicals that were produced in the 1960s by the Cinema industry to lure audiences back to theaters after Television sets kept them at home.

The importance of Sound quality is witnessed by its tremendous evolution over the years as displayed in Table 4 with the increase of the number of channels from mono to stereo, 5.1..., noise processing as well as special effects...

The Cinema industry is developing 3D sound in order to immerse the audience in a total acoustic environment with standards like the 22.2 channel format (13)...

Thus it is important to understand the perceptual properties of eye and ear separately and the correlations between both aspects of perception.

1. The eye:

- (a) Non uniform spatial resolution (fovea).
- (b) Frequency response limited to visible ($0.4 \mu\text{m}-0.8\mu\text{m}$).
- (c) Logarithmic response to light intensity (amplitude).

2. The ear:

- (a) Spatial resolution sensitive to pinnea shape.
- (b) Frequency response limited to $[20 \text{ Hz}-20 \text{ kHz}]$ (10 Octaves) interval.
- (c) Double logarithmic response to sound intensity (amplitude) and frequency.
- (d) Fourier processing in cochlea basilar membrane.

	Years Used	film Gauge	Technology Employed	Noise or Data Reduction	Left	Mid Left	Center	Mid Right	Right	Mono SR	Left SR Effects	Right SR	Low Frequency Effects
Fantasound	1940	35mm	3-T AO		X		X		X				
Cinerama	1952-62	3 strips of 35mm	7-T AM		X	X	X		X		X	X	
Cinemascope	1953-67	35mm	4-T AM		X		X		X	X			
Todd-AO	1955-92	70mm	6-T AM		X	X	X	X	X				
Dolby ST	1976-P	35mm	2-T MAO	Dolby A	X		X		X	X			
Ultra ST		35mm	2-T MAO		X		X		X	X			
Dolby Discrete Six-Track	1976-P	70mm	6-T AM	Dolby A	X	X	X	X	X	X			
Dolby "Baby Boom" Six-Track	1977-P	70mm	6-T AM	Dolby A	X		X		X	X			X
Dolby "Split SR"	1979-P	70mm	6-T AM	Dolby A	X		X		X	X	X	X	X
Dolby ST SR	1986-P	35mm	2-T MAO	Dolby SR	X		X		X	X			
Kodak CDS	1990-91	35/70mm	5.1-C DO	DM	X		X		X		X	X	X
Dolby Digital	1992-P	35mm	5.1-C DO	AC-3	X		X		X		X	X	X
DTS	1993- P	35/70mm	5.1-C DO	DTS CA	X		X		X		X	X	X
SDDS	1993- P	35mm	7.1-C DO	ATRAC	X	X	X	X	X		X	X	X

Table4: Sound standard evolution over the years with the goal of attracting the audiences. P is Present, C is Channel, CA is Coherent Acoustics AM is Analog Magnetic, MAO is Matrixed Analog Optical, DO is Digital Optical, DM is Delta Modulation, T is Track, SR is Surround and ST is Stereo. DTS is Digital Theatre Sound and SDDS is Sony Dynamical Digital Sound.

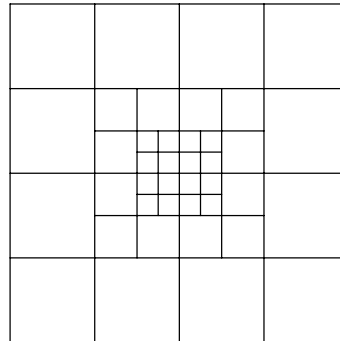


Fig.5: Fovea structure

The ear frequency response spans 20 Hz to 20 kHz (10 Octaves) whereas the eye has a frequency response from 0.4 μm to 0.8 μm (1 Octave). Ear temporal response spans the interval μs (internal inter-oral delay between R and L) to the ms (external inter-oral delay between R and L $\sim 660 \mu\text{s}$). Eye temporal response is typically on the order of a ms). As far as fusion time (echo for ear and flicker for the eye) it is about 35 ms for both. Ear frequential sensitivity is about a Hz, however it may increase to several tens of Hz with frequency. Eye frequential sensitivity is about 1 nm (since $f = c/\lambda$ and $|\delta f| = c\delta\lambda/\lambda^2$ we obtain taking $\lambda=600 \text{ nm}$: $\delta f \sim \frac{3 \cdot 10^8 \times 10^{-9}}{(600 \cdot 10^{-9})^2} \sim 10^{11} \text{ Hz}$). This may increase to several nm with frequency.

Considering eye with rods and cones (1+3 critical bands) and ear cochlear sensitivities we get 24 critical bands.

Rods top sensitivity is at 498 nm (photopic) whereas blue cones is at 437 nm, green cones are at 533 nm and red cones are at 564 nm. The eye top sensitivity is 555 nm (photopic) and 507 nm (scotopic case).

The cones nomenclature is LMS that means Lens, Macular and Scotopic or Long, Middle, Short in terms of wavelength (cf Fig. 6 and Fig. 7) .

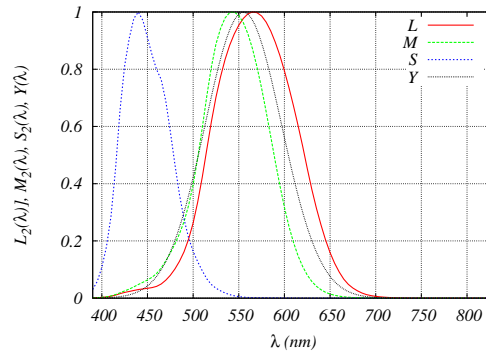


Fig.6: Properties (14) of Rods and Cones versus wavelength. All responses are normalized in order to display the respective behavior versus wavelength (8).

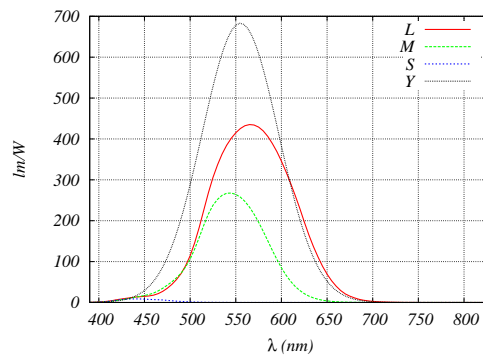


Fig.7: (Color on line) Sensitivities (14) of Rods and Cones versus wavelength without normalization (8). The LMS respective maxima are: 0.637162 lm/W at 565.000 nm, 0.391958 lm/W at 545.000 nm and 0.01295 lm/W at 440.000 nm. Sensitivity of the blue cones (S graph in dashed blue between 400nm and 500 nm) is the smallest justifying the luminance formula: $Y = 0.2126 R + 0.7152 G + 0.0722 B$, transforming an RGB signal into luminance or B&W signal (cf. Grayscale section III.C).

Retinal frequential masking leads to negative chromatic weight values whereas the ear frequential masking screens low intensity sounds. The eye can perceive 10 millions colors (we have about 1-2 nm/400 nm resolution yielding 200 possibilities per R-G-B cone type and $200^3 \sim 8$ millions). In the ear case, we have 0.3 dB/100 dB = 1/300 amplitude sensitivity and Hz/15 kHz ($\sim 3/15\ 000$) frequency sensitivity yielding $300 \times 5\ 000 \sim 150\ 000$ tones. A human can distinguish 1600 tones and amplitude sensitivity being 0.3 dB/100 dB, we get 480 000 tones downsized to 300 000 because of non-uniformities in amplitude and frequency.

Sound spatialization is done geometrically with L/R pinnea structure and inter-aural delay (external and internal), whereas the eye performs scene spatialization with L/R perception. Eye dynamic range is about 120 dB like the ear (120 dB is in fact for a newborn, it is 100 dB for a young adult steadily decreasing with age). Audio Signal (symmetrical) processing is done over three levels: external, intermediate and internal. Optical signal (asymmetrical) processing is done over five levels/layers: photoreceptor cells, (rods and cones), horizontal cells (in-layer averaging),

bipolar cells (performs signal difference between first two layers), amacrine cells (motion detection and scotopic vision tasks as well as signal compression by ~ 150) and ganglion cells (motion detection direction tasks and support to fast eye motion caused by swift change of light intensity).

