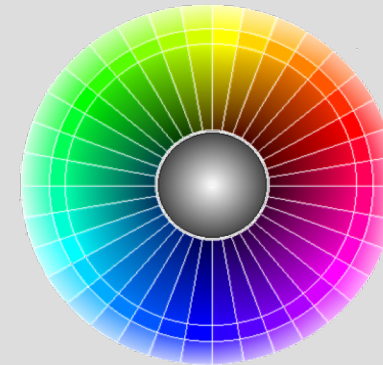


Luz e Cor

*fontes
luminosas
geram
luz*



*que
interagem
com
o meio
(supeficies)*



*que
produzem
sensações
no nosso
cérebro*



*que nosos
olhos
captam*

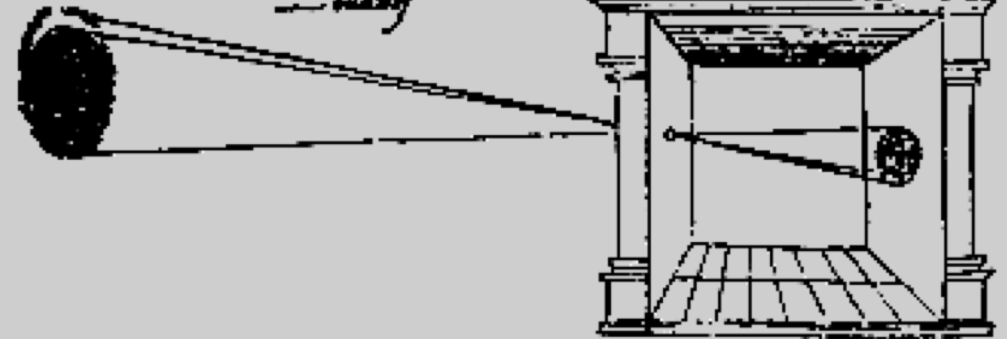
Estudo da luz é muito antigo ...

“*camera obscura (latim)*”

1. Mo-Ti (V século antes de Cristo)
2. Aristótes (384-322 AC) – eclipse do sol
3. Alhazen de Basra (X DC)
4. Leonardo da Vince (XVI DC) ...

illum in tabula per radios Solis, quam in caelo contingit: hoc est, si in caelo superior pars deliquiū patiarat, in radius apparebit inferior deficere, vt ratio exigit optica.

*Soli deliquium Anno (1544)
1544. Die 24 Januarij
L. Mazij*



Sic nos exactè Anno .1544. Louanii eclipsim Solis obseruauimus, inuenimusq; deficere paulò plus q̄ dex-

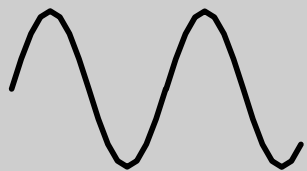
A luz tem um comportamento complexo...

modelos físicos da luz

Huygens



☆1629 †1695



onda

Newton



☆1643 †1727



partículas

Max Planck

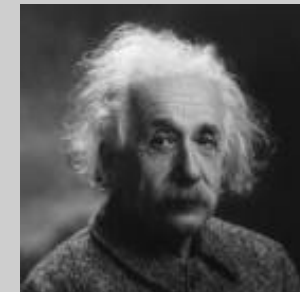


☆1858 †1947



fótons

Eistein



☆1879 †1955

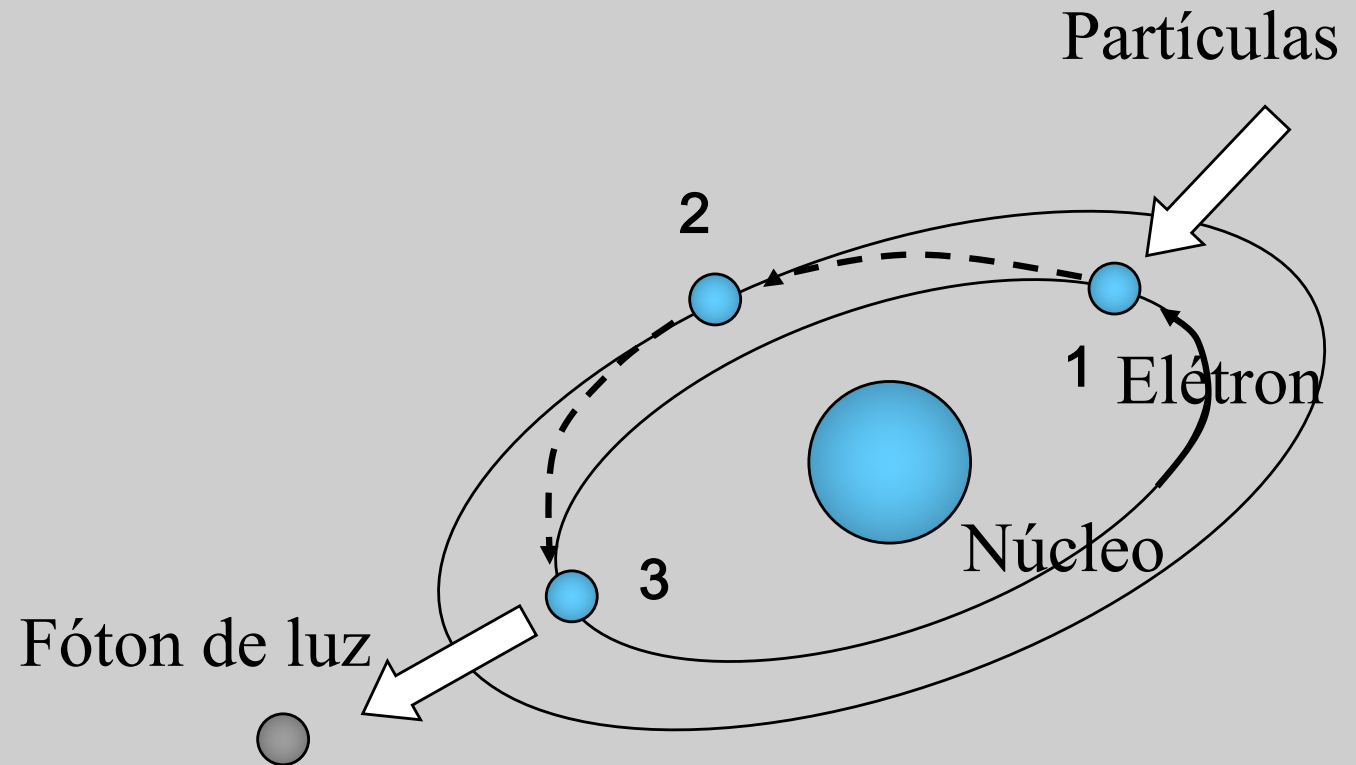


Energia de um fóton

Max Planck



☆ 1858 † 1947



$$e_f = hf$$

h = constante de Planck ($6.626 \times 10^{-34} \text{ J.s}$)

f = frequência (Hz)

Energia da luz: Fluxo Radiante

1 fóton com comprimento de onda λ : $e_\lambda = h \frac{c}{\lambda}$

n_λ fótons com comprimento de onda λ : $Q_\lambda = n_\lambda e_\lambda = n_\lambda h \frac{c}{\lambda}$ [J/nm]

Energia radiante: $Q = \int_0^\infty Q_\lambda d\lambda$ [J]

Fluxo radiante:

$$\Phi = \frac{dQ}{dt}$$

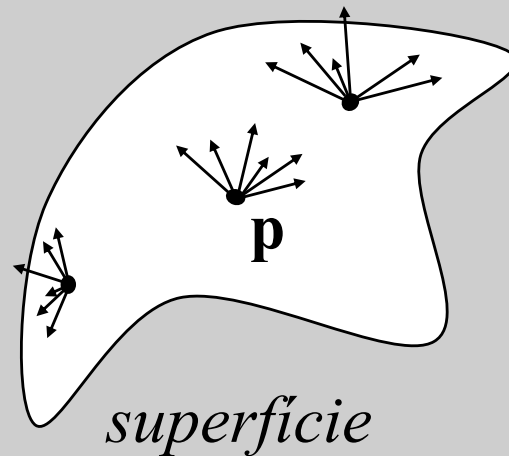
[J/s=Watts]

Energia da luz: Potência (fluxo) radiante

Φ Watts = Joule/seg

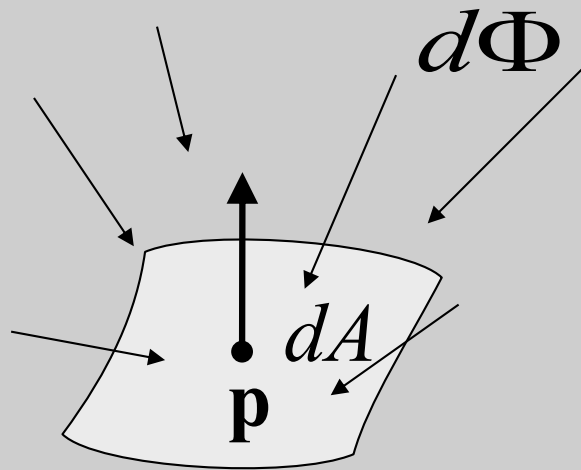
exemplos:

- lâmpadas: $\sim 100\text{ W}$
- Sol: $3.91 \times 10^{26}\text{ W}$



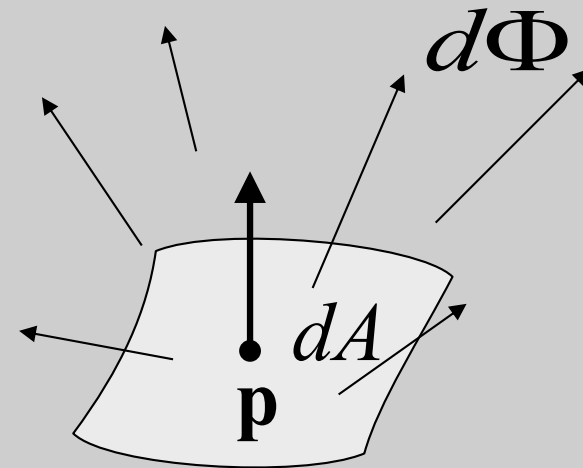
varia de ponto a ponto e depende da direção.

Energia da luz: Irradiação e Radiosidade



irradiação

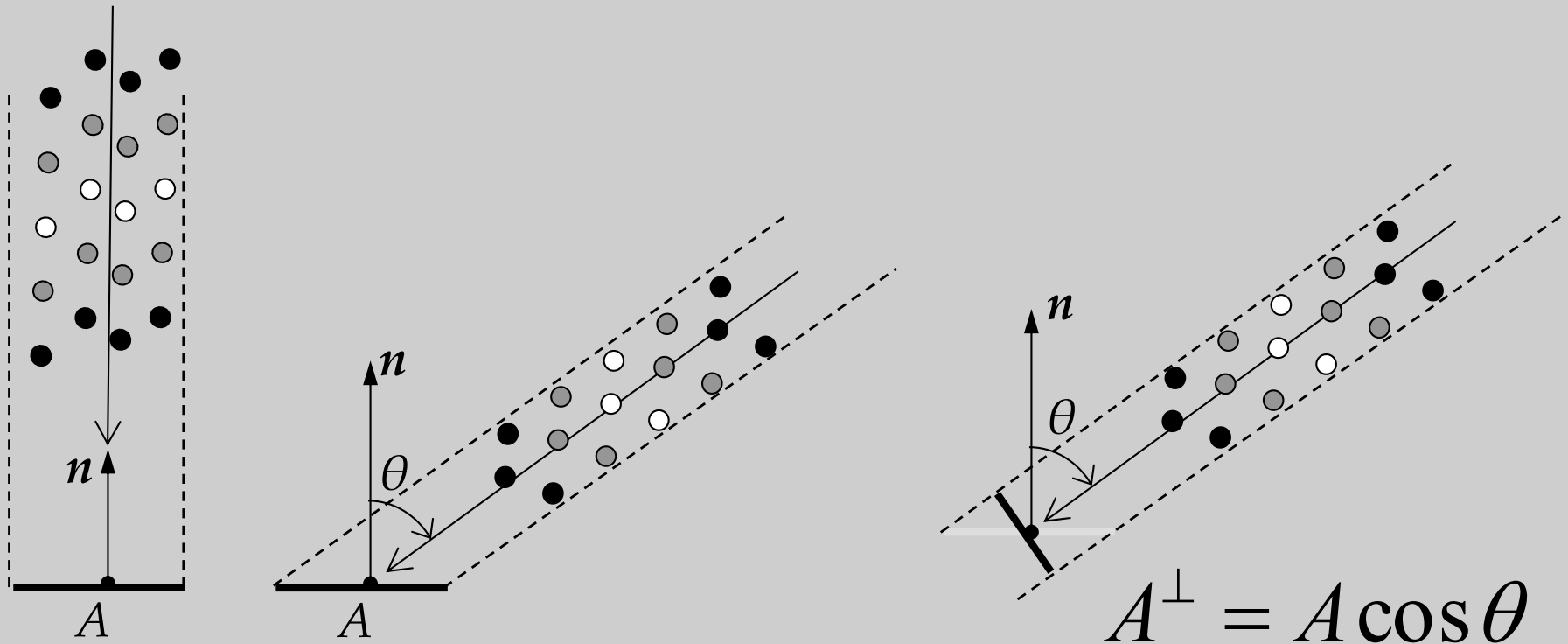
$$E(\mathbf{p}) = \frac{d\Phi}{dA} \left[\frac{W}{m^2} \right]$$



radiosidade

$$B(\mathbf{p}) = \frac{d\Phi}{dA} \left[\frac{W}{m^2} \right]$$

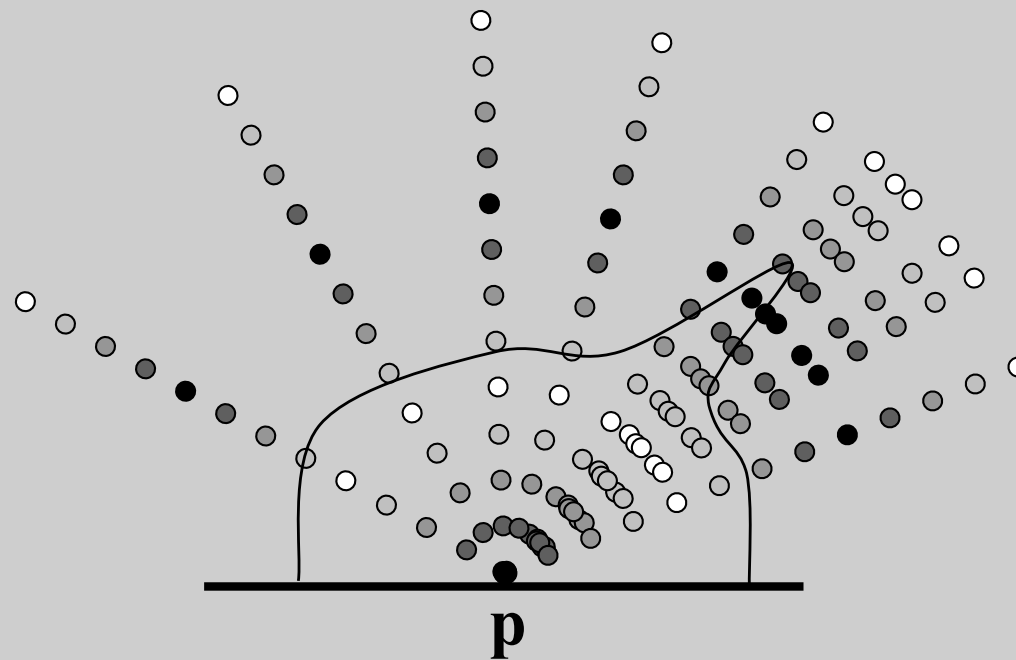
Área aparente (A^\perp)



Área aparente (foreshortening)

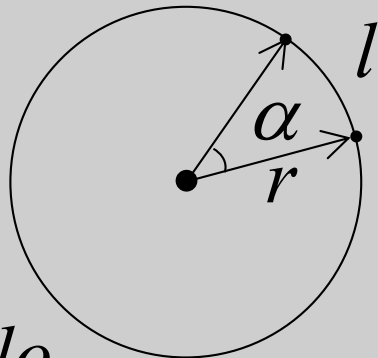
Uma área A vista de um ângulo θ é equivalente a uma área menor, $A \cos \theta$, tanto para emitir quanto para receber radiação luminosa.

Energia da luz: varia com a direção



Ângulo e Ângulo sólido

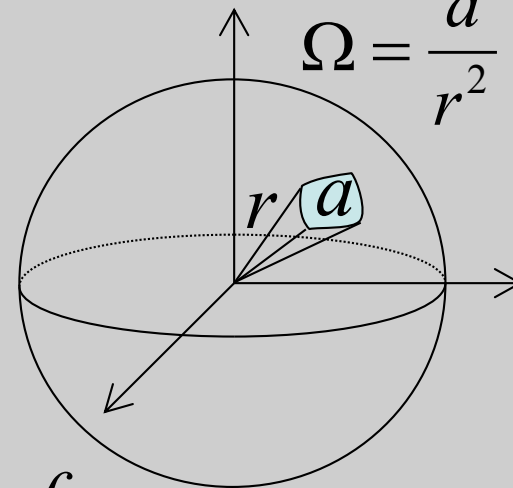
$$\alpha = \frac{l}{r} \quad [rad]$$



círculo

$$\alpha = 0 \dots 2\pi \quad rad$$

$$\Omega = \frac{a}{r^2} \quad [str]$$

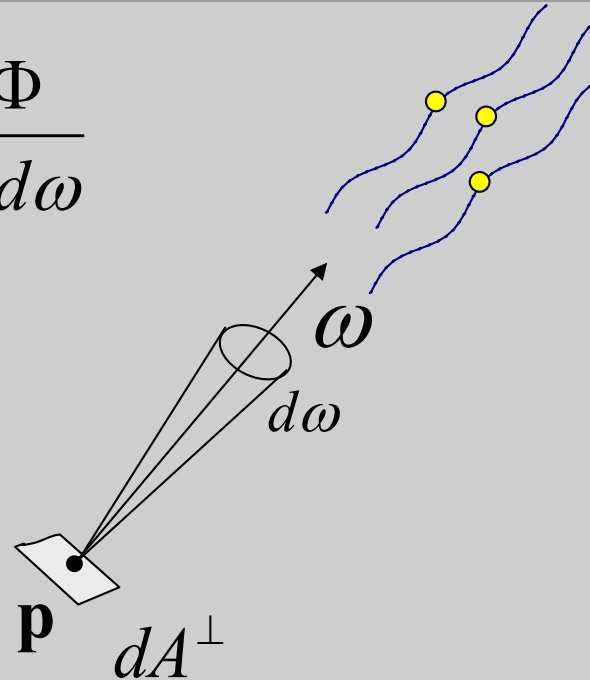


esfera

$$\Omega = 0 \dots 4\pi \quad str$$

Radiância

$$L = \frac{d^2\Phi}{dA^\perp d\omega}$$



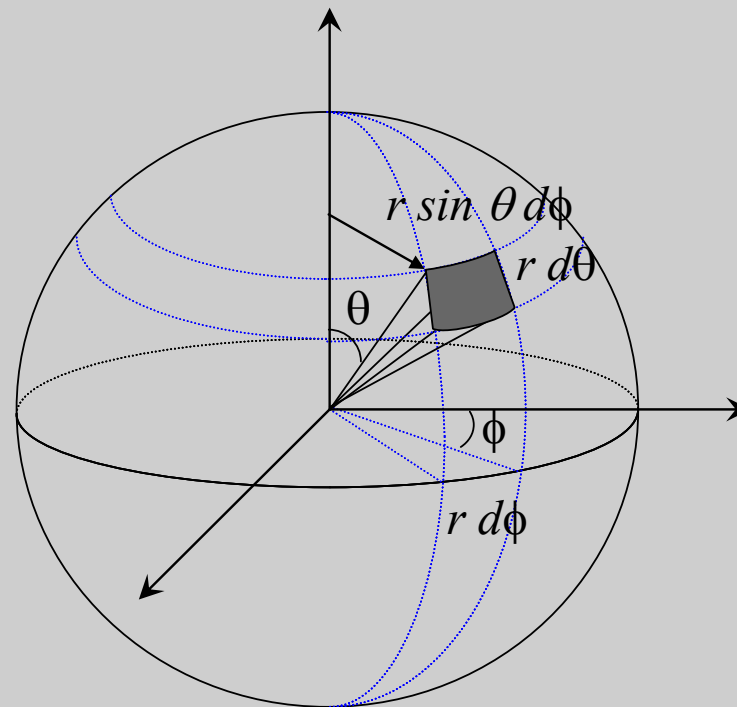
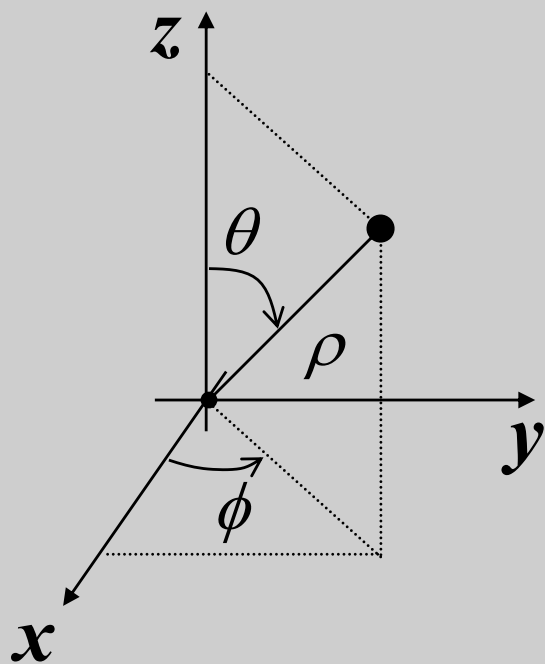
$$\left[\frac{W}{m^2 \cdot sr} \right]$$

$L(\mathbf{p} \leftarrow \omega)$ *recebida*

$L(\mathbf{p} \rightarrow \omega)$ *emitida*

Radiância – quantidade de fluxo radiado por área aparente e por ângulo sólido. A unidade radiométrica de radiação é “watts por metro quadrado por esferoradiano”.

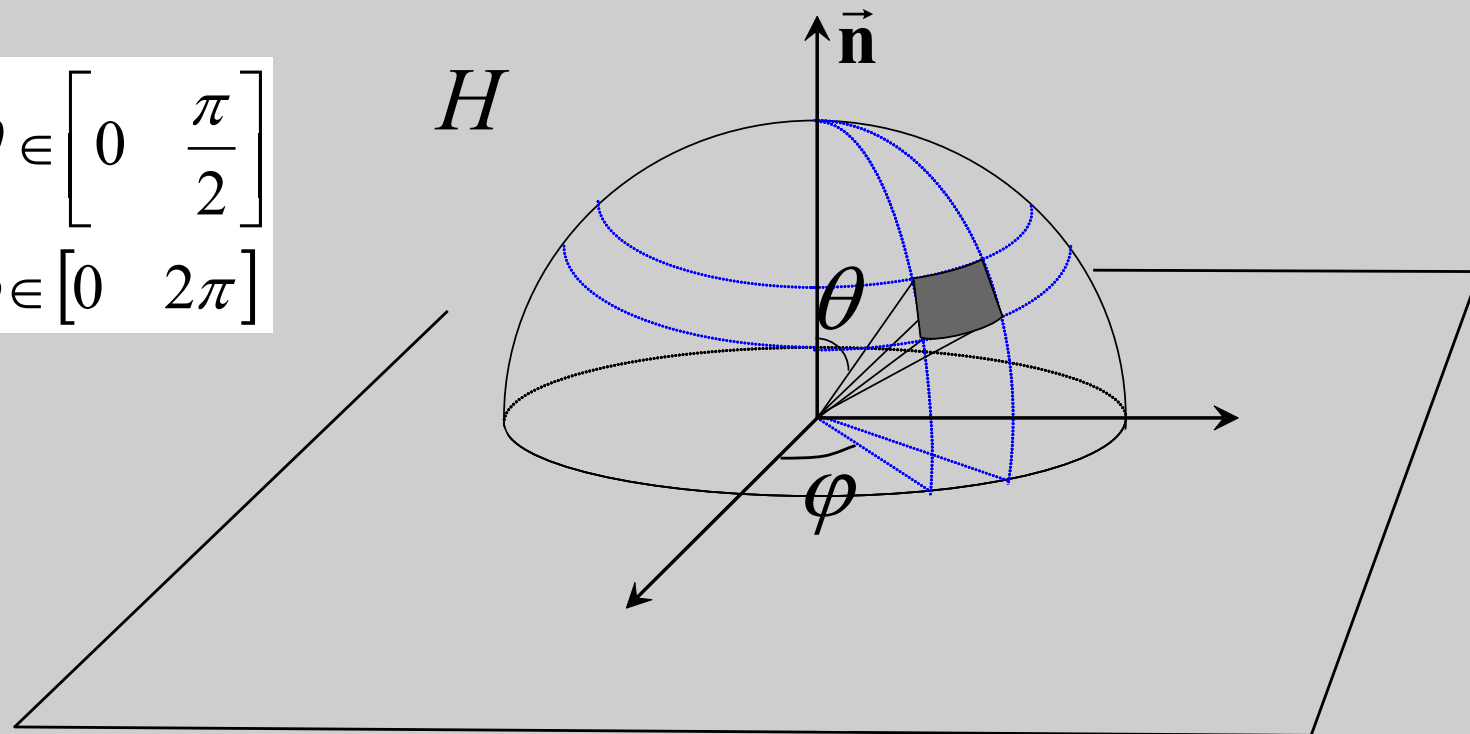
Ângulo sólido em coordenadas polares



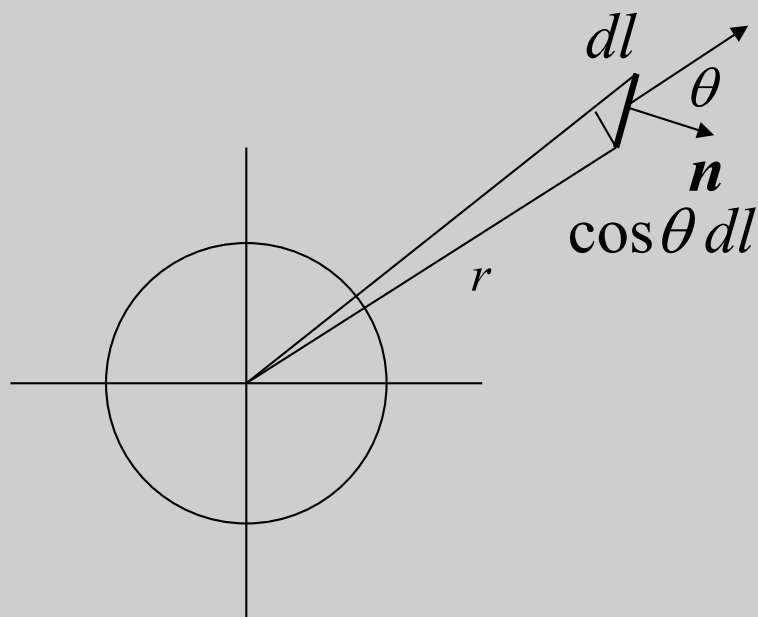
$$d\omega = \frac{dA^\perp}{r^2} = \frac{(\text{base})(\text{altura})}{r^2} = \frac{(r \sin \theta d\phi)(r d\theta)}{r^2} = \sin \theta d\phi d\theta$$

Calota esférica em torno de um ponto

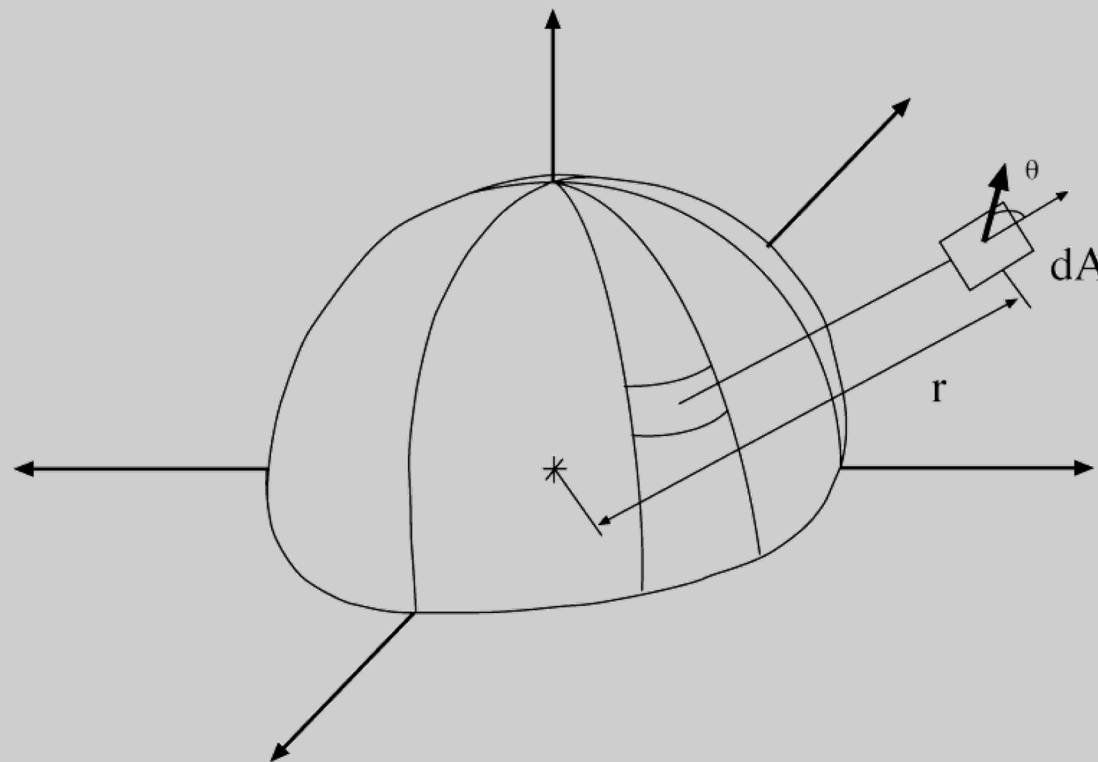
$$\theta \in \left[0 \quad \frac{\pi}{2} \right]$$
$$\phi \in \left[0 \quad 2\pi \right]$$



Ângulos de elementos infinitesimais



$$d\alpha = \frac{\cos \theta dl}{r} \quad (\text{rad})$$



$$d\Omega = \frac{dA \cos \theta}{r^2} \quad (\text{esfero radiano})$$

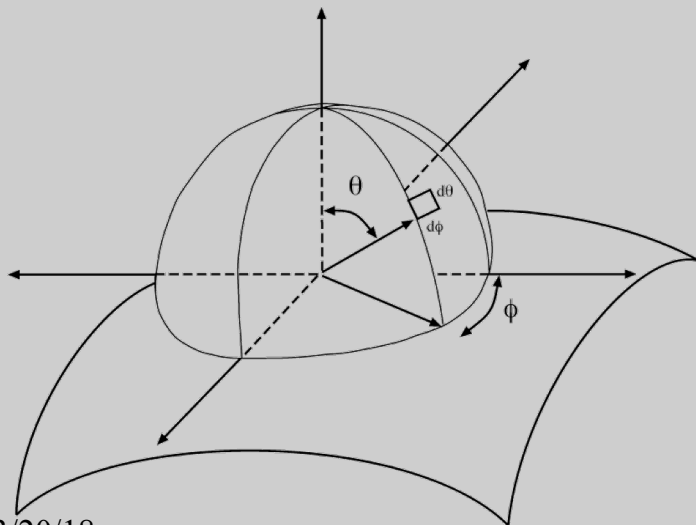
Fluxo luminoso \times Radiância

$$L = \frac{d^2\Phi}{dA^\perp d\omega}$$

$$L(\mathbf{p}, \theta, \phi) = \frac{d^2\Phi}{dA \cos\theta d\omega}$$

$$d^2\Phi = L(\mathbf{p}, \theta, \phi) \cos\theta dA d\omega$$

$$d^2\Phi = L(\mathbf{p}, \theta, \phi) \cos\theta \sin\theta dA d\theta d\phi$$

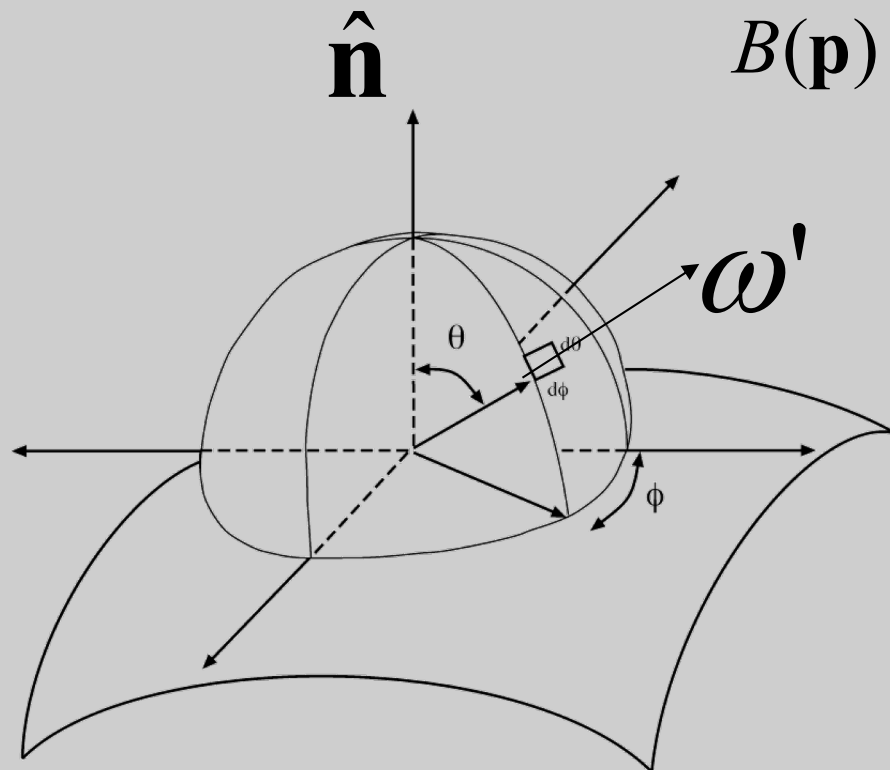


$$\Phi = \int_A \int_{H^2} L(\mathbf{p}, \theta, \phi) \cos\theta \sin\theta dA d\theta d\phi$$

Radiosidade × Radiância

$$B(\mathbf{p}) = \frac{d\Phi}{dA}$$

$$L(\mathbf{p}, \theta, \phi) = \frac{d\Phi}{dA \cos \theta d\omega}$$



$$B(\mathbf{p}) = \frac{d\Phi}{dA} = \int_{\Omega} L(\mathbf{p}, \theta, \phi) \cos \theta d\omega$$

$$= \int_0^{\pi/2} \int_0^{2\pi} L(\mathbf{p}, \theta, \phi) \cos \theta \sin \theta d\theta d\phi$$

$$B(\mathbf{p}) = \int_{\Omega} L(\mathbf{p}, \omega') (\hat{\mathbf{n}} \cdot \omega') d\Omega$$

Cor

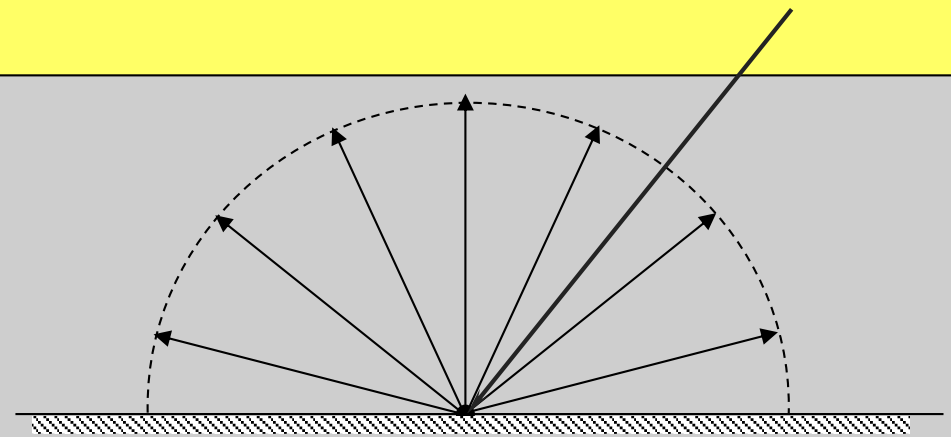
Radiosidade de refletores lambertianos

A reflexão é **lambertiana** quando espalha a luz incidente uniformemente em todas as direções

$$B(\mathbf{p}) = \int_0^{\pi/2} \int_0^{2\pi} L(\mathbf{p}, \phi, \theta) \cos \theta \sin \theta \, d\theta \, d\phi$$
$$= \int_0^{\pi/2} \int_0^{2\pi} L(\mathbf{p}) \cos \theta \sin \theta \, d\theta \, d\phi$$

$$= L(\mathbf{p}) \int_0^{\pi/2} \int_0^{2\pi} \cos \theta \sin \theta \, d\theta \, d\phi = L(\mathbf{p}) \int_0^{2\pi} d\phi \int_0^{\pi/2} \cos \theta \sin \theta \, d\theta$$

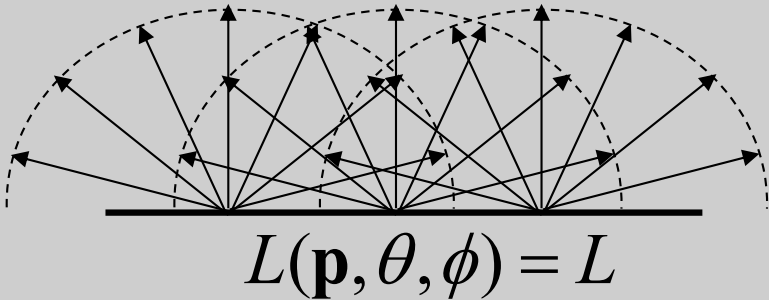
$$= L(\mathbf{p}) 2\pi \left[\frac{\sin^2 \theta}{2} \right]_0^{\pi/2} = \pi L(\mathbf{p})$$



$$L(\mathbf{p}) = \frac{B(\mathbf{p})}{\pi}$$

Cor

Fluxo Radiante de um Emissor Difuso Uniforme



$$L(\mathbf{p}, \theta, \phi) = \frac{d\Phi}{dA \cos \theta d\omega} = L$$

$$d\Phi = L dA \cos \theta d\omega$$

$$\Phi = \int_A \int_{\Omega} L dA \cos \theta d\omega$$

$$\Phi = L \int_A dA \int_{\Omega} \cos \theta d\omega = LA \int_0^{2\pi} \int_0^{\pi/2} \cos \theta \sin \theta d\theta d\phi$$

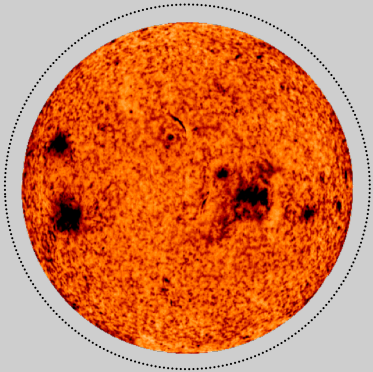
$$\Phi = LA \int_0^{2\pi} d\phi \int_0^{\pi/2} \sin \theta \cos \theta d\theta = \pi AL$$

$$\Phi = \pi L A = BA$$

Cor

$$L = \frac{\Phi}{\pi_{18} A}$$

Radiância do sol



$$R_{sol} = 6.95 \times 10^8 m$$

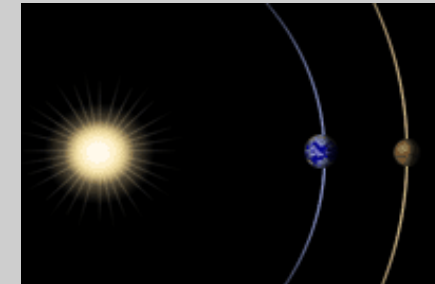
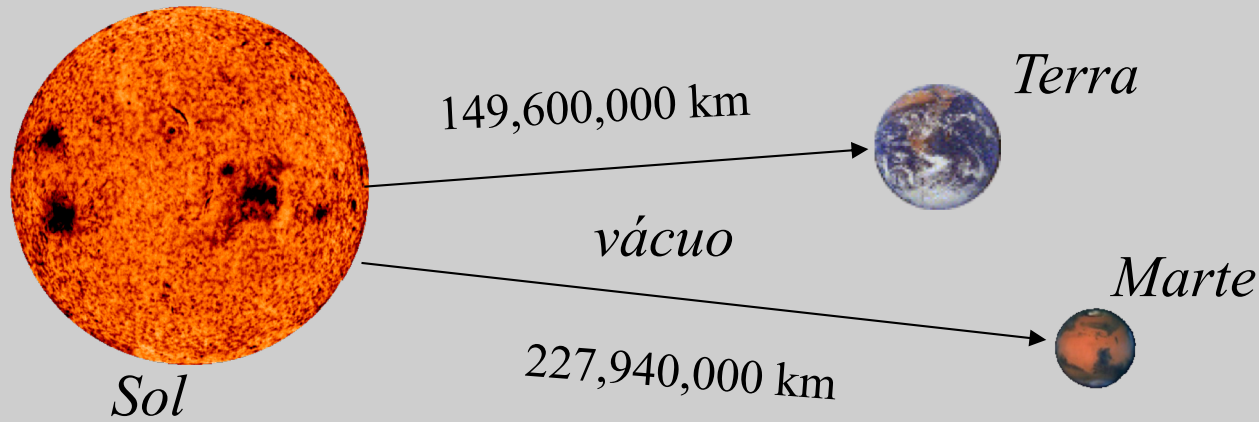
$$\Phi = 3.91 \times 10^{26} Watt$$

$$A = 4\pi R^2 = 4\pi (6.95 \times 10^8)^2 = 6.07 \times 10^{18} m^2$$

supondo uniforme

$$L(sol) = \frac{\Phi}{A\pi} = \frac{3.91 \times 10^{26} Watt}{(6.07 \times 10^{18} m^2)(\pi str)} = 2.05 \times 10^7 W / str \cdot m^2$$

Irradiação do Sol na Terra e em Marte

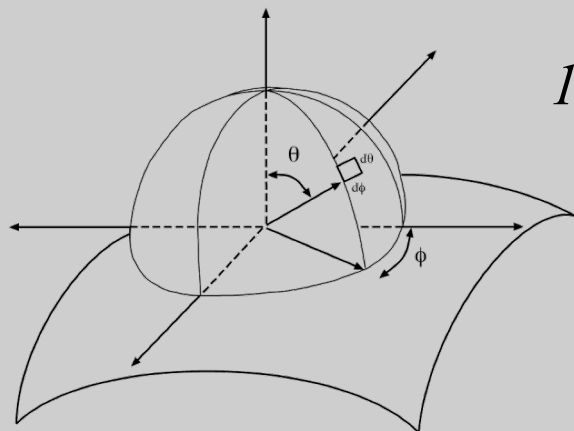


$$E(\mathbf{p}) = \int_{\Omega} L(\mathbf{p}, \omega') (\hat{\mathbf{n}} \cdot \omega') d\Omega$$

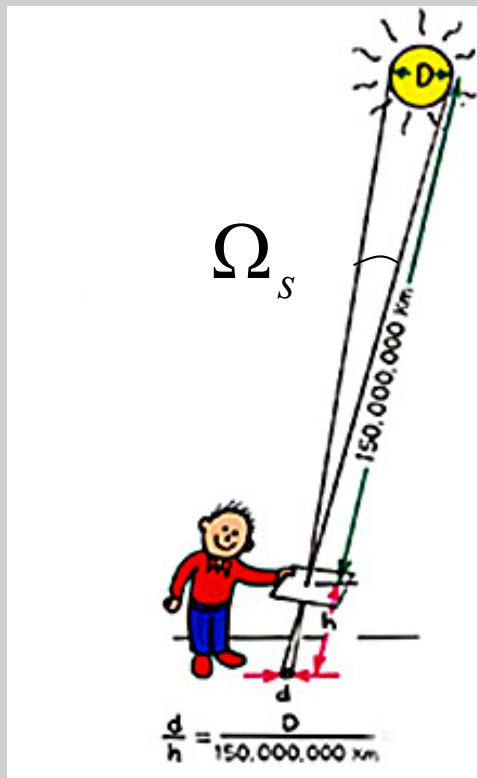
12:00 h $\Rightarrow \hat{\mathbf{n}} \cdot \omega' \approx 1$

$$E(\mathbf{p}) = L_{sol} \int_{\Omega} d\Omega = L_{sol} \Omega_s$$

Cor



Ângulos sólidos do Sol na Terra em Marte



$$\Omega = \frac{A_{\text{disco solar}} \cos \theta}{d^2} \cong \frac{2\pi r^2}{d^2}$$

$$\Omega_{\rightarrow \text{Terra}} = \frac{2\pi r^2}{d^2} = \frac{2\pi (6.95 \times 10^8)^2}{(1.5 \times 10^{11})^2} = 1.35 \times 10^{-8} \text{ srd}$$

$$\Omega_{\rightarrow \text{Marte}} = \frac{2\pi r^2}{d^2} = \frac{2\pi (6.95 \times 10^8)^2}{(2.28 \times 10^{11})^2} = 0.584 \times 10^{-8} \text{ srd}$$

$$E(\mathbf{p}_{\text{Terra}}) \approx 2.3 E(\mathbf{p}_{\text{Marte}})$$

Quem é I em CG?