Property	eye	ear
Signal nature	Asymmetric	Symmetric
Intermediary processing elements	Cornea, iris, lens, aqueous humour, retina, nerve	Pinneas, drum, ossicles, cochlea, Eustachian tube, nerves
Nerves involved	1: Optic	3: Facial, Vestibular and auditive
Sensors	rods and cones R,G,B	cochlea
Processing levels	5 layers	3 levels: external, intermediate and internal
Logarithms	Amplitude	Amplitude and frequency
Frequency range	400 nm-800 nm	20 Hz-20 kHz
Signal bandwidth	6 MHz (SD) to several hundred MHz (UHD)	200Hz (sub) or 15 kHz (sat) per channel
Dynamic range	120 dB	120 dB
Fourier analysis	No	Yes
Number of channels (min-max)	1 B&W, 3 (R-G-B) in 2D or 2 B&W + 2x3 (R-G-B) in 3D	1 (Mono) up to 256 (Total 3D immersion)
Frequential Masking:		
Critical bands	4	24
Critical bandwidth	100 nm ($1\text{nm}=10^{11}$ Hz)	50-500 Hz
Frequential masking effects	Negative chromatic weights	Sound screening
Temporal masking	Post-masking	Pre and post masking
Spatial masking	Fovea gridding	Sound amplitude
Temporal response	1ms	1 μs -1ms
Fusion time	35 ms	40 ms
Spatialization	Geometric L/R	Geometric L/R and inter-aural delay (internal and external)
Signal temporal follow-up via	Focalization inducing eye movement	Undulated pinnea surface without head movement
Total number of octaves	1	10
Day/Night processing	Photopic/Scotopic	No difference
Frequential resolution	1-2 nm ($1\text{nm}=10^{11}$ Hz)	1-300 Hz
Relative Frequential resolution	$(1 \text{ nm}/400 \text{ nm})=2.5 \cdot 10^{-3}$	$(1 \text{ Hz}/15 \text{ kHz})= 6.66 \cdot 10^{-5}$
Amplitude resolution	1-2 dB/120 dB	0,3 dB/120 dB
Global Perception	8-10 million colors (Amplitude and frequency)	60-300 thousand tones (Amplitude and frequency)
Compression rate (lossless)	10	3
Compression rate (lossy)	300	10

Table5: Summary of eye/ear perceptual performances. Note that eye dynamic range is 120 dB which is almost agreeing with cones: $8+8+8=24$ bits thus 144 dB as well as with the number of perceivable colors that is 10 millions or 16 millions originating from 2^{24} . In addition, 8 bit sensitivity of each cone agrees with 1-2 nm/400 nm spectral sensitivity since $2^8=256$ and 1-2 nm/400 nm yield an estimate between 1/250 and 1/200.

III. CIE CHROMATICITY COORDINATES

The SI system changed the definition during the 16th General Conference on Weights and Measures in October 1979 to:

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of

frequency 540×10^{12} Hz with a radiant intensity, in that direction, of $1/683$ Watts per unit solid angle.

In order to relate these two definitions, despite the obvious equivalence of 555 nm wavelength and 540×10^{12} Hz frequency, some interesting features of Black-Body radiation must be recalled.

This led to the existence of color matching functions (CMF) $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ corresponding to the red, green, blue weight coefficients that matched the color λ .

The study showed that not all matching weights are positive and that some values were negative. The algebraic values of the coefficients meaning that CMF functions took positive and negative values originating from the overlap versus wavelength between human cone sensitivities.

This pushed the CIE to define a set of primaries as displayed in fig. 8 and perform a linear transformation over $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ in order to define three strictly positive CMF functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ displayed in fig. 9

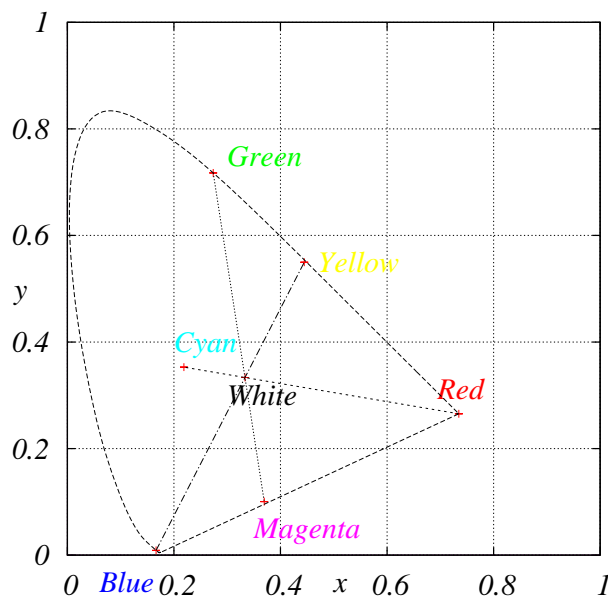


Fig.8: (Color online) Primaries and their complements in the CIE diagram. Note that cyan and magenta are not on the saturated color curve.

The linear transformation is based on equal area of $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ over the visible spectrum and the choice for the middle spectrum function $\bar{y}(\lambda)$ to be taken equal to $V(\lambda)$, the photopic eye sensitivity depicted in fig. 1.

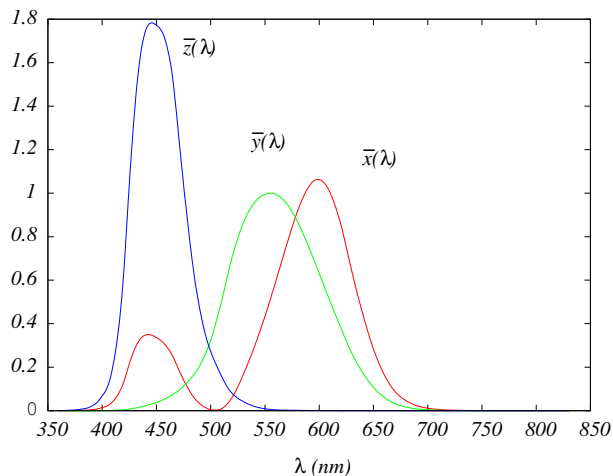


Fig.9: (Color online) Color matching functions of the CIE for eye opening of 2° . Functions \bar{x} (in red), \bar{y} (in green) and \bar{z} (in blue) cover approximately the corresponding RGB color zones. $\bar{y}(\lambda) = V(\lambda)$ as decided by the CIE.

If we have a radiation source characterized by an EPS function $P(\lambda)$ its tristimulus coordinates are given by:

$$\begin{aligned} X &= K_{cd} \int_{\lambda_{min}}^{\lambda_{max}} P(\lambda) \bar{x}(\lambda) d\lambda, \\ Y &= K_{cd} \int_{\lambda_{min}}^{\lambda_{max}} P(\lambda) \bar{y}(\lambda) d\lambda, \\ Z &= K_{cd} \int_{\lambda_{min}}^{\lambda_{max}} P(\lambda) \bar{z}(\lambda) d\lambda, \end{aligned} \tag{5}$$

Thus, X, Y, Z are respectively akin to a PER that is proper to the corresponding CMF with Y corresponding to eye sensitivity since $\bar{y}(\lambda) = V(\lambda)$.

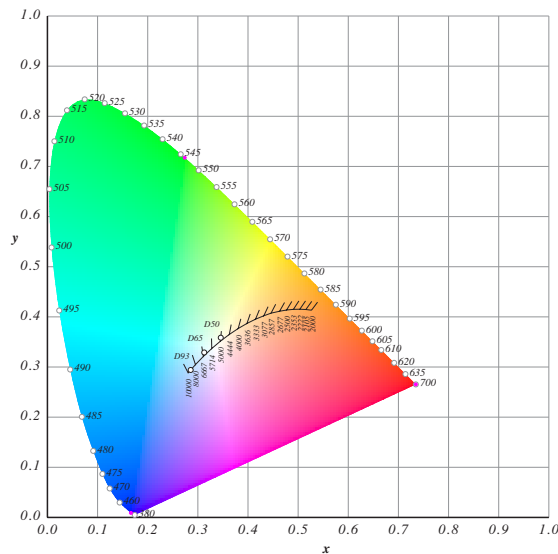


Fig.10: (Color online) CIE diagram displaying SMPTE colors of points with coordinates (x, y) and the Black-Body radiation color path as a function of absolute temperature. The D_{50}, D_{65}, D_{93} are illuminants or artificial sources designed to mimic daylight (thus prefix D) with different temperatures corresponding to one hundredth of the real temperature. Thus D_{50} means a source mimicking daylight at 5000K. Saturated colors are indicated by their wavelength in nm on the borderline. Pastel colors are around the white point $x = 0.3127, y = 0.3291$. Illuminant or artificial source RGB primaries are also indicated. The primary SMPTE illuminants (x, y) values are: Red: $(0.6300, 0.3400)$, Green: $(0.3100, 0.5950)$, Blue: $(0.1550, 0.0700)$. Adapted from Hoffmann (15).

The color of the $P(\lambda)$ source is given by a point with coordinates (x, y) in the CIE diagram displayed in fig. 10. (x, y) are called chromaticity coordinates with values explicitly given by:

$$x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z} \tag{6}$$

The CIE diagram (called tongue or horseshoe diagram) proper to the SMPTE (Society of Motion Picture and Television Engineering) shown in fig. 10 displays several important characteristics:

1. The contour contains pure colors (completely saturated or free of any white content) having wavelengths indicated on the borderline in nanometers. The corresponding wavelengths are called dominant since they control the color from pure (on the border) to white point at the center with coordinates around $x = \frac{1}{3}, y = \frac{1}{3}$.
2. Colors within the horseshoe diagram are unsaturated and as we move forward toward the white point they become pastel like due to increase of white content as we proceed toward the white point.

3. Black-Body color appears on a path as a function of absolute temperature. It follows the red, orange, yellow, white and finally blue sequence as temperature is increased. This describes heated metals and agrees with Kirchhoff observations (2).
4. The CIE contour is closed from below by a straight line (called also the purple line) that does not carry any dominant wavelength. It means that most purple colors cannot be obtained by altering the white content of some main (dominant) color as done before. This is another consequence of the cone overlap that resulted in negative CMF weights.
5. A triangular domain called an RGB gamut with vertices at some chosen red (700 nm), green (545 nm) and blue (380 nm) primary colors represent a subset of colors managed by the corresponding device (monitor or camera...).

A. From CIE Chromaticity Coordinates to RGB components

We use a simple linear transformation model to go from CIE x,y,z Chromaticity Coordinates to RGB components. This model may be a correct approximation for CCD sensor (RGB to XYZ transform) and CRT display (XYZ to RGB transform). We can use for example this transformation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (7)$$

where matrix M is:

$$M = \begin{pmatrix} 3.06322 & -1.39333 & -0.475802 \\ -0.969243 & 1.87597 & 0.0415551 \\ 0.0678713 & -0.228834 & 1.06925 \end{pmatrix} \quad (8)$$

and the inverse transform simply uses the inverse matrix:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M^{-1} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad (9)$$

In digital technology, examples of color quantization are given by:

1-bit monochrome
8-bit grayscale
8-bit color
15/16-bit color (High color)
24-bit color (True color)
30/36/48-bit color (Deep color)

Table6: Color quantization. JPEG (photos and pictures format) uses 24 bit quantization based on DCT (Discrete Cosine Transform) compression with 8 bit for each R,G,B component. JPEG2 (Digital Cinema format) uses Wavelet compression rather than DCT.

B. Gamut in analog and digital technologies

Color selection, manipulation and representation is of the utmost importance in Movies and Video media (Streaming, Blu-Ray, DVD...).

Color reproduction is basically analog (i.e. with continuous values) whether we are in Analog or Digital technologies. In analog movies, color is obtained from a superposition of emulsions whereas in Video it is a superposition of electric voltages. In digital movies, color is obtained from angular rotation of liquid crystal rods in LCD (Liquid Crystal Displays) or angular tilts of a Digital Micro-mirror Device (DMD) pixel in DLP (Digital Light Processing) technology. Its importance is crucial in the areas explicated below:

1. Desaturation

After mass introduction of Television and particularly Color TV in homes, Cinema industry reacted by producing Movie musicals in the 1960s to lure audiences back to Theatres on the promising basis of a show that will trigger emotions a TV set at home will not be able to provide.

Perhaps the best musical movie example in this respect is "Paint your Wagon" directed by Joshua Logan. The film was released in October 1969 after a long delay due to a series of harsh events among them the need to desaturate many scenes. The intriguing reason for desaturation was that during shooting, light was too bright potentially deflecting audience attention from caring about music. Desaturation is done by replacing the Yellow layer with another one producing the desired coloring effect. The agency that performed the lengthy desaturation process had to remove and replace for each film slide, the overcoat, the UV absorbing layer and the Yellow layers.

2. Flashback scenes

An ordinary flashback scene is generally represented by a foggy environment representing the past rememoration of some past event. In Ray Charles movie directed by Taylor Hackford, flashback scenes of the young Ray Charles were displayed in an oversaturated fashion indicating that he had normal sight at that time.

3. Remastering of movies

Aging of tapes occurs with time and each film slide protecting layer should be renewed. This entails removing it and applying a new one.

During this operation the Yellow layer could be thinned away thus a full remastering of the movie entails redepositing a Yellow layer having the correct thickness in order to reproduce the initial color.

This has been done with great success of Alfred Hitchcock "Rear Window" movie.

4. Color correction

Color might be wrong in part of a frame or for the entire frame since the lighting might be different for different parts or some event during the shooting occurred changing locally the right color.

5. Adapting to current technology

During Cinema history several color formats occurred and with digital effects the perception of color has changed for the audience. Thus one has to adapt the color to the best color that would be accepted by the audience according to the current technology and in comparison with other displays such as TV and smartphones where technology is based on liquid crystals illuminated by LEDs... For instance quantum dots have brought a whole new approach to color in TV displays...

C. From Color to Gray

Gray means no color and this is equivalent to having R,G,B values all equal with shades of Gray going from zero to reproduce Black to one reproducing White.

In order to account for contrast also called gamma, the luminance of the grayscale image is matched to the color image using the Digital Cinema (16) color encoding:

$$X' = \left[4095 \left(\frac{X}{52.37} \right)^{1/\gamma} \right], \quad Y' = \left[4095 \left(\frac{Y}{52.37} \right)^{1/\gamma} \right], \quad Z' = \left[4095 \left(\frac{Z}{52.37} \right)^{1/\gamma} \right] \quad (10)$$

X, Y, Z are the tristimulus values above theater black and the notation $[x]$ means integer value that is when $x \in [0 - 0.499]$, $[x] = 0$ and when $x \in [0.5 - 1]$, $[x] = 1$. 12 bit color quantization is assumed, yielding the factor $2^{12}-1=4095$. The denominator 52.37 is a correction to 48 cd/m², the glare luminance threshold value adopted by DCI (10; 11). The value of the inverse exponent $\gamma=2.6$ matches best human vision (16).

Validation is made with modulation threshold measurements as displayed in Fig. 11. Modulation threshold is the

inverse spatial contrast sensitivity or the ratio of minimum to mean luminance amplitudes of a sinusoidal light pattern with 50% probability of being detected (17).

The transformation from a γ compressed to a linear value is (16):

$$X = 52.37 \left(\frac{X'}{4095} \right)^\gamma, \quad Y = 52.37 \left(\frac{Y'}{4095} \right)^\gamma, \quad Z = 52.37 \left(\frac{Z'}{4095} \right)^\gamma \quad (11)$$

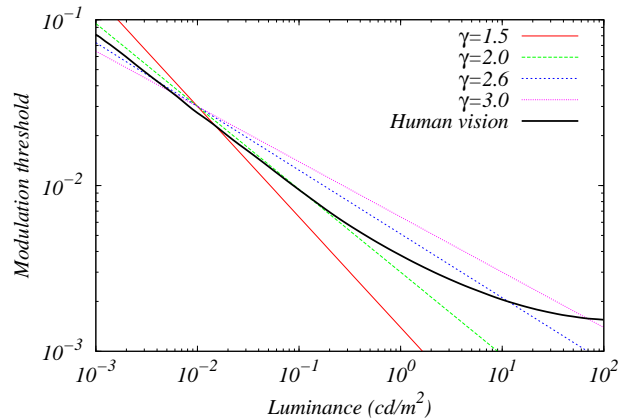


Fig.11: (Color on line) Modulation thresholds versus luminance in cd/m^2 . Human vision threshold (in black) is compared to different gamma curves. Curve in red is for $\gamma=1.5$, green for $\gamma=2.0$, blue for $\gamma=2.6$ and magenta for $\gamma=3.0$. Adapted from Maier (16).