Fluxo, Radiosidade [Irradiação] ou Radiância?

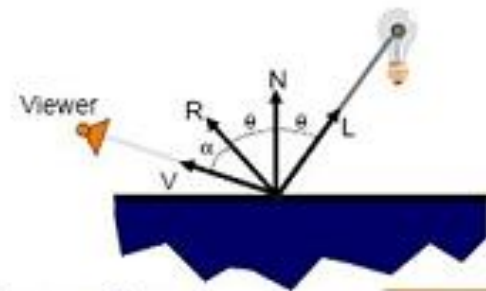
- Term by Term

- Ambient + Emission

- Phong + Shadow

- Specular reflection

- Transmission + Refraction



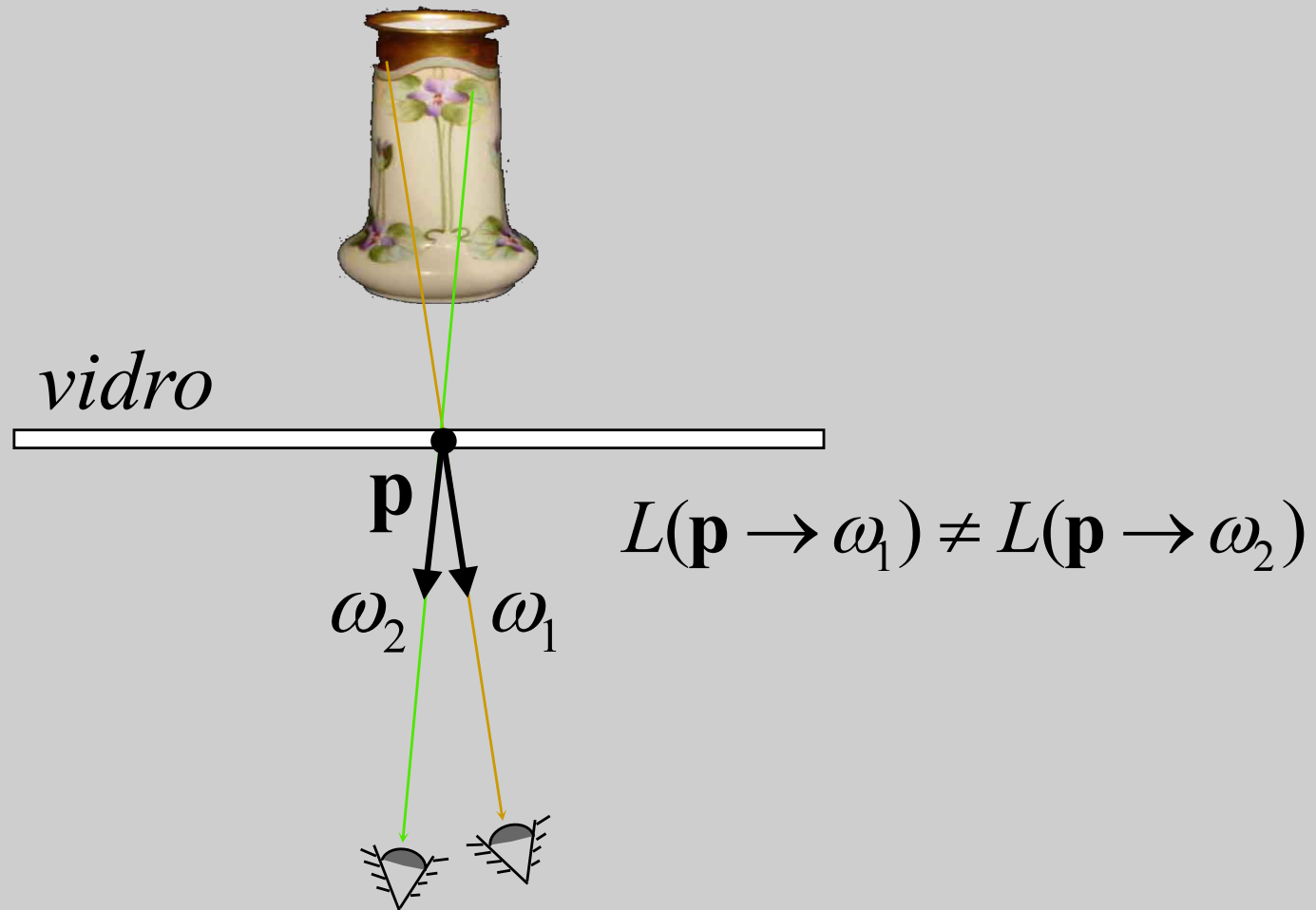
Primary Rays

Secondary Rays

$$I = I_E + K_A I_{AL} + \sum_L (K_D (N \cdot L) + K_S (V \cdot R)^n) S_L I_L + K_S I_R + K_T I_T$$

Picture courtesy of Xiaobai Chen

O que os olhos veem?

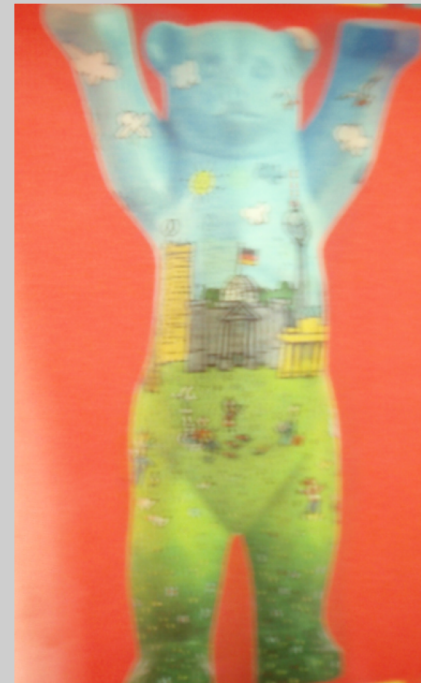


Olhos são sensíveis a radiância de pontos da cena

Cor

23

Fluxo radiante em uma superfície em função da direção

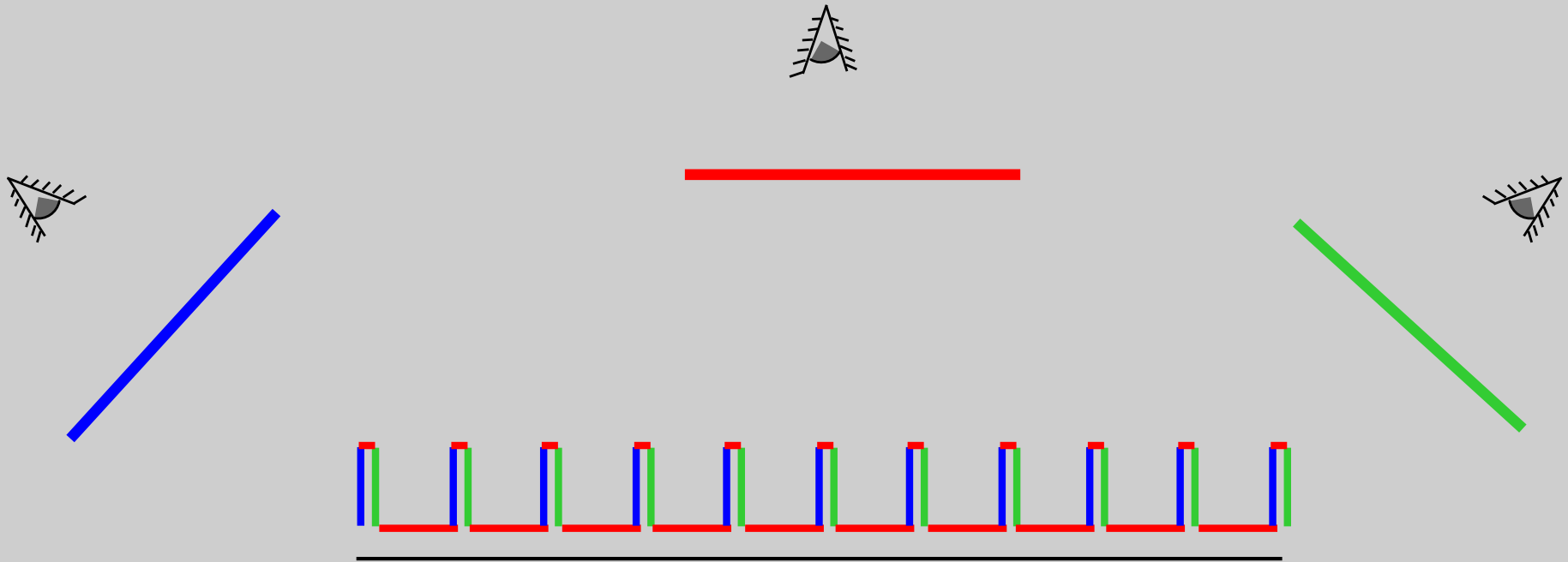


Olhos são sensíveis a radiância de pontos da cena

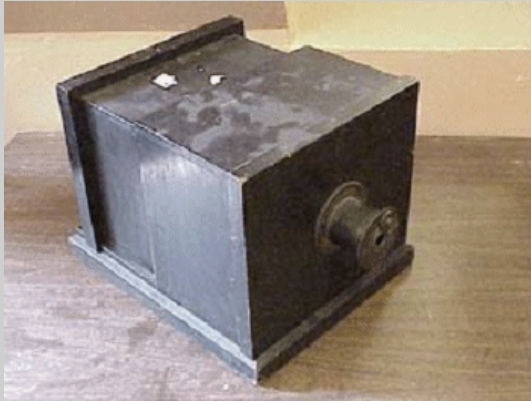
Cor

24

Uma técnica simples para gerar diferentes radiâncias



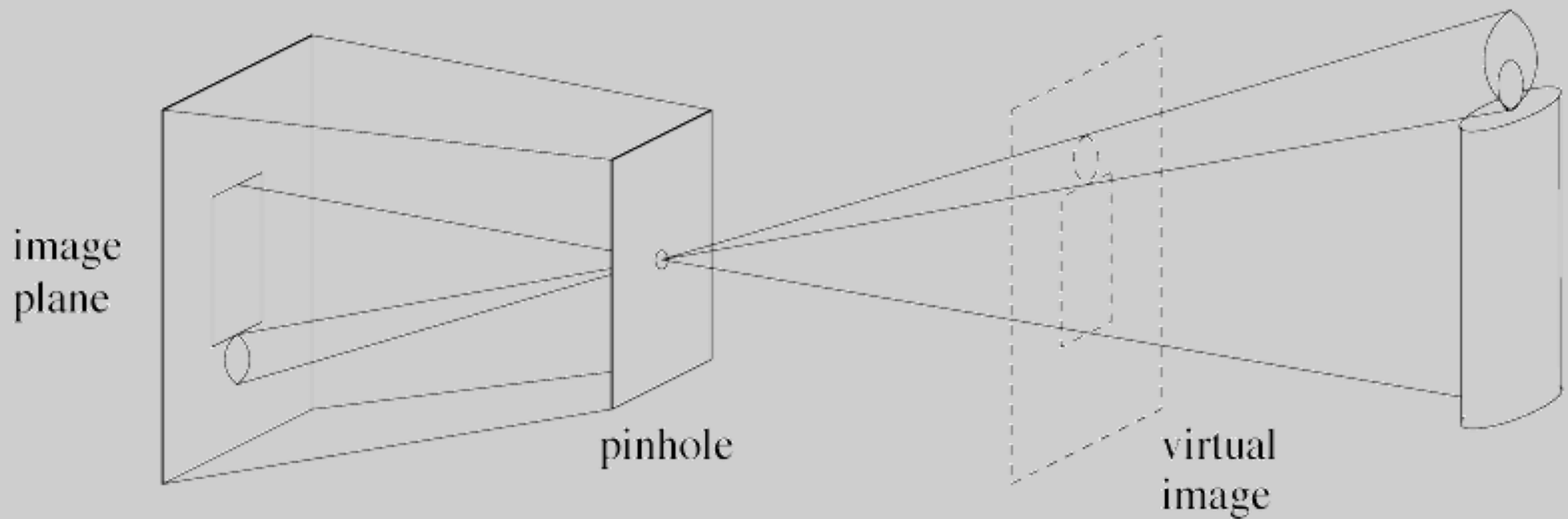
Câmaras fotográficas primitivas



Luis-Jacques-Mandé Daguerre (1839)
Cor

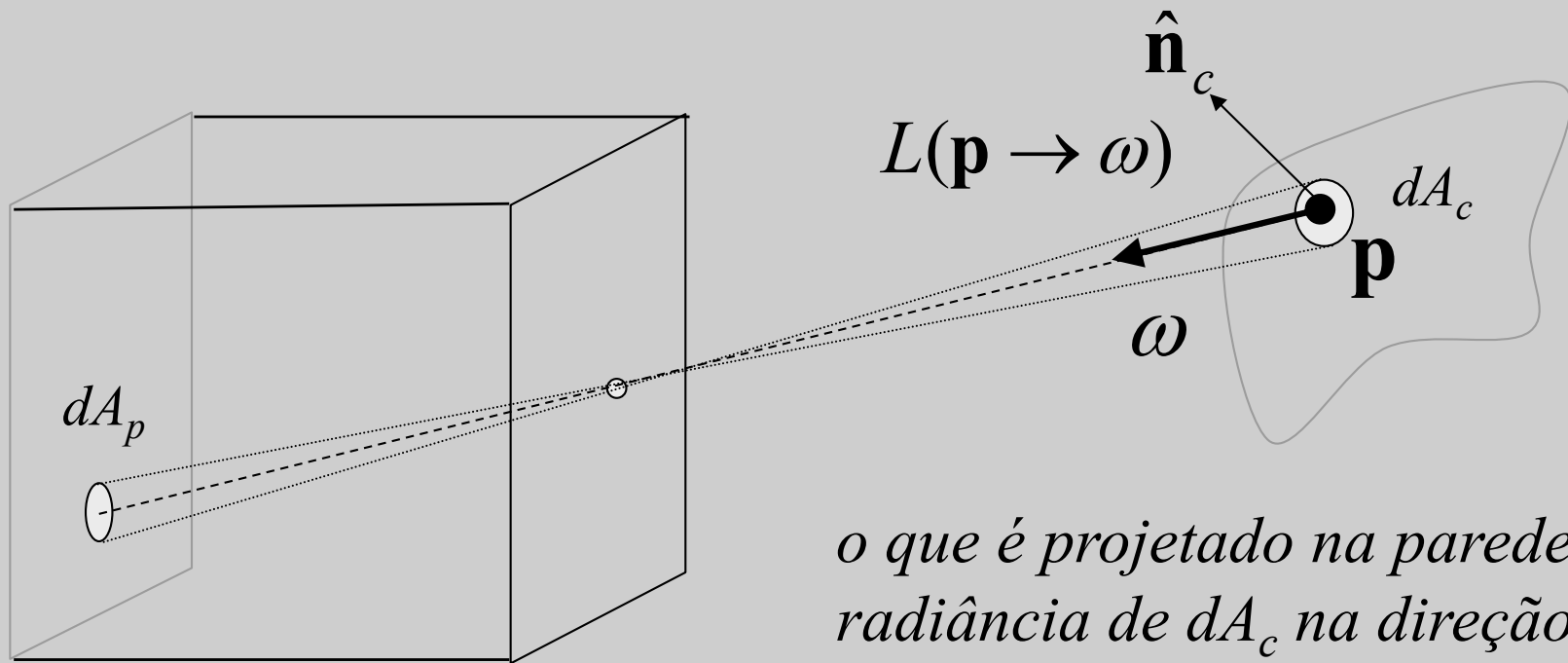
Câmeras de furo (*pinhole*)
26

Geometria da câmera de furo (*pinhole*)



Projeção cônica

O que mede a câmera?

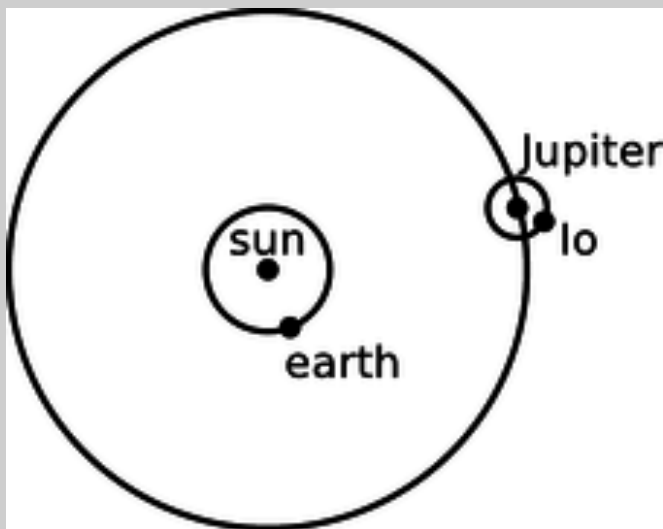


o que é projetado na parede é a radiância de dA_c na direção do furo

Câmeras de furo são sensíveis a radiância de pontos da cena

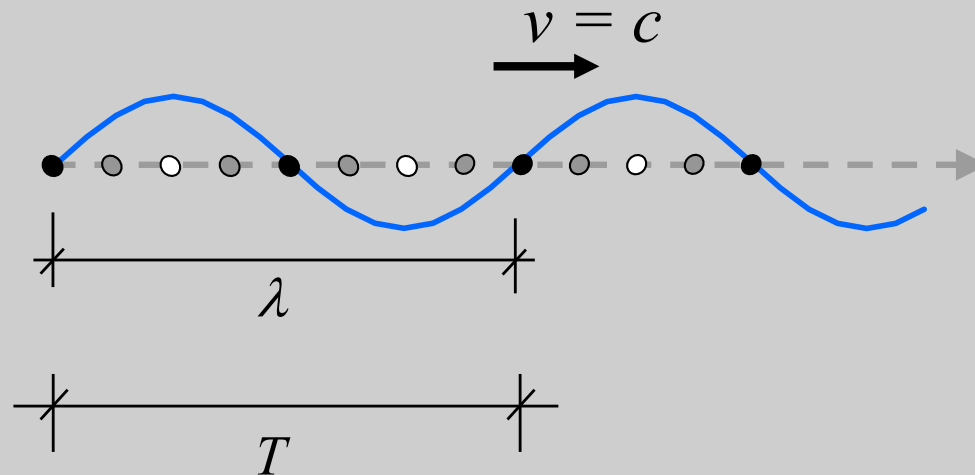
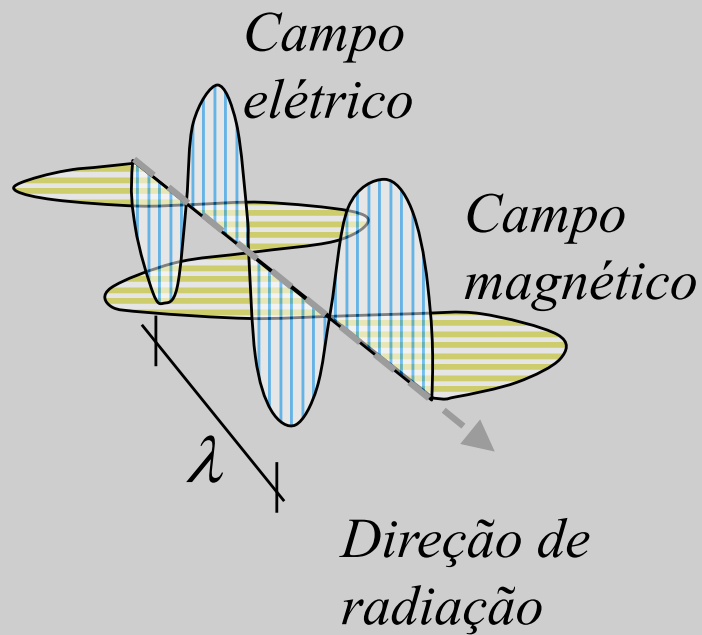
PROPAGAÇÃO DA LUZ