Luminance or gray is obtained from:

$$Y = 0.2126R + 0.7152G + 0.0722B \quad (12)$$

corresponding to eye sensitivity in terms of cones.

D. From Gray to Color: B&W film colorization

It is possible to build a full color image from its grayscale version using transform methods, optimization, neural networks as summarized in Fig. 12.

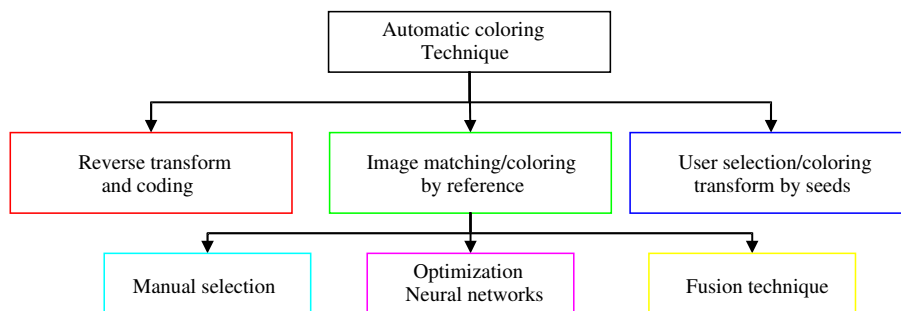


Fig.12: Image colorization methods. Adapted from Kang *et al.* (18)

IV. LIGHT SOURCES FOR CINEMA PROJECTORS

Cinema needs powerful White light projectors enlarging the film slide in Analog displays or Digital display elements such as LCD, DMD-DLP or LCoS over a large White screen. Whiteness of light source and Screen are required in

order not to introduce any color bias from the projection process.

There are several ways to obtain White light:

1. White source as a truncated Black-Body source:

This is a Black-Body source taken at a temperature $T = 5800\text{K}$ with a spectrum limited by definition to $\lambda_{min}=400\text{ nm}$ and $\lambda_{max}=700\text{ nm}$. The PER is obtained from:

$$\eta_P = K_{cd} \frac{\int_{\lambda_{min}}^{\lambda_{max}} P(\lambda)V(\lambda)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} P(\lambda)d\lambda} \quad (13)$$

Using $P(\lambda) = P_B(\lambda)$ we get a PER of about 250 lm/Watt.

2. Equal Energy White Source:

For instance, an "Equal Energy White Source" possesses by definition a flat EPS over the entire visible interval. Mathematically $P(\lambda) = W$ for $\lambda \in [380\text{nm}, 780\text{nm}]$ i.e. $\lambda_{min}=380\text{ nm}$, whereas $\lambda_{max}=780\text{ nm}$. Thus we get:

$$\eta_P = K_{cd} \frac{\int_{\lambda_{min}}^{\lambda_{max}} WV(\lambda)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} Wd\lambda} \quad (14)$$

This yields about 179 lm/Watt. This leads to the conclusion that flatness is not enough to increase PER. We need a compromise between flatness and wavelength interval length.

3. Light Emitting Diodes (LED):

White LED (19) represents tremendous potential in terms of quality and PER increase, a white source maximum is between 350 and 400 lm/Watt which is yet to be reached by white LEDs.

The performance of white LEDs is tricky since they are generally made of a blue LED and a phosphor that converts, partially, blue light into yellow.

A white source is considered as having a flat EPS function $P(\lambda)$ defined over the entire visible interval, nevertheless in practice the interval is limited and one has to define precisely the wavelength interval over which this flatness is observed.

Presently high power white LEDs can produce over 1000 lumens and are used in many types of Cinema Projectors.

4. Halogen lamps:

They are limited to several hundred lumens and are used only in Super 8 and 16 mm Home Cinema projectors.

5. Discharge arc lamps:

Xenon arc lamps are the standard in Digital Cinema Projectors with several thousands of lumens.

The luminous efficacy of some light source type is discussed below.

A. Luminous efficacy of Black-Body radiation sources

Using the SI standard K_{cd} (see Table 1) we are now able to determine the luminous efficacy of any radiation source.

The value of η_P for any radiation source characterized by an EPS function $P(\lambda)$ (akin to the Black-Body $P_B(\lambda)$) is given by:

$$\eta_P = K_{cd} \frac{\int_{\mathcal{D}_\lambda} P(\lambda)V(\lambda)d\lambda}{\int_{\mathcal{D}_\lambda} P(\lambda)d\lambda} \quad (15)$$

In view of the perceived light definition eq. 4, the wavelength interval \mathcal{D}_λ should be $[0, \infty]$, however we can redefine it in order to suit the radiation source spectrum.

In the particular case of a source of the thermal Black-Body type, we apply the above formula 15 with $P(\lambda) = P_B(\lambda)$ and $\mathcal{D}_\lambda = [0, \infty]$:

$$\eta_P = K_{cd} \frac{\int_0^\infty P_B(\lambda) V(\lambda) d\lambda}{\int_0^\infty P_B(\lambda) d\lambda} \quad (16)$$

The result is the temperature dependent PER curve depicted in fig. 13.

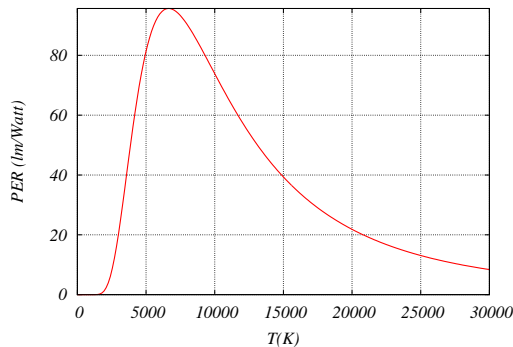


Fig.13: η_P versus temperature of the Black-Body. Notice that the maximum is 95 lm/Watt and that the temperature is about 7000K.

PER has lm/Watt dimensions, thus we define *efficiency* as a dimensionless ratio (in %) yielding the fraction with respect to the ideal efficacy of 683 lm/Watt.

It shows that the Sun efficacy is about 93 lm/Watt (temperature about 6000K) or an efficiency of $93/683=13.6\%$ and that the ordinary Tungsten light bulb based on incandescence phenomenon (20) is about 15 lm/Watt (temperature about 3000K) or 2% only. For a candle considered as a Black-Body at $T=1800K$, we get 0.6 lm/Watt which corresponds to an efficiency of $0.6/683$ or about 0.1%.

The consequence in terms of lighting is that when one acquires a 60 Watts bulb of the Tungsten type, the light produced by the bulb is $60 \text{ W} \times 15 \text{ lm/Watt} = 900$ lumens in total and that has tremendous consequences for the quality and cost of the lighting desired.

B. Luminous efficacy of Lasers and LEDs

White light is considered as broadband source since its radiation should spans (at least) the entire visible spectrum in a somehow flat fashion.

This is not the case of LEDs and lasers since they are somehow closer to monochromatic (narrowband) sources.

The new CIE definition of the mechanical equivalent of the lumen is that a monochromatic source that is an EPS peaking at $\lambda_0=555 \text{ nm}$ (at the maximum sensitivity of the eye) with power of 1 W produces exactly 683 lumens.

This can be understood readily from the general PER definition:

$$\eta_P = K_{cd} \frac{\int_{\lambda_{min}}^{\lambda_{max}} \delta(\lambda - \lambda_0) V(\lambda) d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} \delta(\lambda - \lambda_0) d\lambda} \quad (17)$$

where we used: $P(\lambda) = a\delta(\lambda - \lambda_0)$ with a a constant and the condition that $\lambda_0 \in [\lambda_{min}, \lambda_{max}]$.