Reflexão, Refração e Difração



Natureza ondulatória

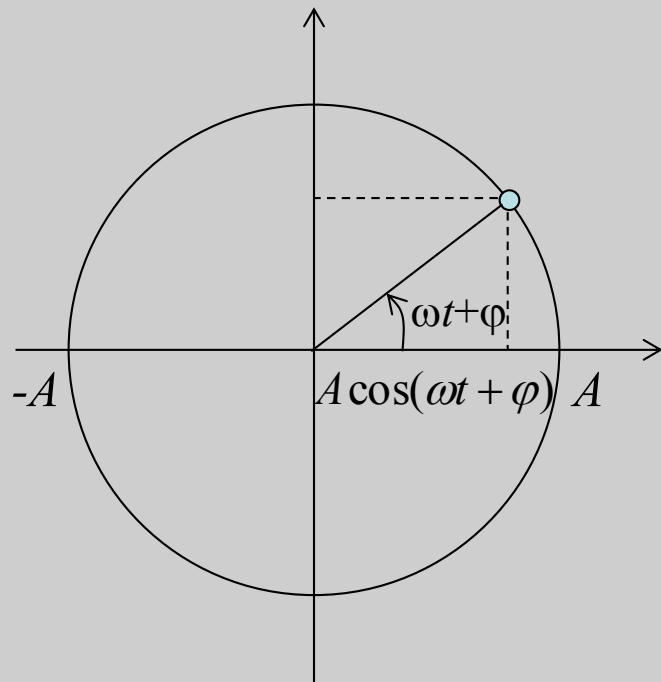
c = velocidade da luz = 2.997925×10^8 m/s \cong 300.000 km/s



$$v = \frac{\text{distância}}{\text{tempo}} = \frac{\lambda}{T}$$

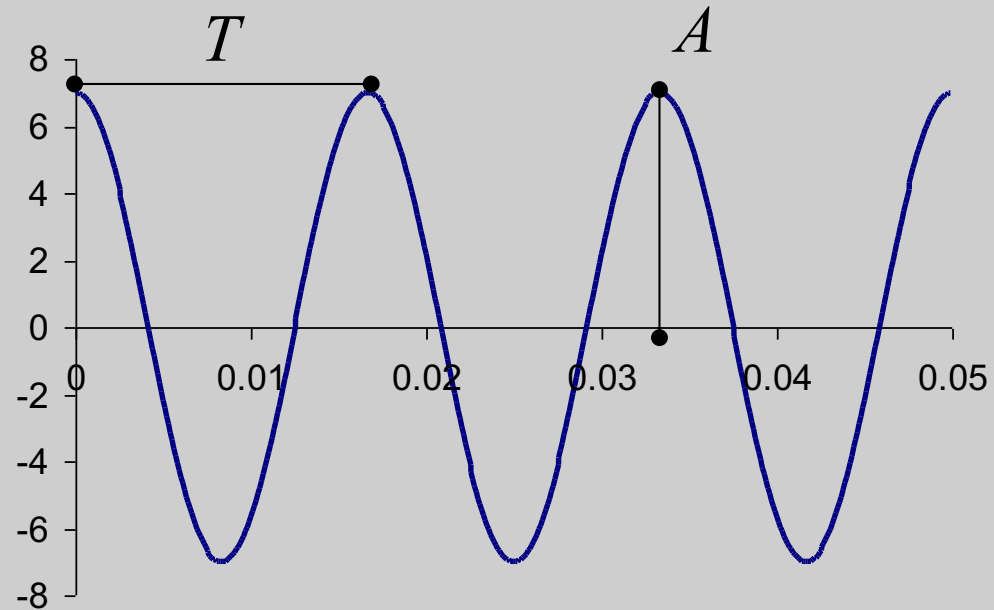
Oscilador Harmônico

revisão



frequência

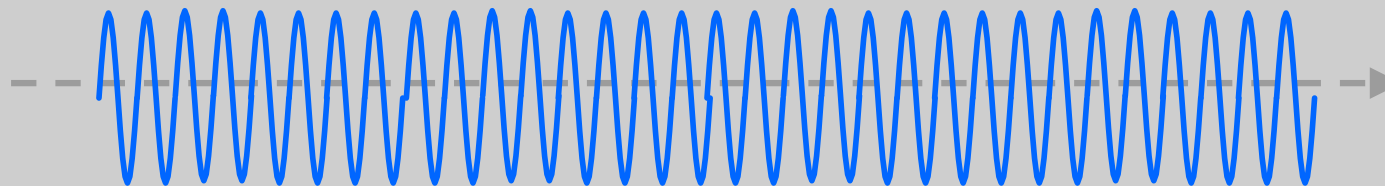
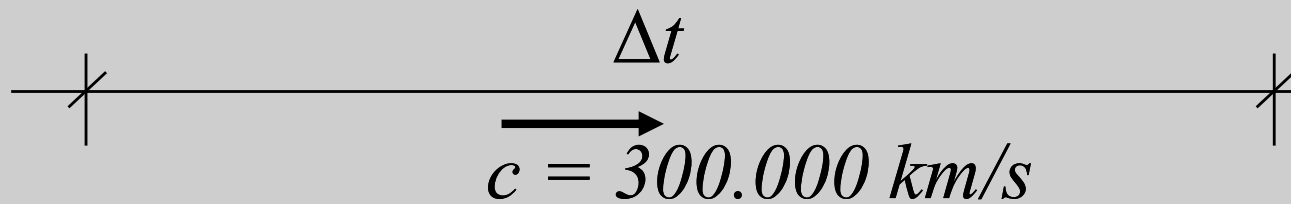
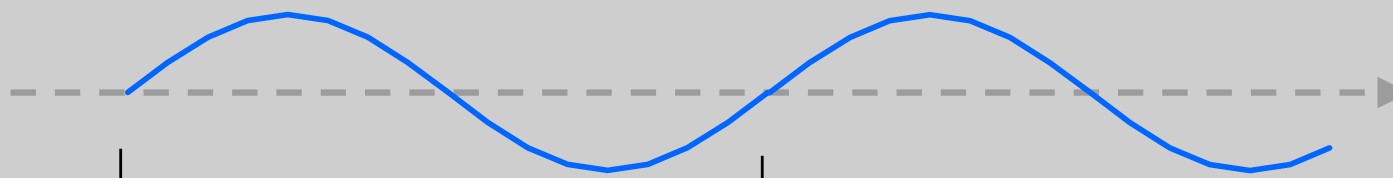
$$f = \frac{1}{T} \text{ (Hz)}$$



velocidade angular

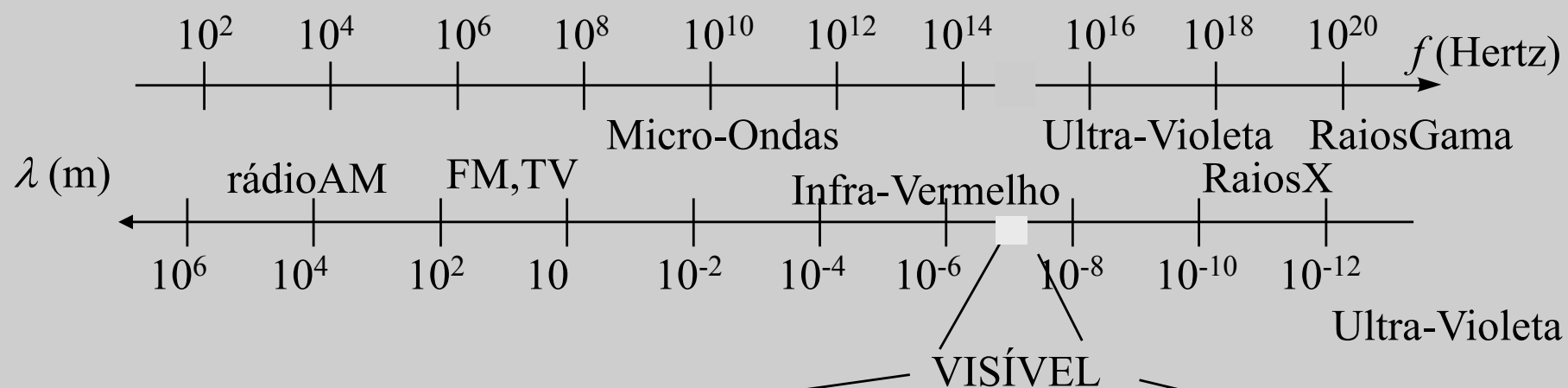
$$\omega t = 2\pi f t = \frac{2\pi}{T} t \text{ (rad)}$$

Ondas de comprimentos diferentes



$$c = \lambda f$$

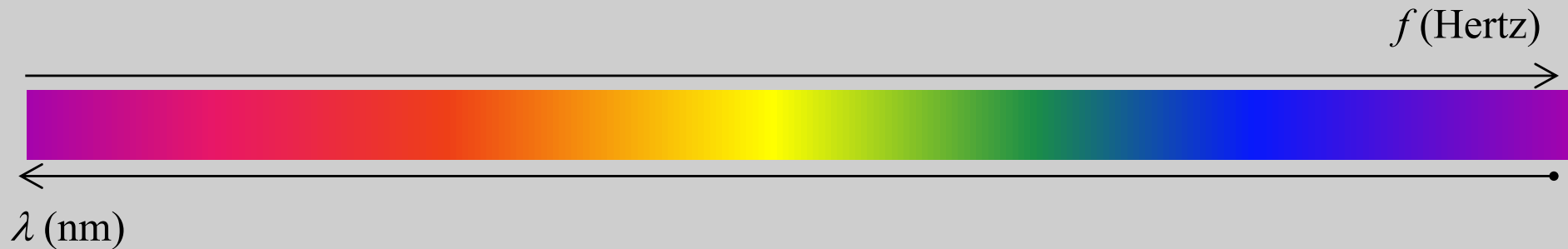
Ondas eletromagnéticas na natureza



vermelho (4.3×10^{14} Hz), laranja, amarelo,..., verde, azul, violeta (7.5×10^{14} Hz)



Luzes mono freqüência [mono λ]



$$c = \frac{\lambda}{T} = \lambda f \quad \lambda = \frac{c}{f} = \frac{3 \times 10^8 \frac{m}{s}}{f \text{ Hz}} = \frac{3 \times 10^{17} \frac{nm}{s}}{f \text{ Hz}} = 3 \times 10^{17} \frac{1}{f} \text{ nm}$$

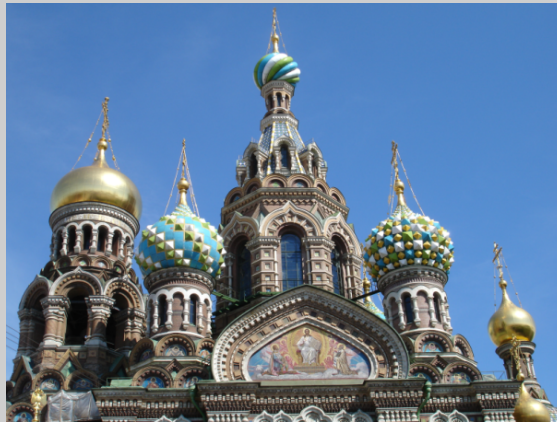
λ	Cor
380 - 440 nm	Violeta
440 - 490 nm	Azul
490 - 565 nm	Verde
565 - 590 nm	Amarelo
590 - 630 nm	Laranja
630 - 780 nm	Vermelho

A vertical color spectrum bar is shown to the right of the table, with a downward-pointing arrow on its left side. The bar transitions through colors from violet at the top to red at the bottom.

$$1 \text{ nm} = 10^{-9} \text{ m}$$

A luz nas cenas reais

*Objetos
manufaturados*



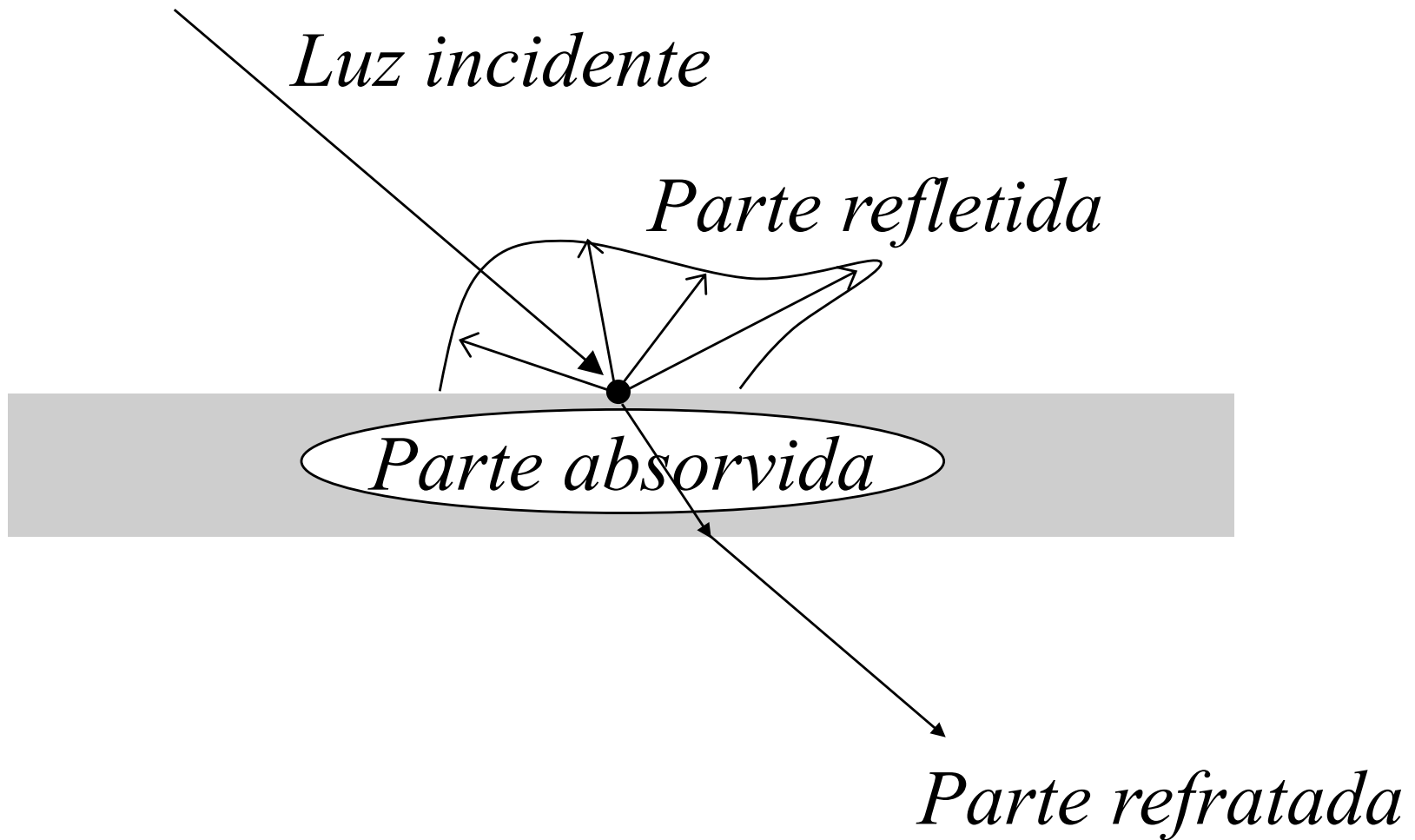
*Objetos
naturais*

*Reflexão
especular*

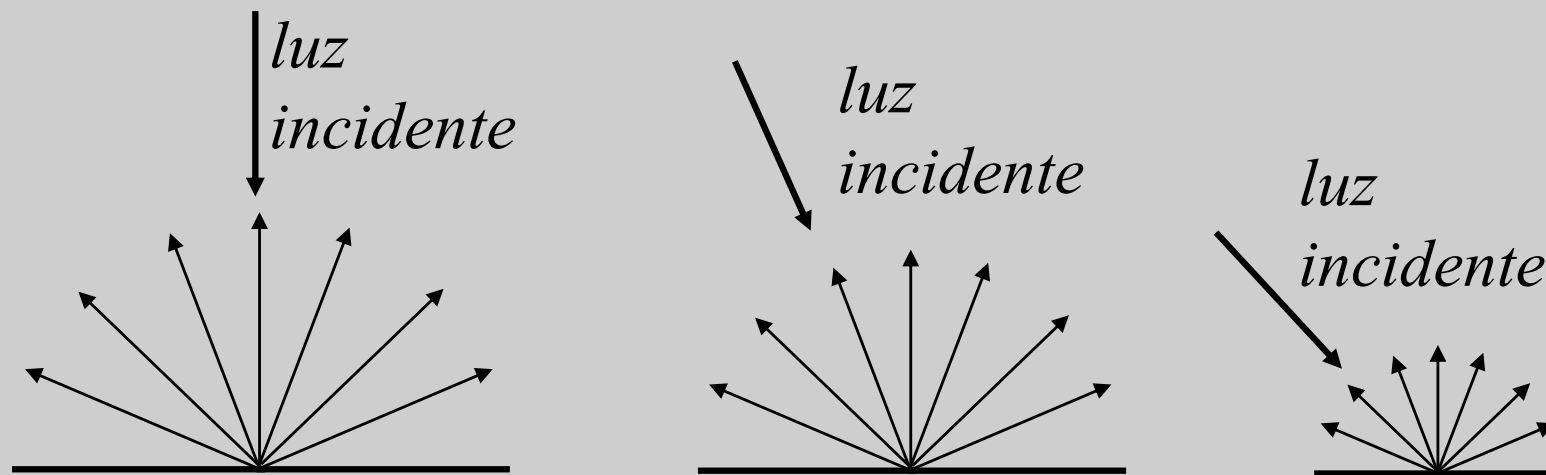


Refração

Luz ao atingir uma superfície

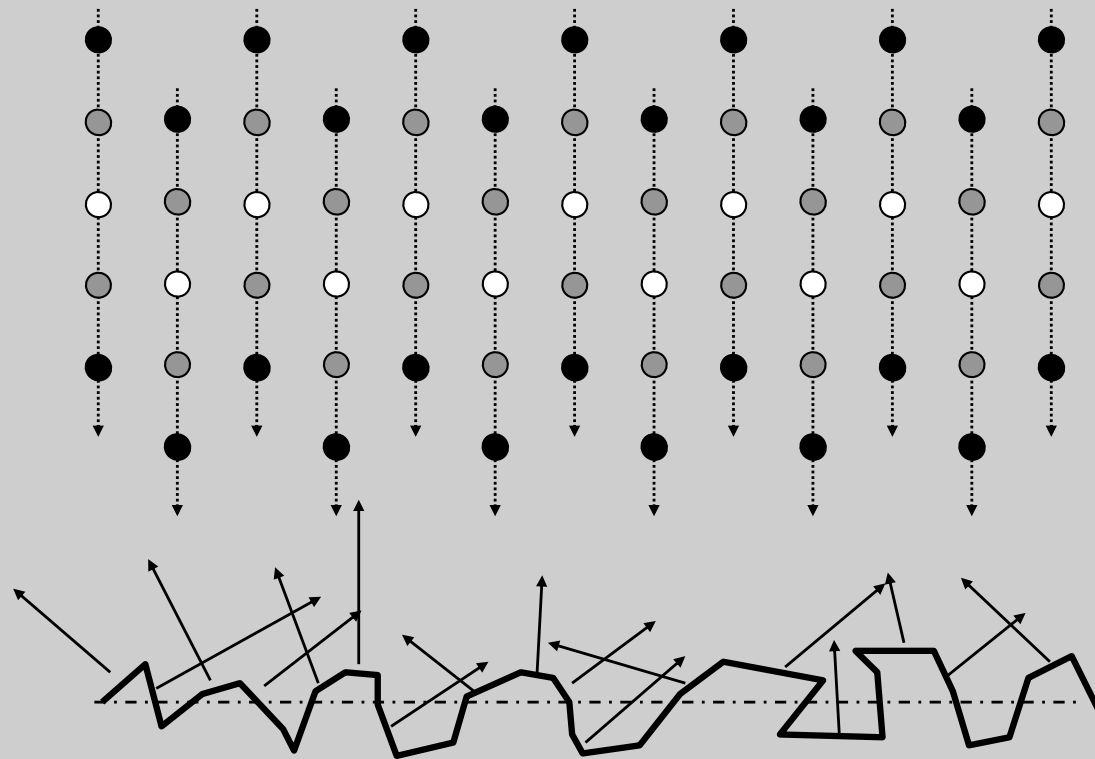


O modelo de mais simples de reflexão - superfícies Lambertianas



1. *Reflete igualmente em todas as direções*
2. *A intensidade é proporcional ao co-seno [área aparente]*

Razão do espalhamento



Cor

Princípio de Fermat

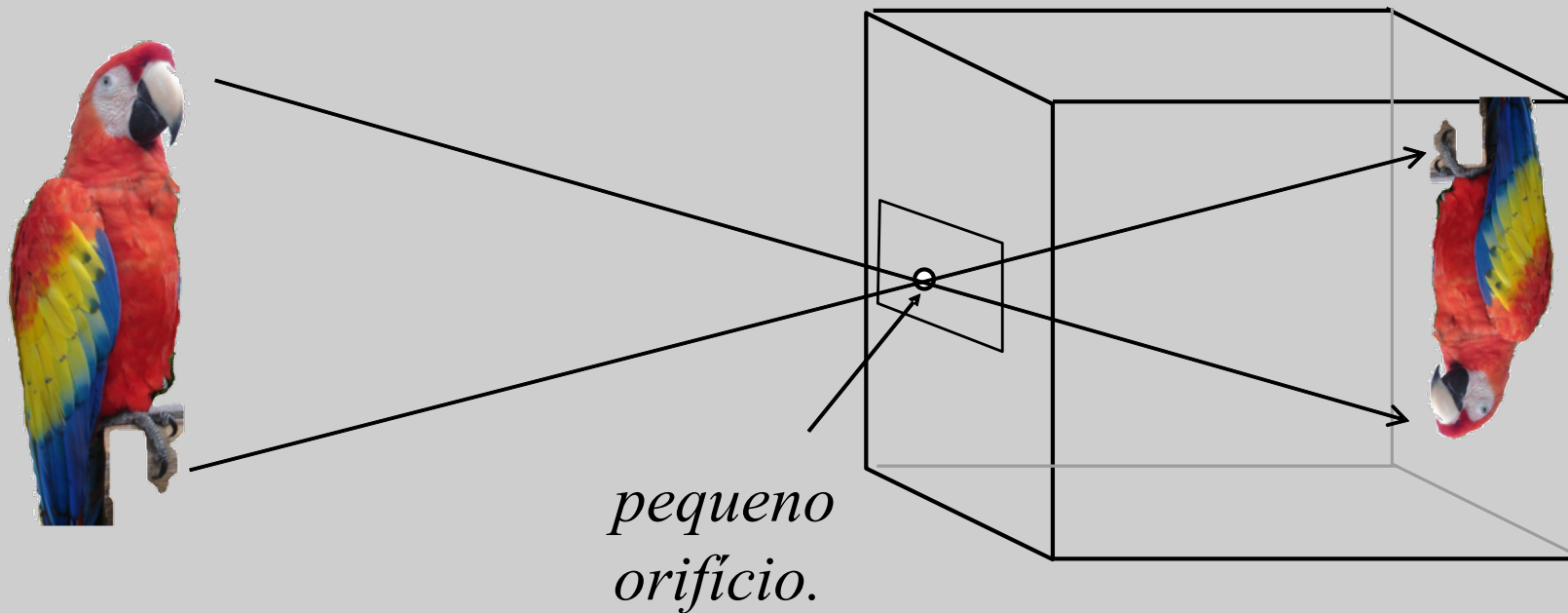


Pierre de Fermat
☆1601 †1665



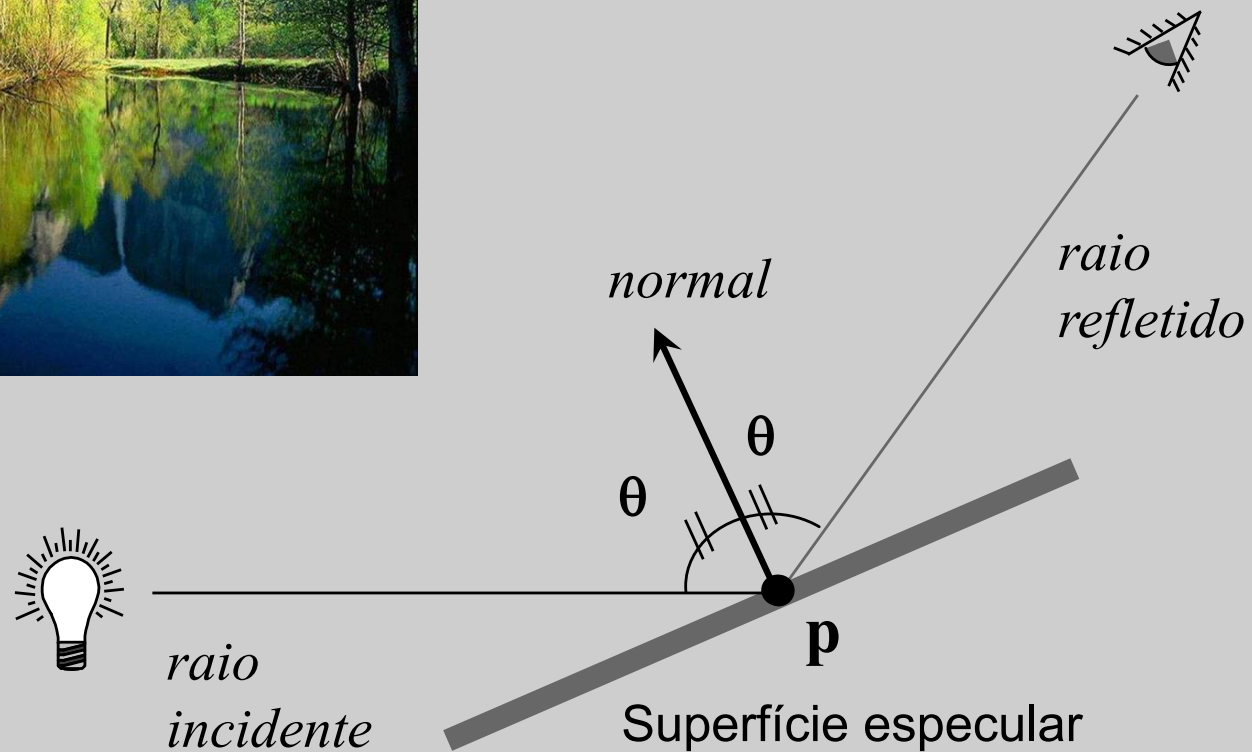
“A trajetória da luz de um ponto a outro segue o caminho de menor tempo.”

Propriedades básicas da luz



A luz viaja em linha reta.

Reflexão especular

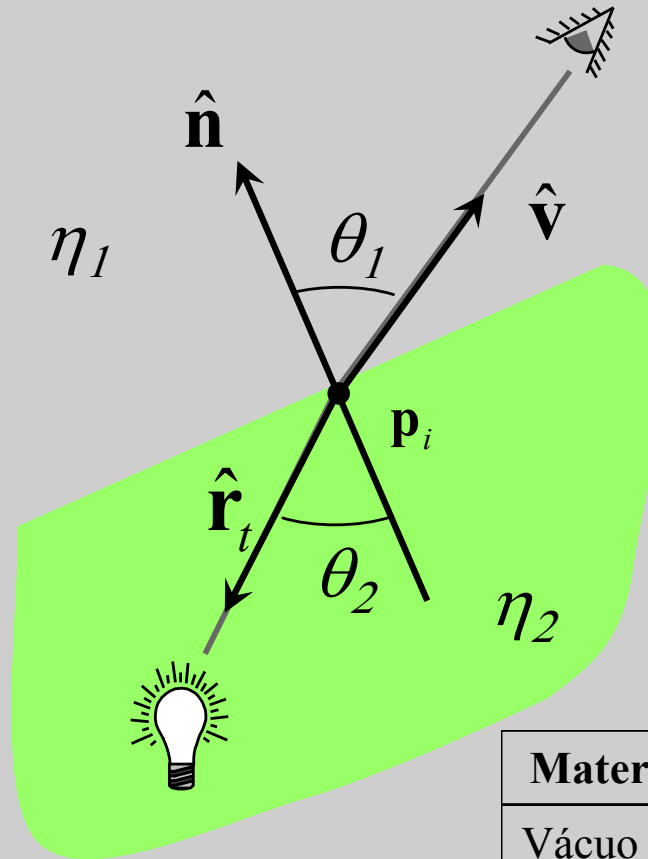


Refração



Cor

Refração



lei de Snell

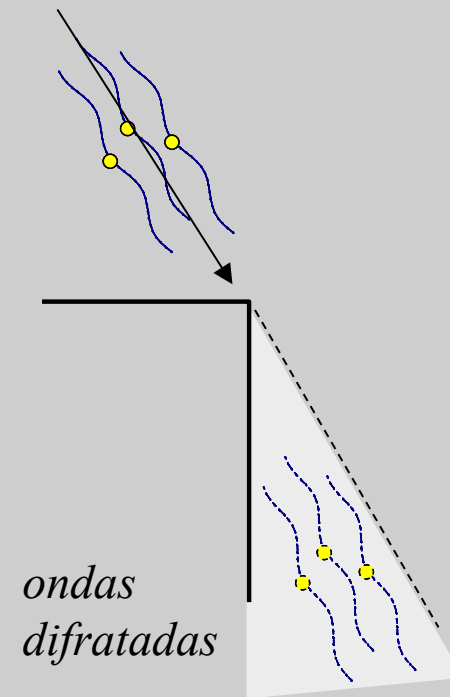
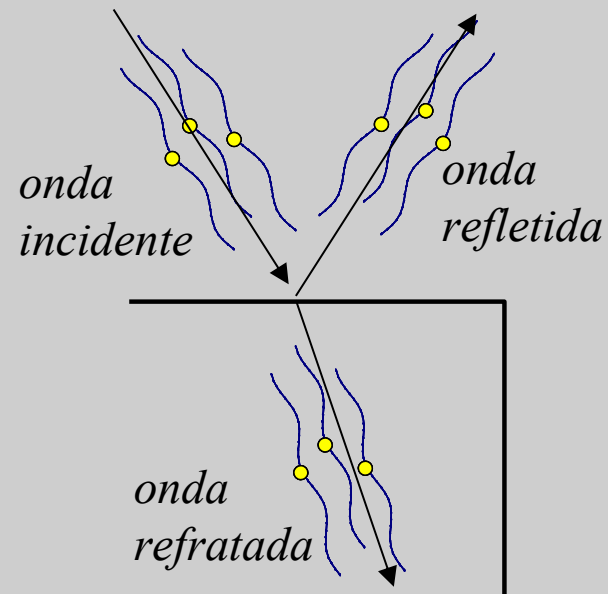
$$\frac{\eta_1}{\eta_2} = \frac{\sin \theta_2}{\sin \theta_1}$$

$$\eta_i = \frac{c}{v_i}$$

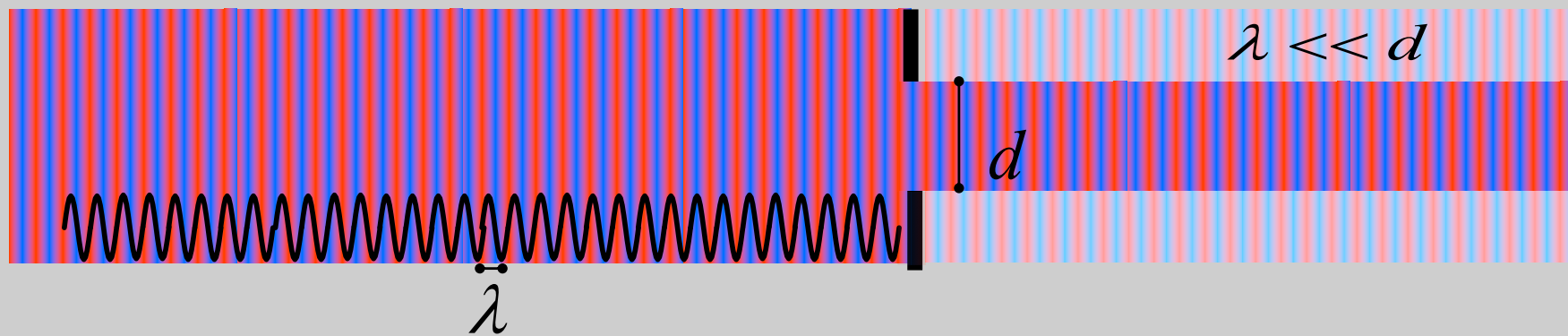
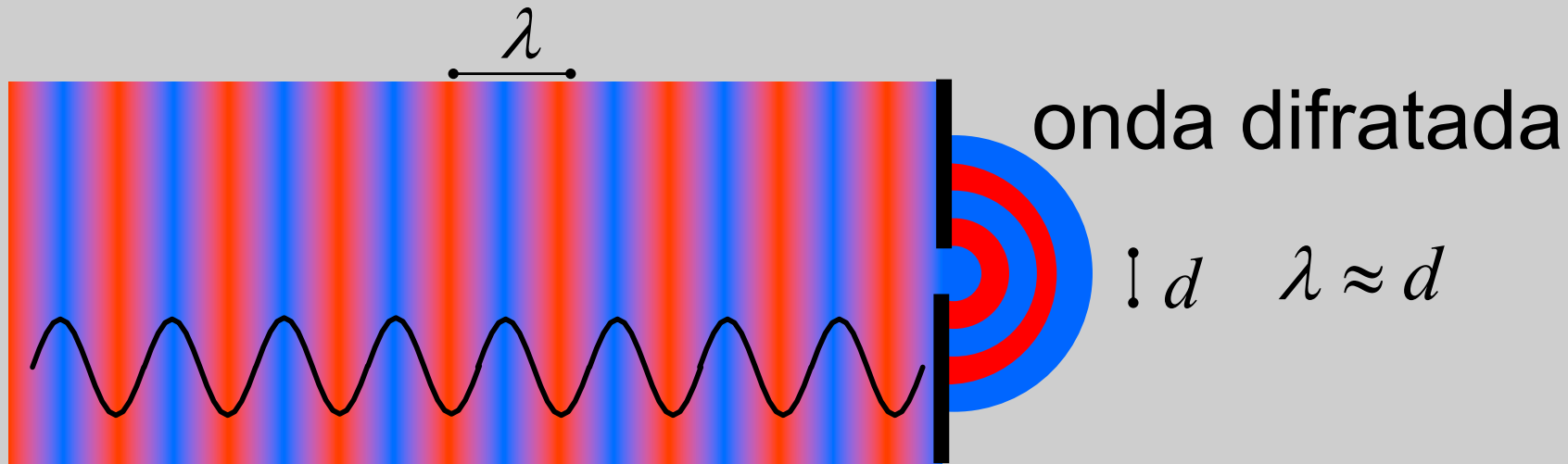
Material	η
Vácuo	1.0
Água	4/3
Vidros	1.5 a 1.75
Ar	1.000277 ⁴³

Cor

Refração, Reflexão e Difração



Difração de ondas



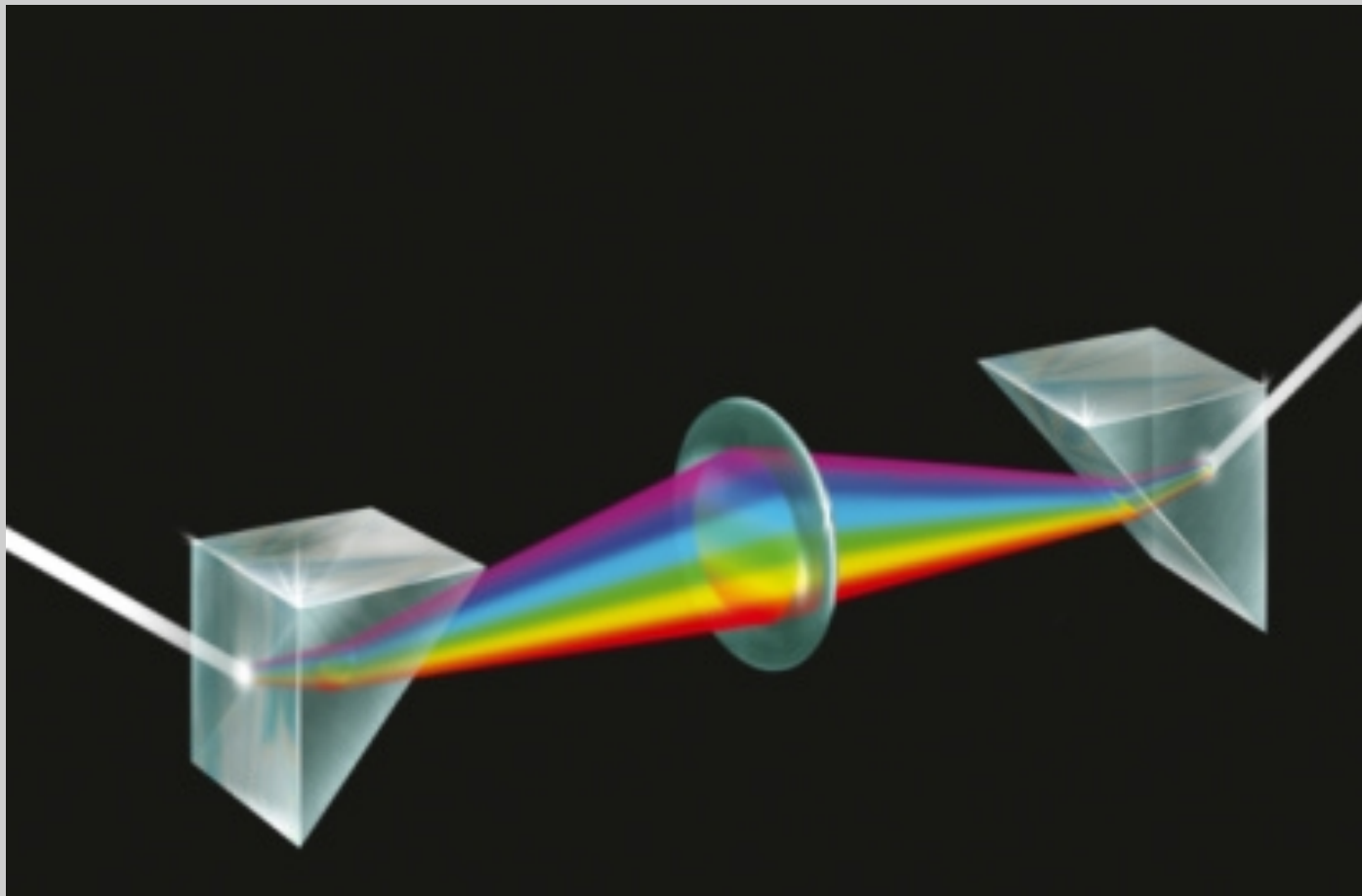
*Em CG raramente ocorre*⁴⁵ 😊

Difração da luz



é um fenômeno pouco frequente

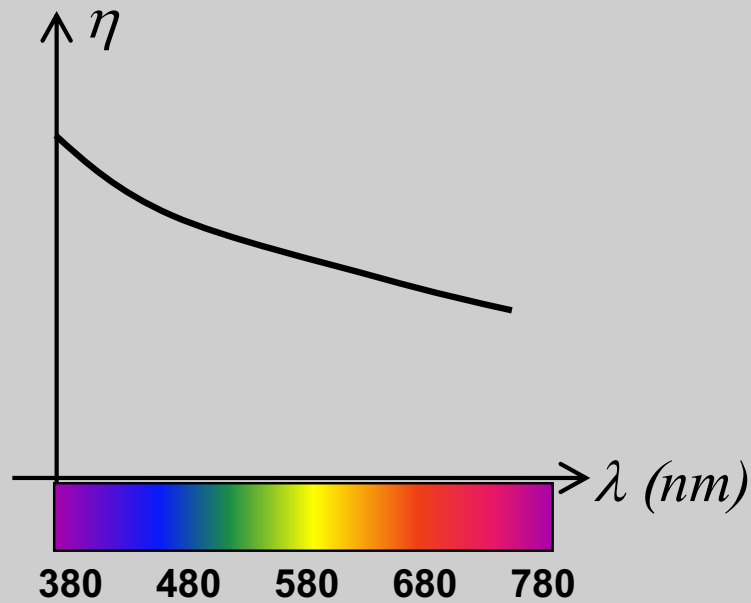
Prisma de Newton



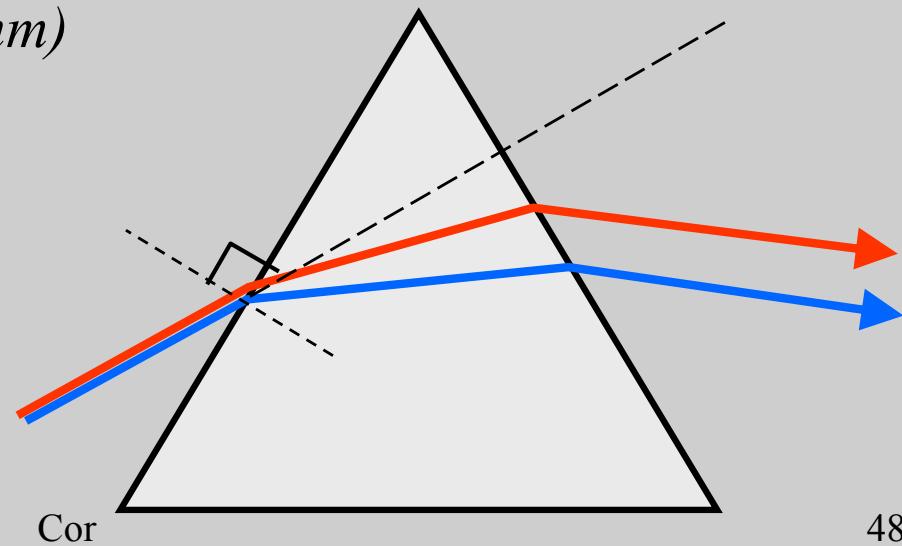
Cor

47

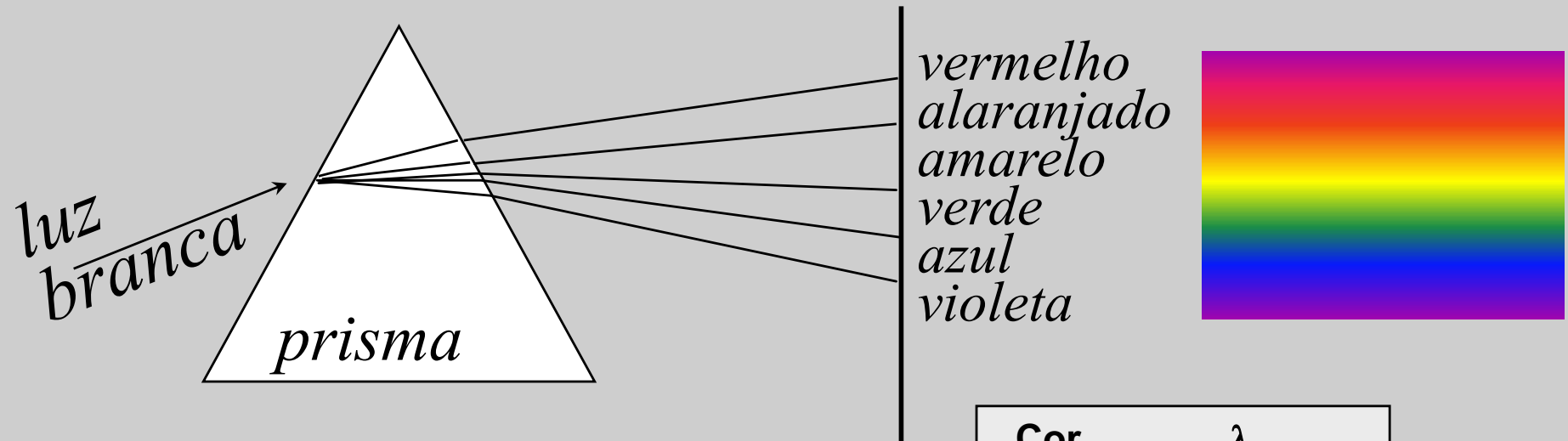
Refração num prisma



*índice refração
variando de acordo
com o comprimento de
onda*



Luz branca (Newton)