The integral gives the result: $\text{PER} = K_{cd} V(\lambda_0) = K_{cd}$ since $V(\lambda_0 = 555\text{nm}) = 1$.

As an application, consider a laser emitting at $\lambda_0=570 \text{ nm}$ with a power of 50 mW. It has a $\text{PER} = K_{cd} V(\lambda_0)$ that produces 30 lumens.

In the LED case, the EPS function is usually approximated by a Gaussian or a superposition of several Gaussian functions. In the single Gaussian approximation $P(\lambda) = \exp\left[-\frac{(\lambda-\lambda_0)^2}{2\Delta\lambda^2}\right]$ can be used to evaluate η_P from eq. 13.

The LED is characterized by an average wavelength λ_0 and a standard deviation $\Delta\lambda$. As an example, we consider a blue LED with $\lambda_0=450$ nm and $\Delta\lambda=20$ nm. The PER obtained from eq. 13 is about 39.7 lm/Watt and therefore an efficiency of 6%. The small efficiency is due to small overlap between the blue LED spectrum and the eye sensibility curve $V(\lambda)$, moreover that number is further reduced after multiplication by η_C which is typically anywhere between 20% to 50% yielding a total efficiency of 1.2% to 3%.

C. Luminous efficacy of Xenon arc lamps

Digital cinema offer a more precise colorimetry than traditional 35 mm projection could offer. This performance originated from the Digital Cinema Initiative (DCI) and SMPTE DC-28 to employ non-mainstream image coding technologies (10).

DCI-P3 is a projector standard based on Color space DCI-X'Y'Z' developed by DCI. It is independent of today projection primaries and in order to guarantee a minimal number of colors that can be reproduced on any digital projection system, the P3 reference gamut was defined in SMPTE 431-22 and displayed in fig. 14.

According to DCI standard, 2020 Rec has the largest gamut in comparison with 709 Rec/sRGB and P3 which is very close to Adobe RGB standard.

DCI-P3 covers 45.5% of the CIE 1931 chromaticity diagram, which describes the color gamut of daylight human vision. It is also very close to the CIE gamut avoiding red saturated colors (cf. fig. 14). A P3 projector can only display a subset of the colors encoded in DCI-X'Y'Z', while a prototype laser P3 projector covers extended colors compared to P3 but is still not able to show all valid DCI-X'Y'Z' colors (10).

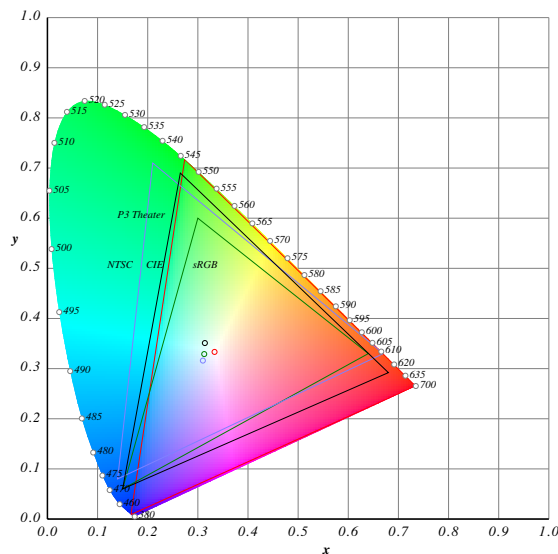


Fig.14: (Color online) (Color on line) Gamut corresponding to P3 projector DCI standard for Cinema theaters (in black) compared to NTSC (in blue), CIE (in red) and sRGB (in green). Corresponding White points are indicated with the same color corresponding to the standard. Adapted from SMPTE 431-22 and Hoffmann (15).

Digital Cinema Projector image parameters and tolerances for the projected image in Review Rooms and Exhibition Theatres, as measured off the screen and including the room ambient light, are summarized in Table 7 regarding White points and primary colors and Table 8 regarding most projector P3 issues.

Xenon arc plasma lamps exhibit the largest output of any White light source approaching the ideal point source of light.

Color space	White point		CCT (K)	Primary R,G,B colors					
	x_W	y_W		x_R	y_R	x_G	y_G	x_B	y_B
P3-D65 (Display)	0.3127	0.3290	6504	0.680	0.320	0.265	0.690	0.150	0.060
P3-DCI (Theater)	0.314	0.351	6300	0.680	0.320	0.265	0.690	0.150	0.060
P3-D60 (ACES Cinema)	0.32168	0.33767	6000	0.680	0.320	0.265	0.690	0.150	0.060

Table7: DCI-P3 color space indicating positions of White point and primary colors for Display, Theater and ACES Cinema according to SMPTE Standard (11). Note that the primary color coordinates $x_R; y_R, x_G, y_G, x_B, y_B$ are same for the three standards P3-D65 (Display), P3-DCI (Theater), P3-D60 (ACES Cinema), however the white point coordinates x_W, y_W are different. ACES is an interoperable mastering format for digital cinema. CCT is Correlated Color Temperature (K).

Image Parameters	Nominal	Tolerances	Tolerances
Pixel Count	(Reference Projector) 2048× 1080 or greater	(Review Rooms) 2048×1080 or greater	(Theatres) 2048×1080 or greater
Luminance Uniformity, corners and sides	85% of center	80% to 90% of center	70% to 90% of center
Calibrated White Luminance, center	48 cd/m ² (14 fL)	±2.4 cd/m ² (±0.7 fL)	±10.2 cd/m ² (±3.0 fL)
Sequential Contrast	2000:1 minimum	1500:1 minimum	1200:1 minimum
Intra-frame Contrast	150:1 minimum	100:1 minimum	100:1 minimum
Grayscale Tracking	No visible color shading	No visible color shading	No visible color shading
Color Uniformity of White field, corners	matches center	±.008 x, y Relative to center	±.015 x, y Relative to center
Contouring	Continuous, smooth ramp, with no visible steps	(same)	(same)
Color Gamut	Minimum Color Gamut enclosed by white point, black point(cf Note 2) and Red: 0.680 x , 0.320 y , 10.1 Y Green: 0.265 x , 0.690 y , 34.6 Y Blue: 0.150 x , 0.060 y , 3.3 Y	(same)	(same)
Transfer Function	$\gamma = 2.6$	±2% (cf. Note 1)	±5% Best fit

Table8: Reference Projector Image Parameters and Tolerances for Review Rooms and Theatres according to SMPTE Standard ISO 26431-1:2008. Note 1. Least squares fit of slope of log/log plot of measured luminance vs. input code value, using a range from peak white luminance down to 5% of peak white. Note 2. The luminance of the black point is limited by the sequential contrast ratio of the projector plus the ambient light falling on the screen. fL is footLambert a deprecated unit equal to 3.426 cd/m². Adapted from SMPTE Standard ISO 26431-1:2008 (11)

Xenon arc lamp produces a largely continuous and uniform spectrum across the entire visible spectral region. Because the Xenon lamp emission profile features a color temperature of approximately 6000 K (close to that of sunlight) and lacks prominent emission lines, it is more advantageous than mercury arc lamps for many applications and specially in Digital Cinema.

In Xenon arc lamps, the total lamp output ranges over 1000 nanometers in spectral bandwidth with the plasma arc and electrodes each accounting for approximately half of the total emission. The substantial contribution by the electrodes is due to their large surface areas and high temperatures. Most of the lower wavelength emission (visible light) originates from the plasma arc, whereas the electrodes account for most of the infrared radiation (above 700 nanometers) with maximum luminance distribution adjacent to the cathode in the arc region (often termed a hot

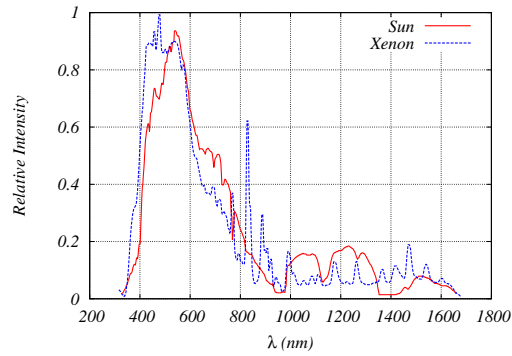


Fig.15: (Color online) Relative intensities in arbitrary units of filtered Xenon arc lamp and Sun. Xenon data source is taken from Saloman (21) whereas Sun data is taken from QlabTM (22).

spot or plasma ball).