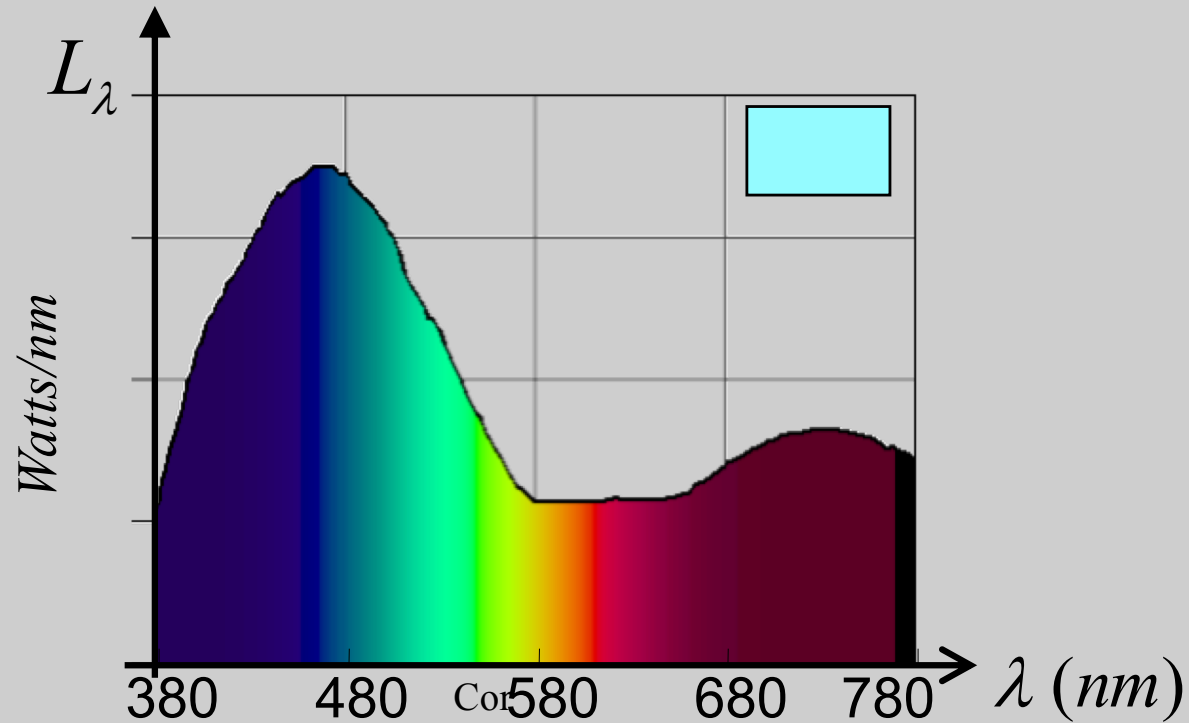
Cor	λ
Violeta	380-440 nm
Azul	440-490 nm
Verde	490-565 nm
Amarelo	565-590 nm
Laranja	590-630 nm
Vermelho	630-780 nm

1 nm = 10^{-9} m

luz branca (acromática) tem todos os comprimentos de onda



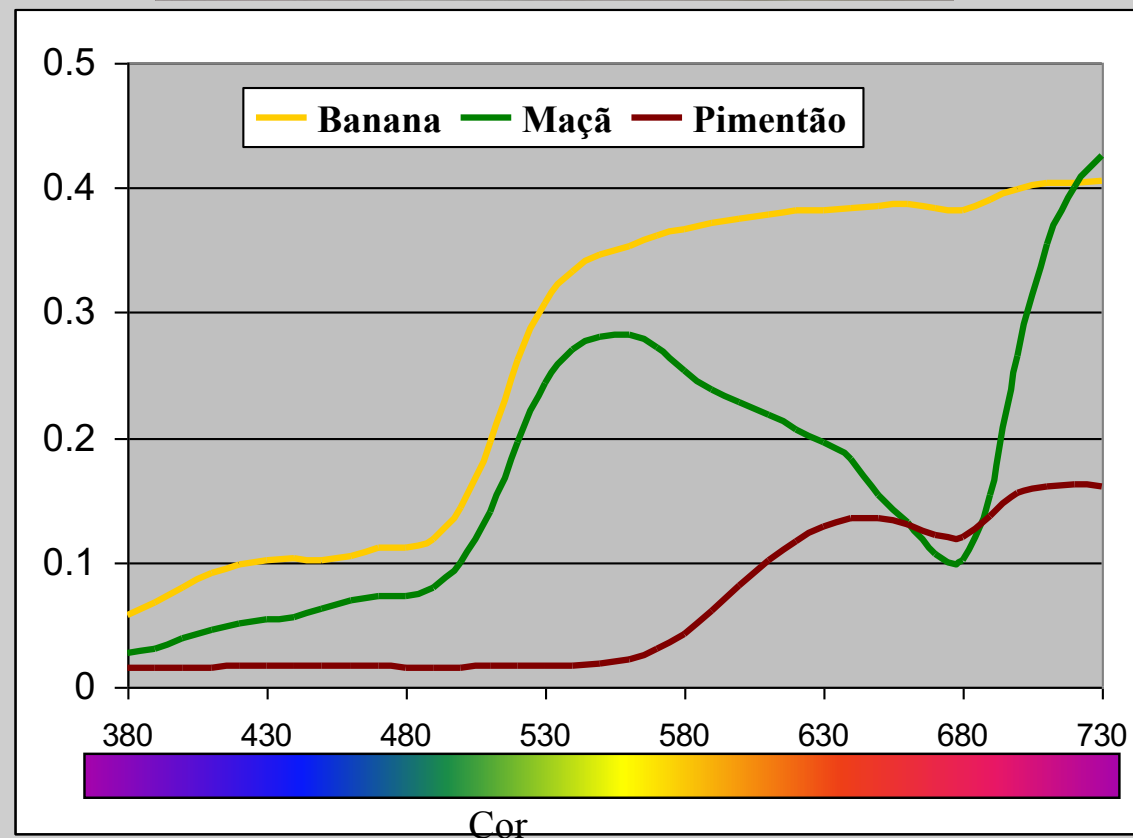
Espectro da luz



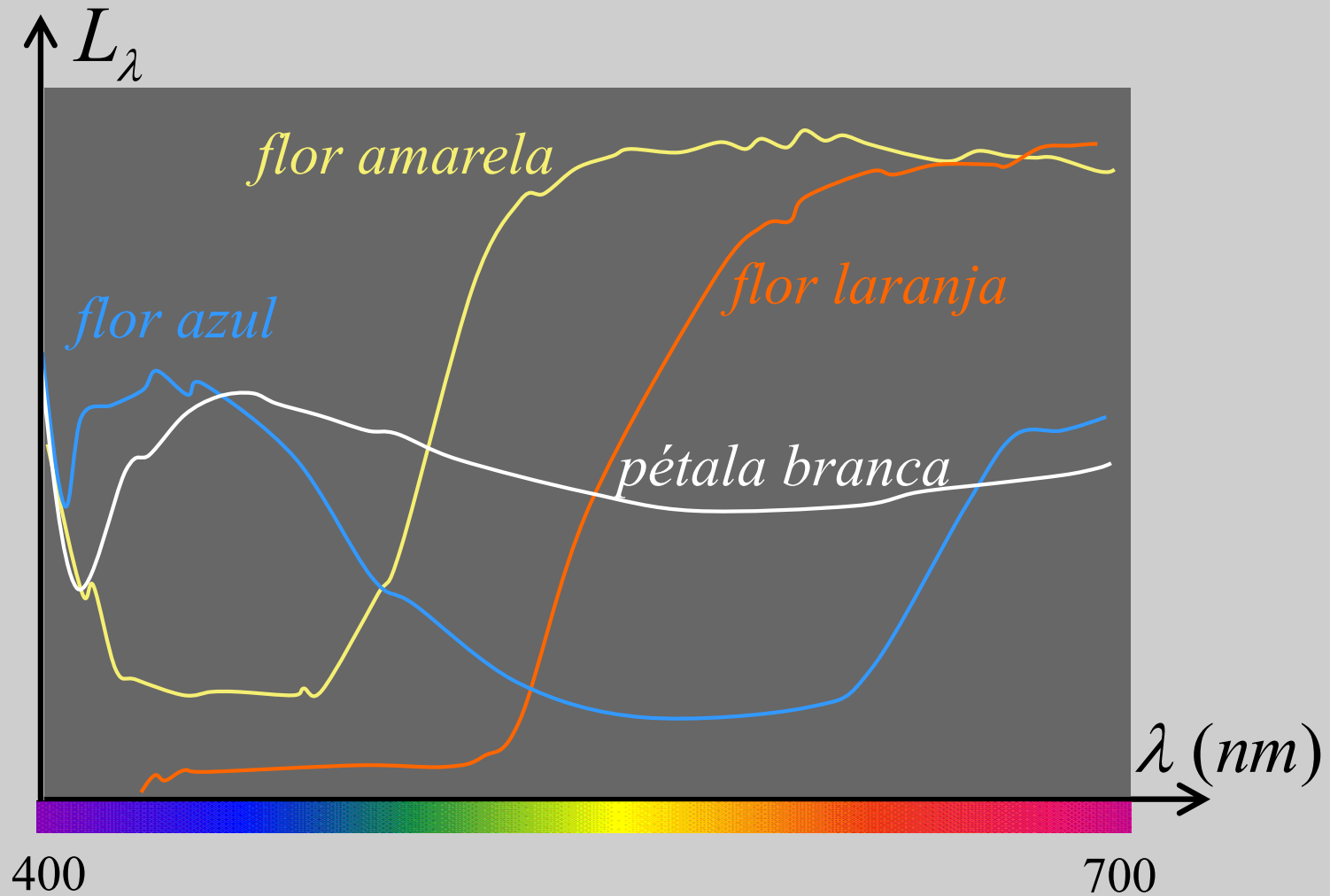
Espectro da luz refletida em objetos



Espectro da luz refletida em objetos



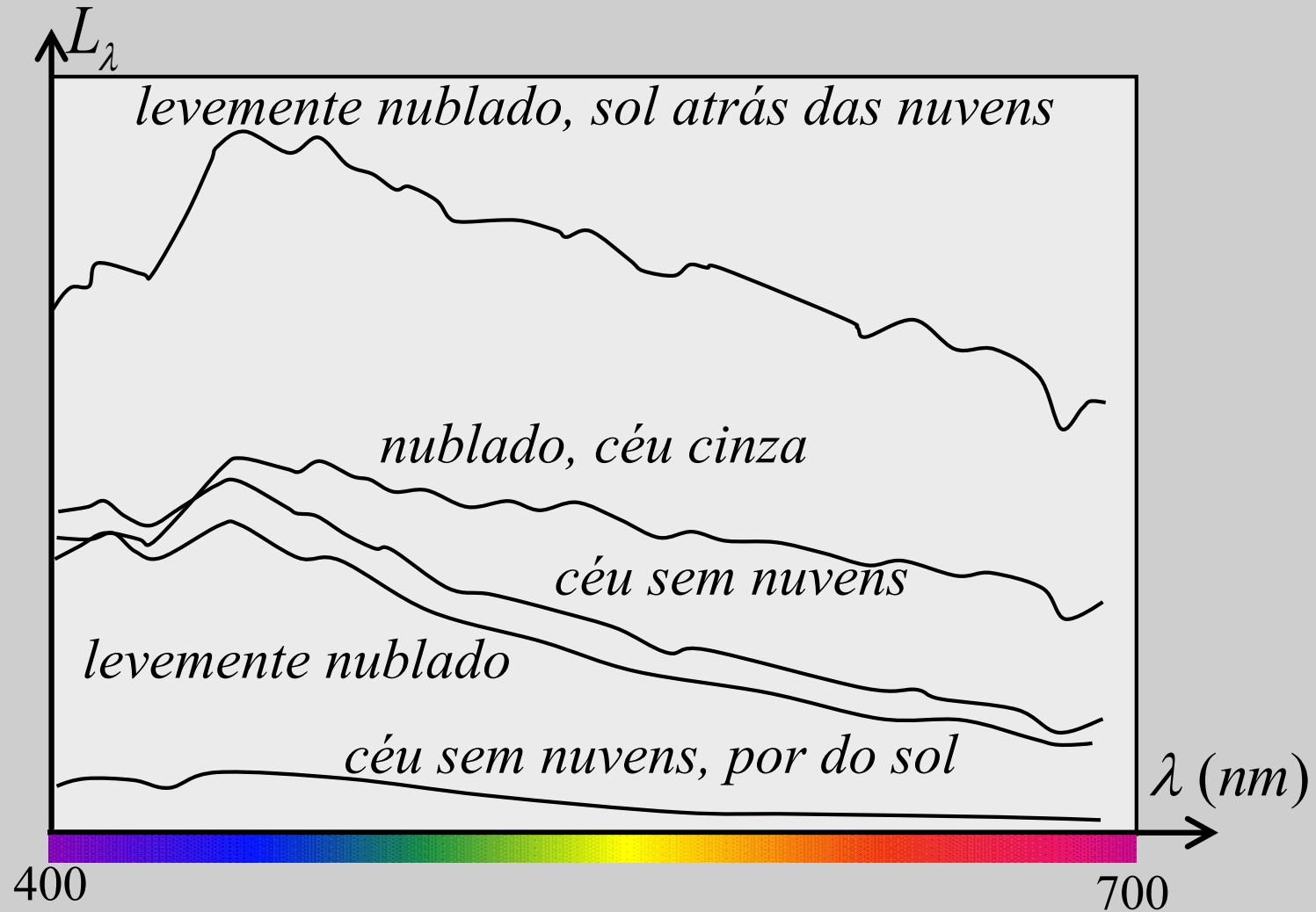
Espectro de luz refletidas



Cor

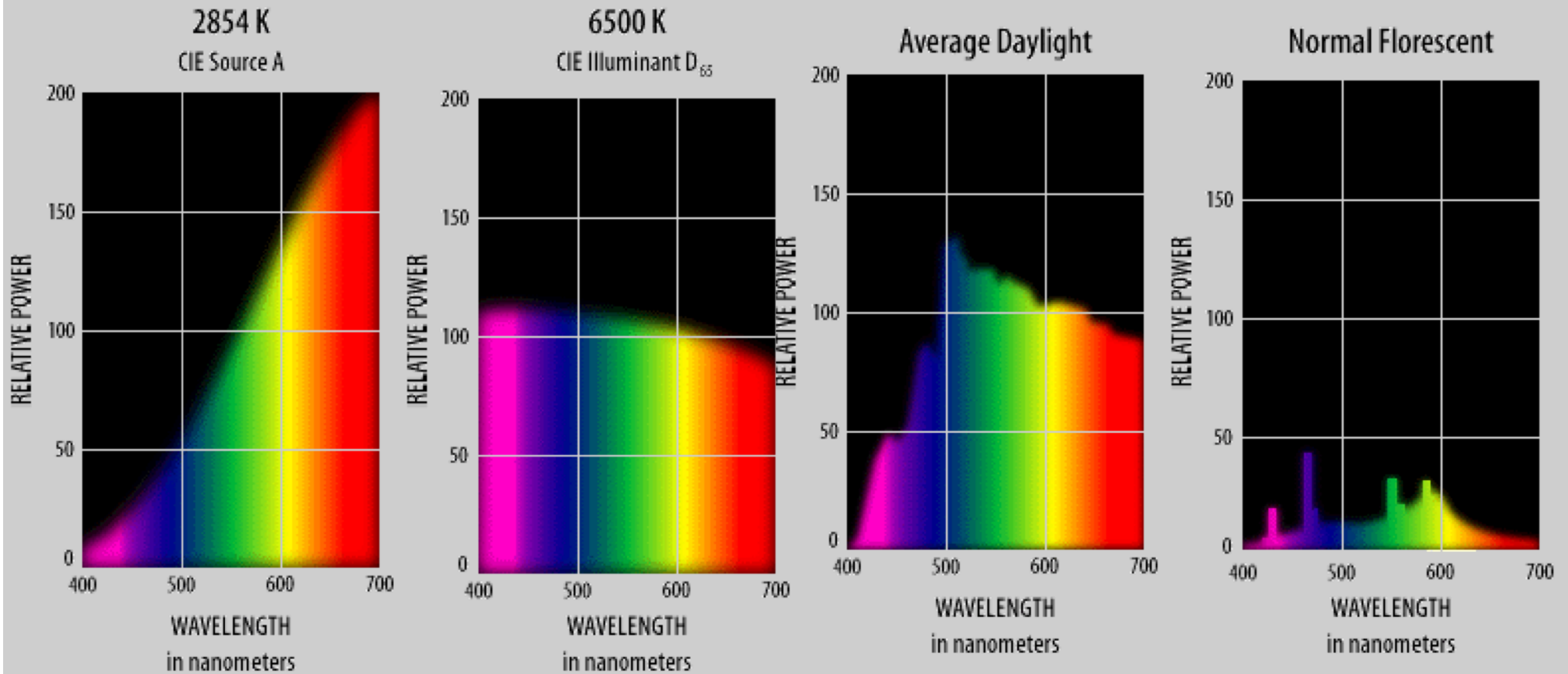
Measurements by E. Kõivisto.⁵³

Medidas do espectro da luz solar



Cor medidas feitas por J. Parkkinen and P. Silfsten.

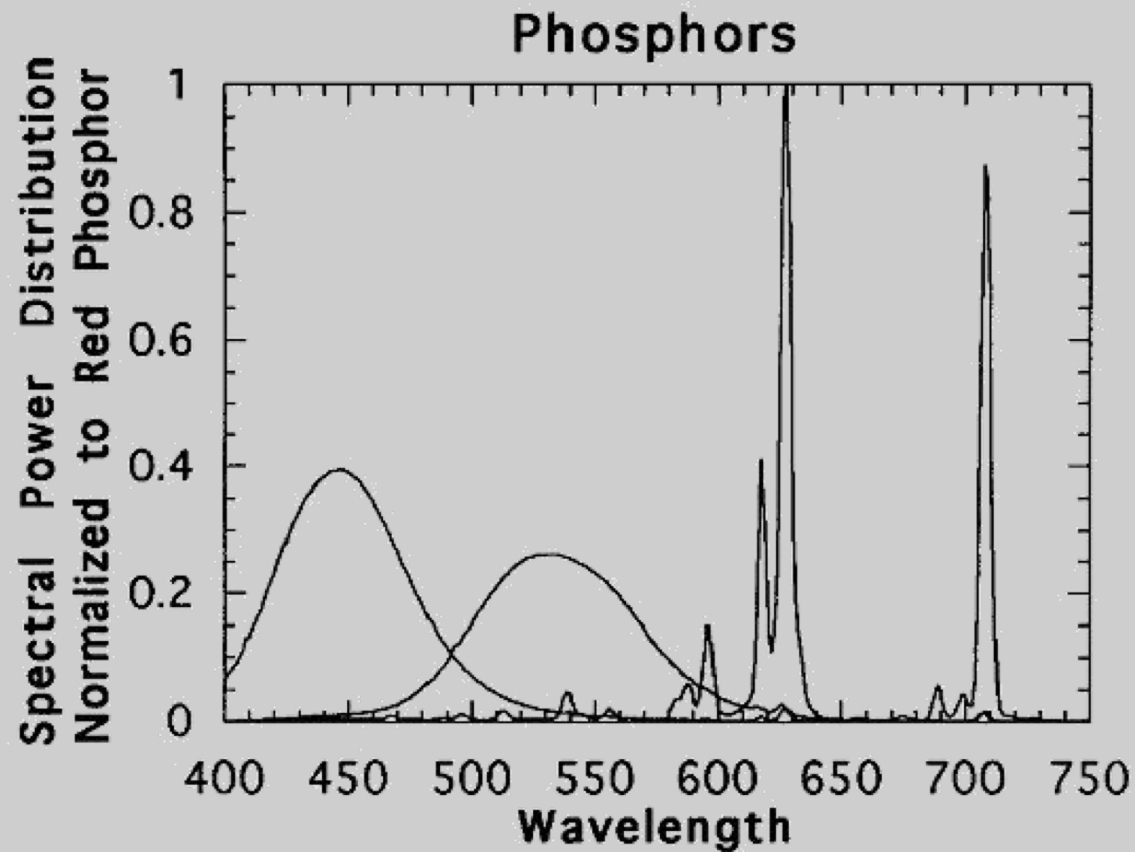
Espectros de luz “branca”



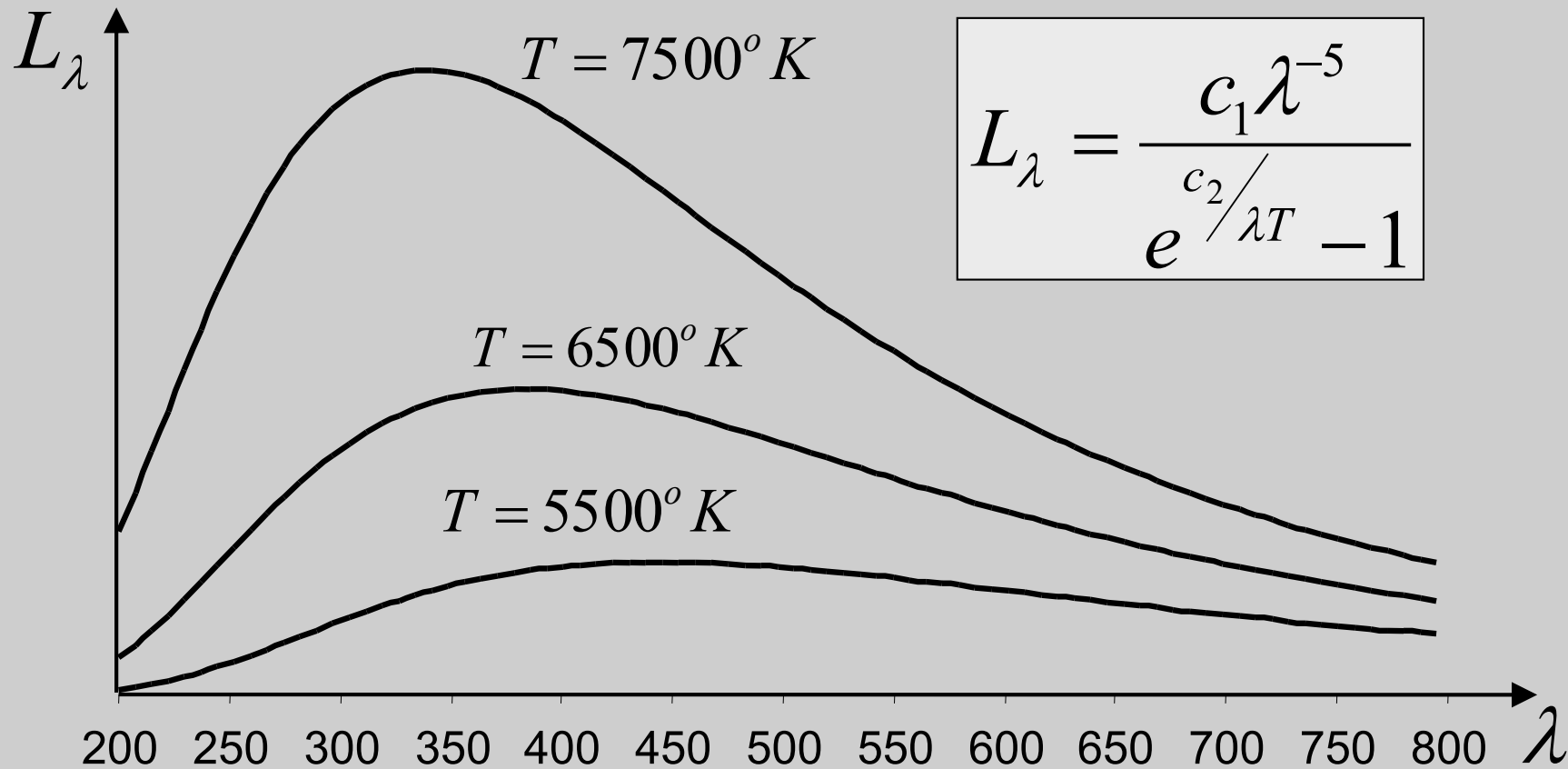
Cor

Idit Hiran

Espectro dos fósforos dos monitores



Corpo negro (*blackbody*)

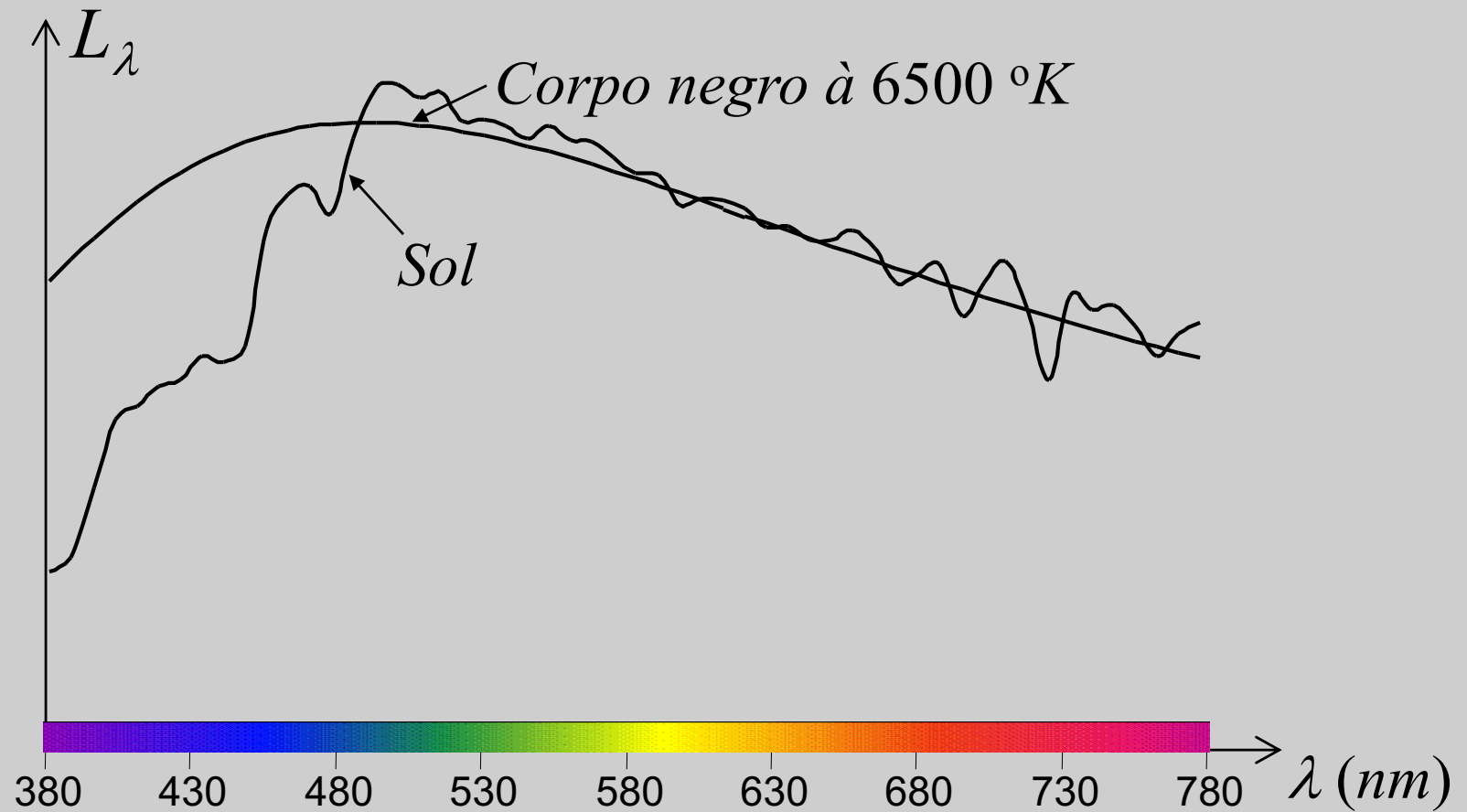


$$L_\lambda = \frac{c_1 \lambda^{-5}}{e^{c_2/\lambda T} - 1}$$

$$c_1 = 2\pi hc^2 = 3.74183 \times 10^{-16} \text{ W m}^2,$$
$$c_2 = hc/k = 1.4388 \times 10^{-2} \text{ m K}.$$

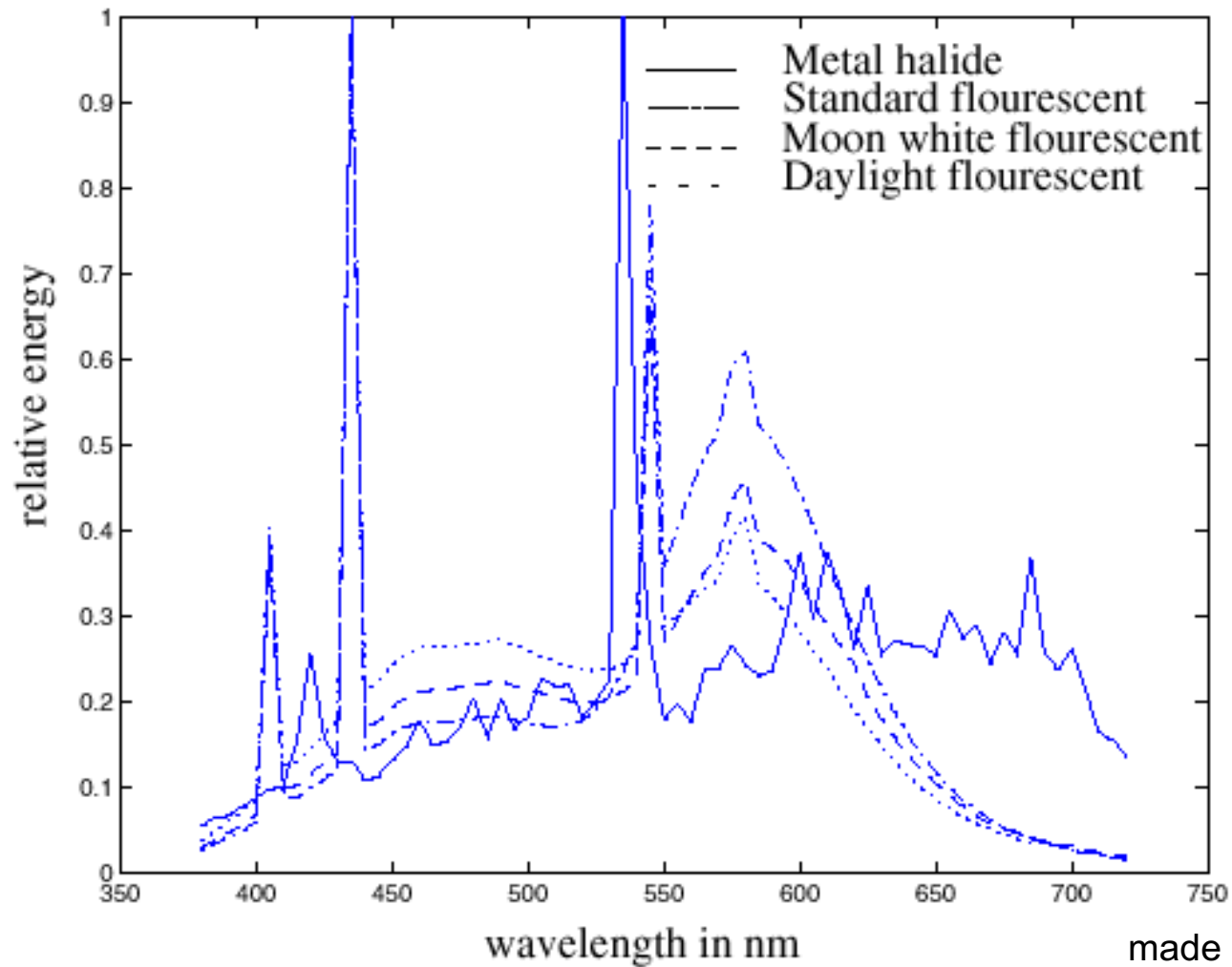
Cor

Temperatura de uma fonte luminosa



Espectro da luz solar e de um corpo negro a 6500° K

Espectro de quatro fontes luminosas artificiais



made by H.Sugiura.

Color temperature e back body temperature

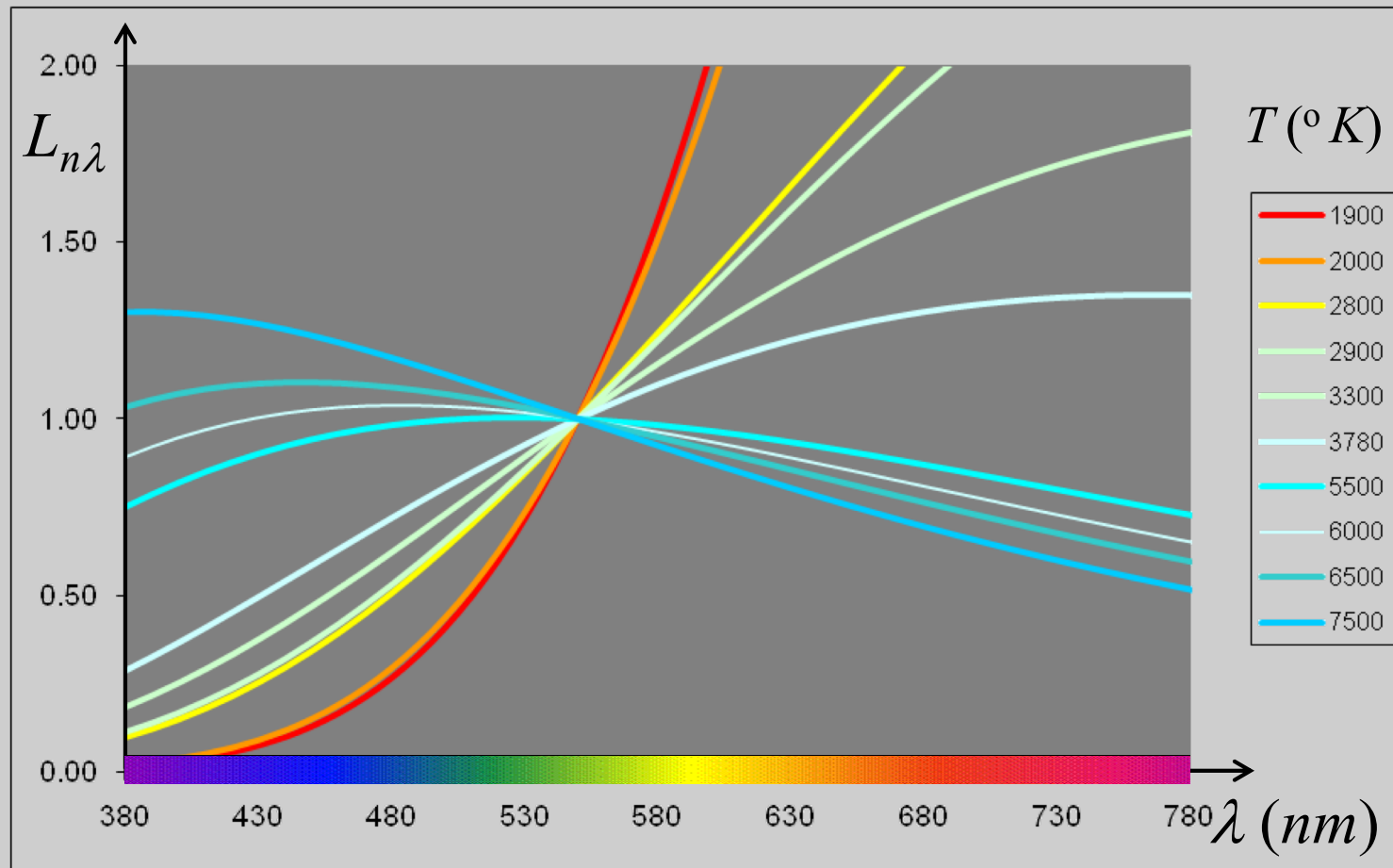
Color temperature - Any light source that has the same chromaticity coordinates as a black body can be described as having the color temperature of that black body . The terms color temperature and black body temperature are not synonymous. Color temperature is derived from colorimetric calculations. There are limitless different spectra that possess a particular color temperature and have little or no resemblance to the black body curve for that temperature.

Black Body – a heated material that emits light as a result of being hot. The spectrum of a black body is determined by the temperature alone. An incandescent lamp and a hot electric stovetop have spectra that are good approximations to black body spectra.

Correlated Color Temperature - the color temperature of the the black body that is closest to the chromaticity coordinates of the light source.

<http://www.sunriseinstruments.com/terminology.html>

Variação da distribuição espectral da radiação de um corpo negro em função da temperatura



Espectros normalizados de um corpo negro

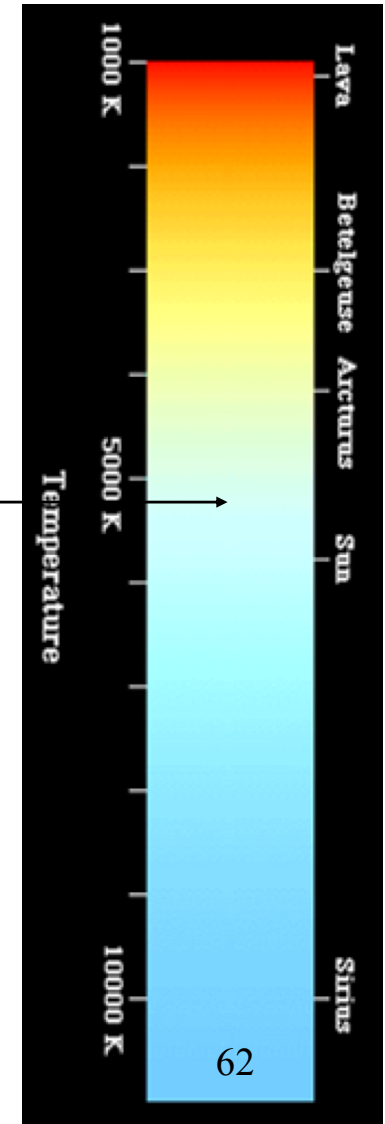
Cor

61

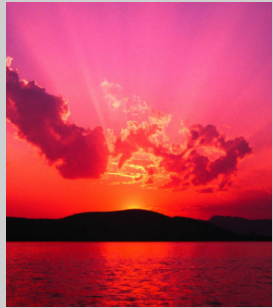
Temperatura da cor

Temperature	Typical Sources
1000K	Candles; oil lamps
2000K	Very early sunrise; low effect tungsten lamps
2500K	Household light bulbs
3000K	Studio lights, photo floods
4000K	Clear flashbulbs
5000K	Typical daylight; electronic flash
5500K	The sun at noon near Kodak's offices :-)
6000K	Bright sunshine with clear sky
7000K	Slightly overcast sky
8000K	Hazy sky
9000K	Open shade on clear day
10,000K	Heavily overcast sky
11,000K	Sunless blue skies
20,000+K	Open shade in mountains on a really clear day