Approximately 70 percent of the Xenon arc lamp output occurs at wavelengths longer than 700 nanometers, while less than 5 percent of the output consists of wavelengths less than 400 nanometers. The exceedingly high pressure of Xenon lamps during operation (ranging from 40 to 60 atmospheres) broadens spectral lines to yield far more uniformly distributed excitation of fluorophores when compared to the narrow and discrete emission lines produced by mercury lamps.

Lamp Wattage and specs	Lamp voltage (V)	Control current range (A)	Luminous flux (lm)	Luminous intensity (cd)	Average luminance (cd/cm ²)	Lifetime (Hours)
1600W	24	45-75	60000	6000	65000	3500
1600W/HS	23	50-75	70000	5500	65000	2500
1600W/HSC	23	50-75	70000	5500	65000	2500
2000W/H	28	50-85	80000	7500	80000	3500
2000W/HTP	28	50-85	80000	7500	80000	3500
2500W/HS	28	70-100	100000	10000	80000	2200
3000W/H	29	60-110	130000	12000	90000	2200
3000W/HS	29	60-110	130000	12000	90000	2200
3000W/HTP	29	60-110	130000	12000	90000	2200
4000W/HS	30	80-150	155000	17000	90000	1500
4000W/HTP	30	80-150	155000	17000	90000	1500
4500W/HS	32	80-150	190000	22000	105000	1400
4500W/HTP	32	80-150	190000	22000	105000	1400
5000W/H	35	100-150	225000	27000	95000	1200
5000W/HBM	34	100-150	225000	27000	95000	1200
6000W/HS	37	110-165	280000	40000	105000	750
6000W/HTP	37	110-165	280000	40000	105000	750
7000W/HS	42	110-165	350000	35000	100000	650

Table9: OsramTMXenon arc lamps wattage, characteristics and technical specifications.

V. DISPLAY TECHNOLOGIES

A. Analog display technology

Film (23) is the basic display ingredient of Analog Cinema. Its structure is explained below:

1. Film base

The supporting layer in film is called the base. This base has to be transparent (with some optical density), free from imperfections, chemically stable, insensitive photographically, and resistant to moisture and processing chemicals, while remaining mechanically strong, resistant to tearing, flexible, and dimensionally stable.

Three plastics have been widely used as a motion picture film base (23):

- (a) Cellulose nitrate was the first material used. Discontinued in the 1950s because of its high flammability. It is chemically unstable if stored in damp (decomposition risk) or too hot conditions (self ignition risk).
- (b) Cellulose acetates were developed to replace nitrate. Cellulose triacetate, called safety base, is much safer to use and store than nitrate.
- (c) Polyester base is used for all print films, most duplicating films, and some specialty films. Polyester is stronger and wears better than triacetate. Polyester storage life is up to ten times that of acetate.

2. Emulsion

It is the photographic part of the film, and consists of dispersions of light-sensitive materials in a colloidal medium, usually gelatin, carried as a thin layer(s) on a film base.

In each emulsion layer, color couplers are dispersed in tiny oil droplets around silver halide crystals.

There are three types of color couplers, one for each of the color emulsion layers. Each color coupler forms a dye of one of the three subtractive primary colors and is located in a layer that is sensitive to light of its complementary color.

3. Subbing Layer

The subbing layer is applied to the film base so that the emulsion adheres to the base.

4. Ultraviolet Absorbing Layer

Although we can't see ultraviolet (UV) radiation, photosensitive silver halide crystals can be exposed by it. An ultraviolet absorbing layer is included to protect the imaging layers from exposure by UV radiation.

5. Overcoat

The purpose of this clear layer of hardened gelatin is to protect the emulsion from damage during transport through the camera.

6. Anti-halation Backing

Light penetrating the emulsion of a film can reflect from the base-emulsion interface back into the emulsion, creating a secondary image around bright objects like a halo, thus the word halation. An antihalation layer e.g. dark coating on or in the film base, will absorb and minimize this reflection.

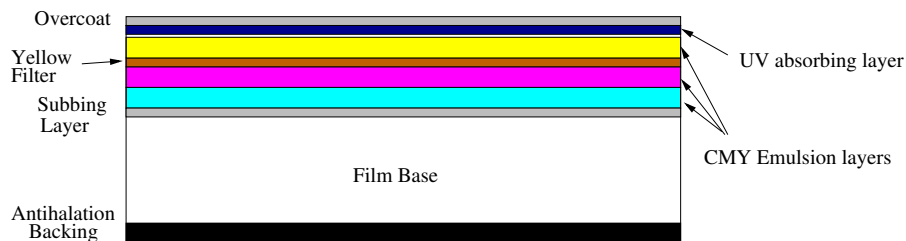


Fig.16: (Color online) Layers making a film slide. The overcoat protects the slide but it should be removed and redeposited after some time making remastering quite subtle.

B. Digital display technologies

There are three technologies for digital cinema requiring high power LED or discharge arc lamps such as Xenon:

1. Transmission through Liquid crystal displays (LCD)
2. Reflection by Digital Micro-mirror Devices and Digital Light Processing (DMD-DLP)
3. Transmission through Liquid Crystal on Silicon (LCoS)

We describe below every display technology in detail:

1. Liquid crystal display (LCD)

In 1888, the Austrian botanist Friedrich Reinitzer discovered liquid crystals having an intermediate state of matter between isotropic liquid and lattice structured crystal (24).

The development of the twisted nematic (TN) and super-twisted nematic (STN) cell configurations, along with the necessary manufacturing technologies, resulted in the birth of the LCD industry in the late 1970s and early 1980s. The subsequent development of thin-film transistor (TFT) technology provided an electronic way to control the orientation of liquid crystal rods (24).

The application of LCD expanded rapidly from purely information technology applications to television, e-tablets, smartphones and digital cinema projectors displays (24).

2. Digital Micro-mirror Devices with Digital Light Processing (DMD-DLP)

3D Cinema requires two well-synchronized projectors (for left and right eyes) implying many technical and financial problems for the Cinema industry. Thus, Texas Instruments was asked by the Cinema industry to develop a solution for projecting 3D pictures with a single projector.

Texas Instruments (TI) is the inventor of DLP (Digital Light Processor) Cinema, implemented by nearly 90% of the world digital theater screens. TI DLP technology provides the Digital Micromirror Device (DMD), or DLP chip, a high speed, efficient MEMS (Micro-Electro-Mechanical System) light steering device that can work with many sources of light (lamp, LED or laser) including visible, infrared and ultraviolet. Each DMD contains up to 8.8 million individually controlled micro-mirrors (each typically $16 \mu\text{m} \times 16 \mu\text{m}$) sitting on top of a fast SRAM memory.

The DMD technology is also fast enough to support the higher frame rates demanded by 3D Cinema requiring the interleaving two 24 FPS (Frames Per Second) streams (for left and right eyes), and to replicate the interleaved stream by a factor of two, resulting in 96 FPS total frame rate.

When White light hits the DMD, shades of Gray are obtained from angular tilts of DMD pixel elements and color is obtained with a color wheel in home cinema projectors. In theaters White light is split in R,G,B primaries with filters to be reflected by three DMD providing the shades of each R,G,B primary resulting in up to 35 trillion colors.

Some of the other important features of DLP technology are:

- Over 20,000 cycles/second
- Extremely high fill factor that minimizes the visibility of structure evident in traditional transmissive LCD displays.
- Polarization independent
- Quintillion cycles tested

3. Liquid Crystal on Silicon (LCoS)

In addition to DLP technology, LCoS (liquid crystal on Silicon) technologies have been applied to large screen digital cinema, including JVC D-ILA (Digitally addressed Image Light Amplifier) and Sony SXRD (Silicon Xtal

Reflective Device) technologies. LCoS display technologies provide high contrast and high display resolution, with a higher fill factor than LCDs.

JVC introduced D-ILA projectors in 2000 for home Cinema, building on the analog ILA technology. Although JVC offers 2K (or 2048 x 858) D-ILA projectors and 4K (or 4096x2160) D-ILA projectors these projectors have been limited to a maximum of 8,000 lumens making them candidates for digital cinema projectors.

In Sony SXR technology, similarly to D-ILA, the organic liquid crystals are vertically aligned for improved contrast. The 4K (4096x2160) digital cinema SXR devices have a pixel pitch of 8.5 μm , with 0.35 μm gaps between pixels, on a 1.55 μm diagonal imager. Liquid crystal devices are organic components in a liquid dispersion that work by rotating polarized light when a field is applied.

In late 2005, Sony introduced SXR digital cinema projectors in two models-the SRX-R110 (10,000 lumens) and the SRX-R105 (5,000 lumens). These products use twin Xenon lamps. The contrast specifications for SXR and SRX-R105 are 1,800:1 and the projectors are calibrated to $\gamma=2.6$ (best for human vision) with the same white point and color primaries as the DCI/SMPTE Reference Projector.

VI. REFLECTANCE DISTRIBUTION FUNCTIONS (RDF)

A. Varieties of scene element properties

In a scene, there are different objects with properties as listed non exhaustively below (25):

- **Fluorescent Samples**
Fluorescent materials not only reflect light but also emit light. Light absorbed at some wavelengths is emitted at longer wavelengths. The amount of light emitted depends on the intensity and the spectral power distribution of the source. Techniques have been recommended by the CIE for assessing the quality of daylight simulators [55]. Measured reflectance factors at the wavelengths of emittance may be greater than 1.0.
- **Metallic samples**
Materials that contain metallic elements are gonio-chromatic, i.e., they change color with illumination and viewing setup.
- **Pearlescent Samples**
Materials containing pearlescent pigments are gonio-chromatic like metallic samples. However the angular distribution of their reflectance is narrower than metals. These samples are very difficult to render properly and characterizing them is still undergoing currently.
- **Retro-reflecting Samples**
Highway signs and some clothing are examples of retro-reflectors. Light shining on a retro-reflector is returned in directions very close to the illumination angle.
- **Hazy and Translucent Materials**
Hazy and translucent materials are measured by placing them in contact with an integrating sphere and measuring their diffuse transmittance. A haze index can be calculated from four diffuse transmittance measurements on a reflecting spectrophotometer (25).

There are several modes of reflection and refraction of light by scene elements presenting surfaces with different optical properties whose nature could be any of:

- Flat: reflecting, non-reflecting
- Rough: reflecting, non-reflecting
- Opaque: reflecting, non-reflecting
- Glossy or mirror-like: simple reflection
- Metallic: Angle dependent reflection

- Pearlescent: Angle dependent reflection
- Retro-reflector: Reflection angle same as incident
- Transparent: reflecting, non-reflecting
- Semi-Transparent: reflecting, non-reflecting
- Translucent: sub-surface propagation

Reflection and refraction nature belong to any of the types (see fig. 17):

- Simple or directional: For a single incoming ray there is a single outgoing ray
- Specular or conical: For a single incoming ray there are several outgoing rays confined to a finite range of angles in 3D space thus the conical term.
- Diffuse or hemispherical: For a single incoming ray there are an infinite number of outgoing rays with angles spanning all available hemispherical propagation space.

Lets us consider some example surfaces:

- Matte surface: Diffuse reflection
- Mirror: Simple reflection
- Home glass window: Simple refraction and simple reflection
- Metallic surface: Diffuse and specular reflection
- Bowling ball: Simple+Specular+Diffuse reflection
- Precious stone: Simple+Specular reflection and Simple+specular refraction

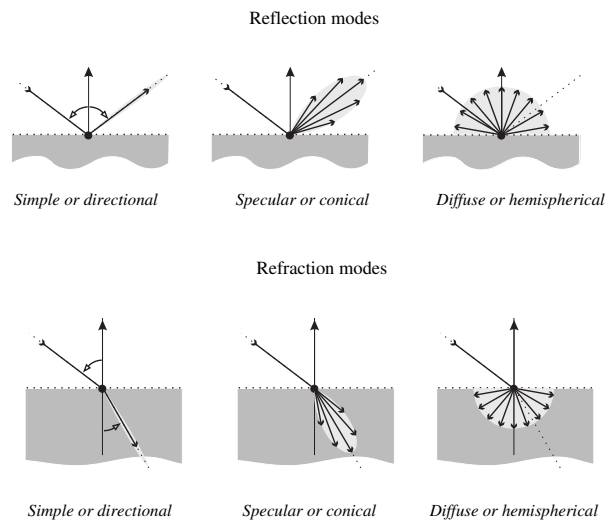


Fig.17: Reflection and Refraction modes (26).

Reflectance Distribution Function (RDF) type
1. Directional-Directional reflectance factor
2. Directional-Conical reflectance factor
3. Directional-Hemispherical reflectance factor
4. Conical-Directional reflectance factor
5. Conical-Conical reflectance factor
6. Conical-Hemispherical reflectance factor
7. Hemispherical-Directional reflectance factor
8. Hemispherical-Conical reflectance factor
9. Hemispherical-Hemispherical reflectance factor

Table10: Reflectance function nine possibilities. Note that the prefix Bi is used instead of repeating the term as for instance: Bidirectional replaces "Directional-Directional".

Acronym	Reflectance Distribution Function (RDF) type
Directional	
BRDF	bidirectional RDF
BRIDF	bidirectional reflected-intensity-distribution function
BRRDF	bidirectional reflected-radiance-distribution function
BSSRDF	bidirectional sub-surface RDF

Table11: Bidirectional reflectance function nomenclature.

B. Directional, Conical and Hemispherical RDF

This results into nine reflectance factors (26) by combining the three possibilities: Directional, Conical and Hemispherical:

with the additional nomenclature related to radiance, intensity and sub-surface issues:

The BRDF is used in computer graphics (CG) for realistic rendering of synthetic scenes in digital cinema. Another important function used in CG digital cinema is the BSSRDF (Bidirectional sub-surface RDF or Bidirectional surface scattering RDF) relates outgoing radiance and incident light including sub-surface propagation as displayed in fig. 18.

BRDFs can be measured directly from real objects using calibrated cameras and light sources; however, many phenomenological and analytic models have been proposed including the Lambertian reflectance model frequently assumed in computer graphics.

Highly scattering materials such as milk and skin require accounting for hundreds of scattering events in order to be well rendered.

The BSSRDF can describe light transport between any two rays that hit a surface, whereas the BRDF assumes that light entering a material leaves the material at the same position (see fig. 18). This approximation is valid for metals, but it fails for translucent materials, which exhibit significant transport below the surface.

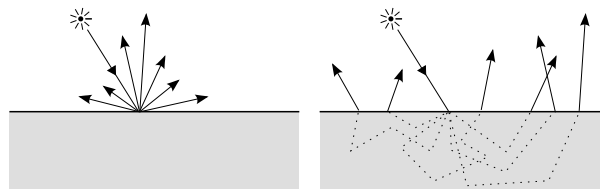


Fig.18: Reflectance distribution functions: BRDF (left) showing incident and reflected rays at the same point whereas BSSRDF (right) shows an incident ray at some point, transport beneath the surface and an emerging ray at another point.

Scene object	Reduced Scattering coefficient [mm ⁻¹]			Absorption coefficient [mm ⁻¹]			Diffusion reflectance			Relative refraction index
	R	G	B	R	G	B	R	G	B	
Apple	2.29	2.39	1.97	0.0030	0.0034	0.046	0.85	0.84	0.53	1.3
Potato	0.68	0.70	0.55	0.0024	0.0090	0.12	0.77	0.62	0.21	1.3
Cream	7.38	5.47	3.15	0.0002	0.0028	0.0163	0.98	0.90	0.73	1.3
Ketchup	0.18	0.07	0.03	0.061	0.97	1.45	0.16	0.01	0.00	1.3
Skim milk	0.70	1.22	1.90	0.0014	0.0025	0.0142	0.81	0.81	0.69	1.3
Whole milk	2.55	3.21	3.77	0.0011	0.0024	0.014	0.91	0.88	0.76	1.3
Chicken	0.15	0.21	0.38	0.015	0.077	0.19	0.31	0.15	0.10	1.3
Human skin #1	0.74	0.88	1.01	0.032	0.17	0.48	0.44	0.22	0.13	1.3
Human skin #2	1.09	1.59	1.79	0.013	0.070	0.145	0.63	0.44	0.34	1.3
Marble	2.19	2.62	3.00	0.0021	0.0041	0.0071	0.83	0.79	0.75	1.5

Table12: Measured scattering, absorption, diffusion reflectance parameters decomposed into R,G,B components for several scene objects. The reduced scattering coefficient is the scattering coefficient multiplied by $(1 - \langle \cos \theta \rangle)$ where θ is the scattering angle and $\langle \cos \theta \rangle$ is the mean value of its cosine. Adapted from Reference (27)

Even for many materials that do not seem very translucent, using the BRDF creates a hard, distinctly computer-generated appearance because it does not locally blend surface features such as color and geometry. Only methods that consider sub-surface scattering can capture the true appearance of translucent materials, such as marble, cloth, paper, skin, milk, cheese, bread, meat, fruits, plants, fish, ocean water, snow, etc.

Skin is a material that is particularly difficult to render using methods that simulate subsurface scattering by sampling ray paths through the material. This is due to the fact that skin is highly scattering and also very anisotropic (typical average cosine of the scattering angle is 0.85).

Both of these properties mean that the average number of scattering events of a photon is very high (often more than 100). In addition, skin is very translucent, and it cannot be rendered correctly using a BRDF. A complete skin model requires multiple layers, but a reasonable approximation can be obtained using just one layer. The skin measurements in Table 12 are from an arm (which is likely more translucent than skin on the face), but the overall appearance is still realistic considering the lack of spatial variation (texture).

BSSRDF is used within in a ray-tracing context. At each ray-object intersection traditional lighting models (based on BRDFs) need just a point and a normal to compute the outgoing radiance.

For the BSSRDF it is necessary to integrate the incoming lighting over an area of the surface. This is done by sampling randomly the location of both endpoints of the shadow ray.

In order to account for texture, a few small changes should be introduced in BSSRDF. Only texture variation at the surface are considered whereas effects due to volumetric texture variation would require a greater computational effort.

APPENDIX A: Radiometric and Photometric units

Several concepts in Digital Cinema are based on Radiometric and Photometric quantities in addition to Colorimetric ones.

Table. 13 summarizes the most common radiometric and photometric quantities, along with their symbols and units.

Quantity	Symbol	Radiometric Units	Symbol	Photometric Units
Wavelength	λ	nanometer (nm)	λ	nanometer (nm)
Radiant and luminous energy	Q	watt-seconds (W-s)	Q_ν	lumen-seconds (lm-s)
Radiant and luminous energy density	U	watt-seconds/m ³ (W-s/m ³)	U_ν	lumen-seconds/m ³ (lm-s/m ³)
Radiant and luminous flux (power)	Φ	watts (W)	Φ_ν	lumens (lm)
Irradiance and illuminance	E	watts/cm ² (W/cm ²) or watts/m ² (W/m ²)	E_ν	lux (lx; lm/m ²)
Radiance and luminance	L	watts/m ² /steradian (W/m ² /sr)	L_ν	lumens/m ² /steradians (lm/m ² /sr)
Radiant and luminous intensity	I	watts/steradian (W/sr)	I_ν	candela (cd; lm/sr)

Table13: Radiometric and Photometric Quantities

References

- [1] G. Kirchhoff, *On the relation between the radiating and absorbing powers of different bodies for light and heat*, Phil. Mag. Series 4, Volume 20, 1-21 (1860).
- [2] F. Grum and R. J. Becherer, *Optical radiation measurements, Volume 1: Radiometry; Volume 2: Color Measurements*, Academic Press (New-York, 1979).
- [3] N. Ohta and A. R. Robertson, *Colorimetry: Fundamentals and Applications*, J. Wiley and Sons, (New-York, 2005).
- [4] J. C. Maxwell, *On the theory of compound colors and the relations of the colors of the spectrum*, in Proc. Roy. Soc. London 10, 404, 484 (1860); Phil. Mag. (4) 21,141 (1860); Scientific Papers (Cambridge 1890).
- [5] Report of the 21st meeting (23-24 February 2012) of the Consultative Committee for Photometry and Radiometry (CCPR), Bureau International des Poids et Mesures (2012).
- [6] R. Haitz in *Advances in Solid State Physics* **43**, 35-50, edited by B. Kramer, Springer-Verlag, Berlin and Heidelberg (2003).
- [7] J. M. Palmer, Chapter 36: *Radiometry and Photometry: Units and Conversions*, p. 36.10 in *Handbook of Optics*, Third edition, edited by M. Bass, SPIE and McGraw-Hill (New-York, 2010).
- [8] W. H. Press, W. T. Vetterling, S. A. Teukolsky and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*, Second Edition, Cambridge University Press (New-York, 1992).
- [9] S. Hecht, *The dark adaptation of the human eye* The Journal of General Physiology, 499 (1920).
- [10] J. Froehlich, S. Grandinetti, B. Eberhardt, S. Walter, A. Schilling, and H. Brendel, *Creating Cinematic Wide Gamut HDR-Video for the Evaluation of Tone Mapping Operators and HDR-Displays*, Proc. of IS&T/SPIE Electronic Imaging, (2014). See also J. Froehlich, A. Schilling and B. Eberhardt *Gamut Mapping for Digital Cinema*, SMPTE Motion Imaging J. (2014).
- [11] SMPTE ISO 26431-1:2008 Standard (2008).
- [12] G. Kennel, *Color and Mastering for Digital Cinema* Focal Press and Elsevier (2007).
- [13] *22.2 Multichannel Audio Format Standardization Activity*, Broadcast Technology, NHK **45**, 15 (2011).
- [14] V. C. Smith and J. Pokorny, *Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm*, Vision Research, 15, 161-171(1975).
- [15] G. Hoffmann, *CIE Color Space*, Web document ciegraph17052004.pdf from University of Emden URL: <http://docs-hoffmann.de>
- [16] T. Maier, SMPTE Motion Imaging J, **116**, 439 (2007)
- [17] I. Reiser, Chapter 18 in *Diagnostic Radiology Physics: A Handbook for Teachers and Students* Edited by D.R. Dance, S. Christofides, A.D.A. Maidment, I.D. McLean and K.H. Ng, IAEA Vienna (2014).
- [18] S H Kang and R. March, IEEE Transactions On Image Processing **16**, 2251 (2007)
- [19] J. Ouellette, *White LEDs poised for global impact*, Phys. Today, 25-26 (December 2007).
- [20] D. C. Agrawal, H. S. Leff and V. J. Menon, *Efficiency and efficacy of incandescent lamps*, Am. J. Phys. **64**, 649-654 (1996).
- [21] E. B. Saloman, *Energy Levels and Observed Spectral Lines of Xenon, Xe I through Xe LIV* J. Phys. Chem. Ref. Data, Vol. 33, No. 3, 766 (2004).
- [22] Q-Lab CorporationTM, *Sunlight, Weathering & Light Stability Testing* Technical Bulletin LU-0822.3 (2011).
- [23] The essential reference guide for filmmakers, KODAK Educational Products, Code: H-845 CAT No. 145 6144, Eastman Kodak Company (2007).
- [24] K-H Kim and J-K Song, *Technical evolution of liquid crystal displays*, NPG Asia Mat. 1(1) 29 (2009)

- [25] R. T. Marcus, *Colorimetry*; Chapter 58 in *Coloring of Food, Drugs, and Cosmetics* CRC Press (1999).
- [26] F.E. Nicodemus, *Directional reflectance and emissivity of an opaque surface*, Appl. Opt. 4, 767 (1965), F.E. Nicodemus, *Reflectance nomenclature and directional reflectance and emissivity*, Appl. Opt. 9, 1474 (1970), F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I.W. Ginsberg, and T. Limperis, *Geometrical considerations and nomenclature for reflectance*, NBS Monograph 160 (1977)
- [27] H. W. Jensen, S. R. Marschner, M. Levoy and P. Hanrahan, *A Practical Model for Subsurface Light Transport*, Proceedings of the 28th annual conference on Computer graphics and interactive techniques, SIGGRAPH (2001).