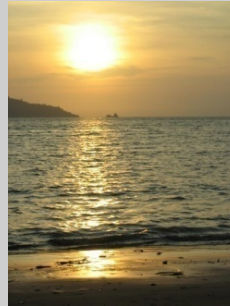
Monitor ideal



Temperatura da cor



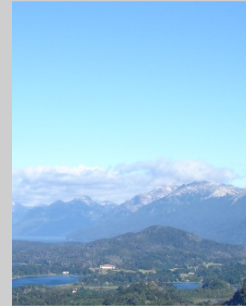
2000



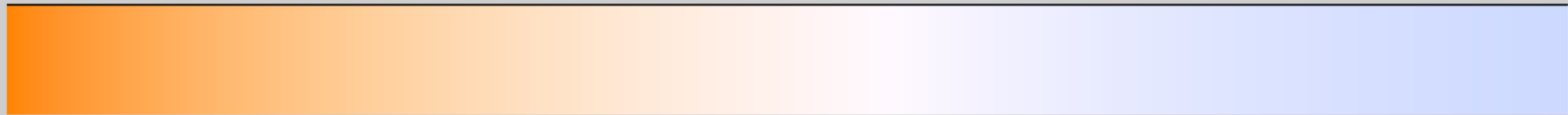
5500



6500



7500



2000 3000 4000 5000 6000 7000 8000 9000 10000

$T (^{\circ}K)$



1900



2800



3300

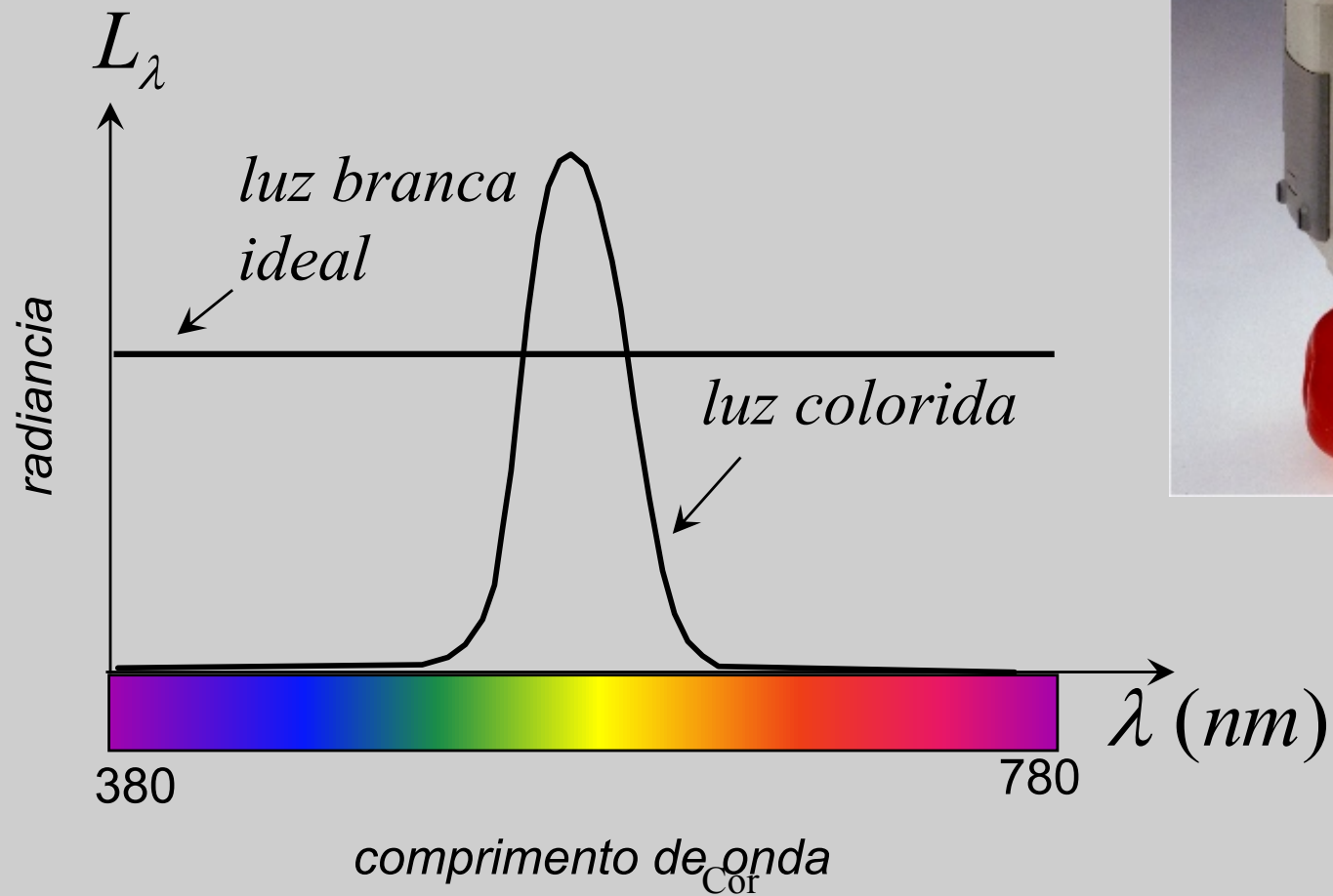


6000

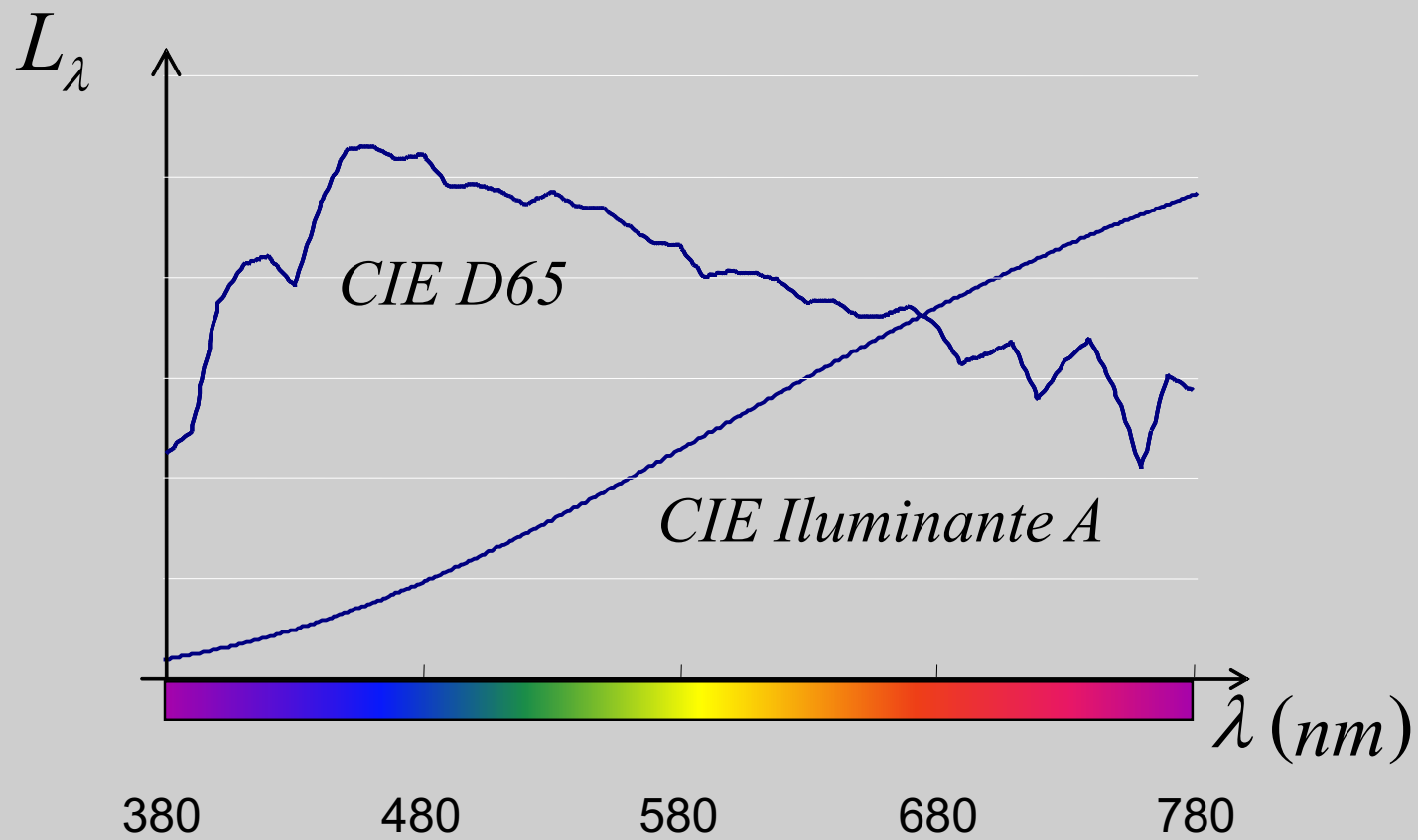
Cor

63

Caracterização do espectro de fontes luminosas

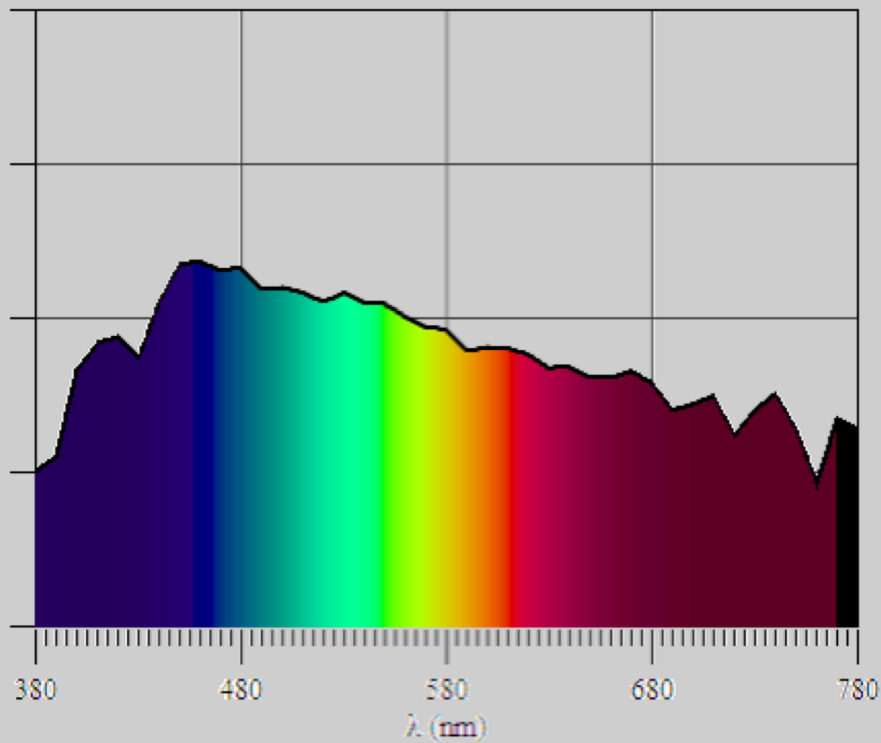


Espectro CIE D65 e da lâmpada incandescente (*illuminant A*)

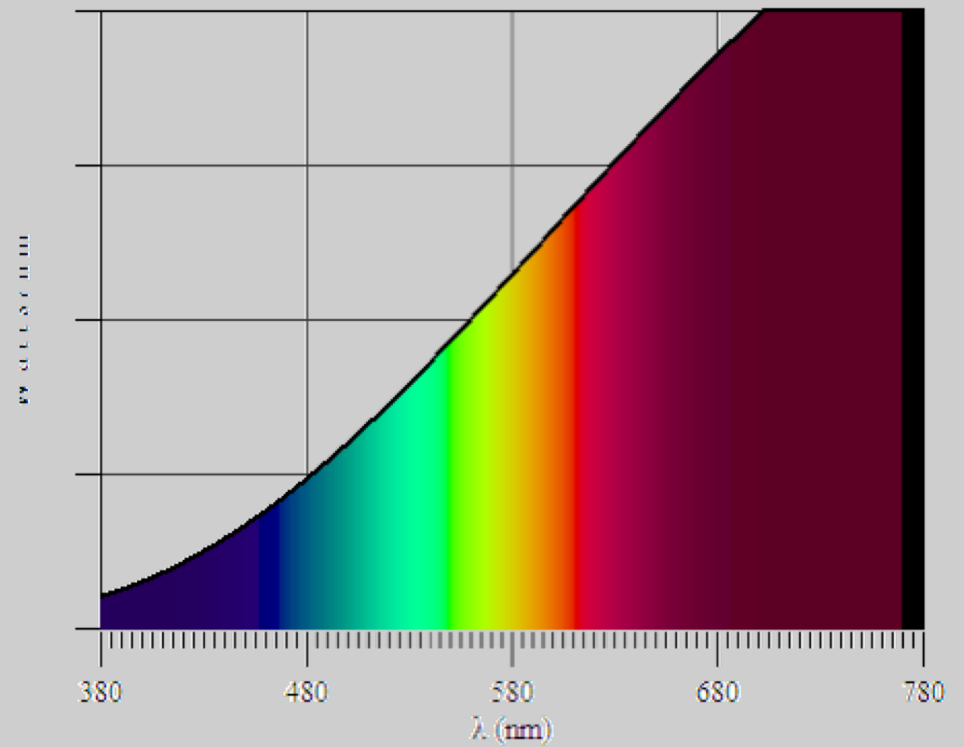


Espectro CIE D65 e da lâmpada incandescente (*illuminant A*)

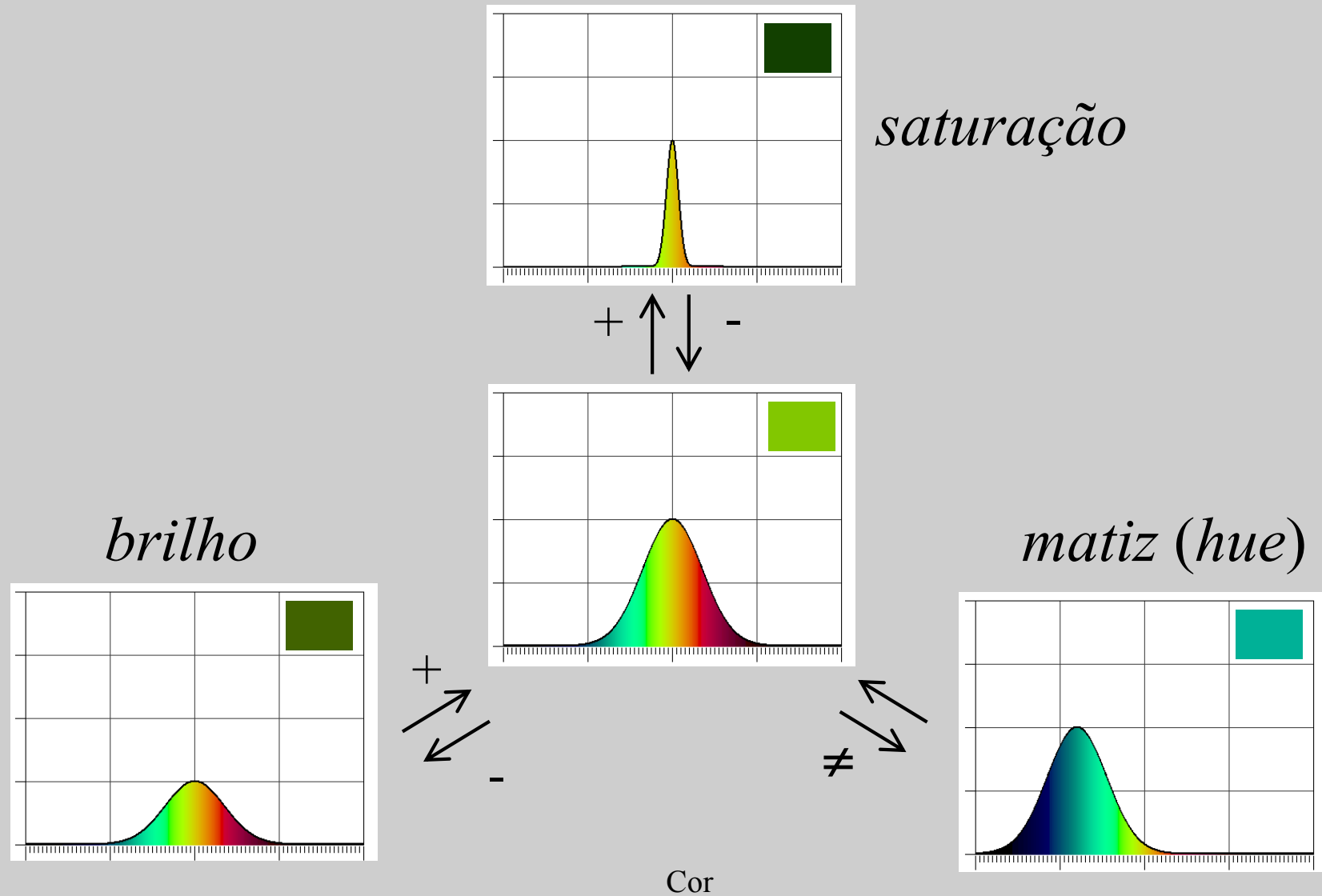
CIE D65



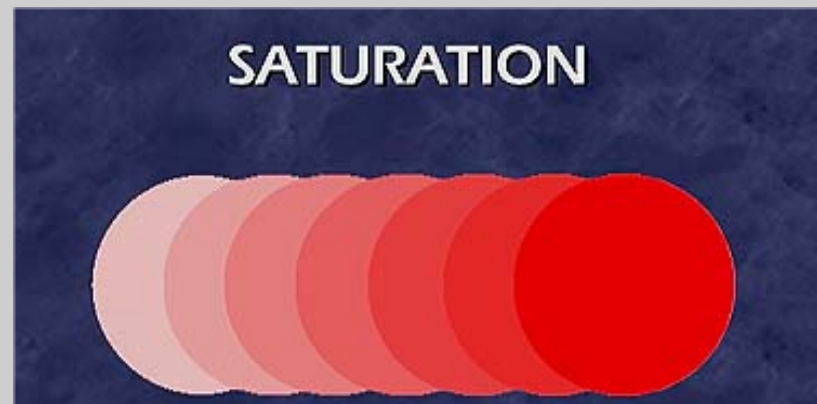
CIE Iluminante A



Características do espectro de fontes luminosas



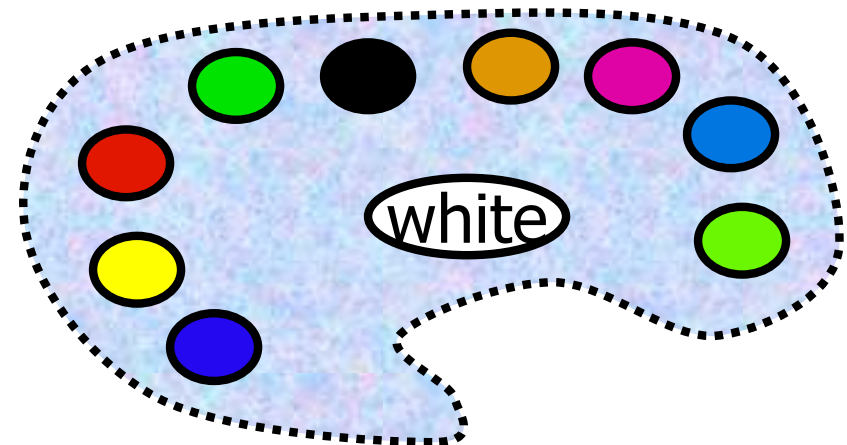
Características das fontes luminosas



Cor

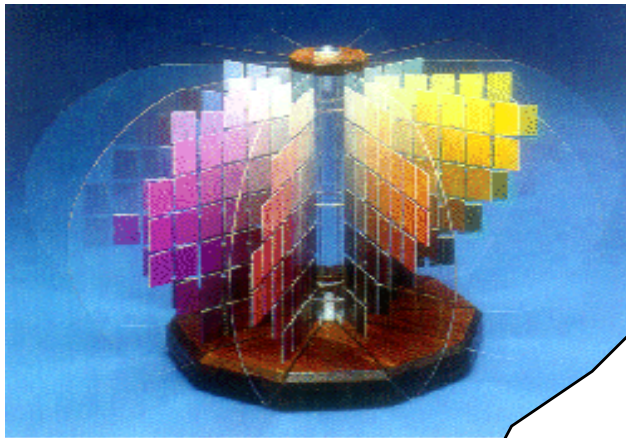
Um ponto de vista artistico

- **Matiz (*Hue*)** - A cor que vemos (vermelho, verde, roxo)
- **Saturação (*Saturation*)** - Até que ponto é a cor de cinza (cor de rosa é menos saturado que o vermelho, o azul do céu é menos saturado do que o azul royal)
- **Brilho (*Brightness*)** - Quão brilhante é a cor

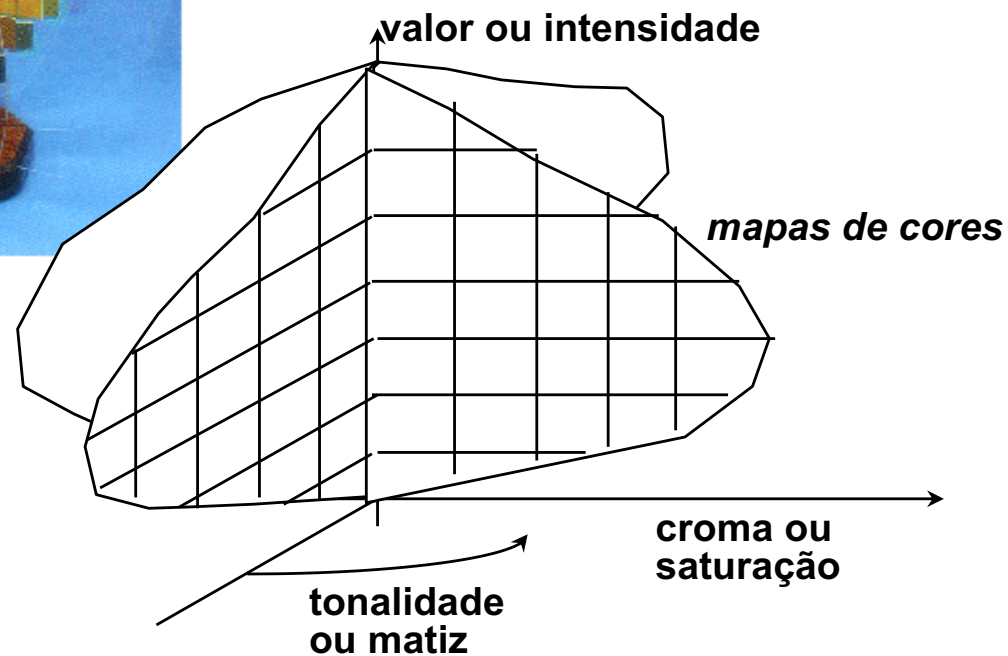


Sistemas de cores por enumeração

Munsell



Albert H. Munsell - artista plástico (1905)

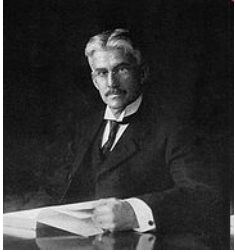


Pantone (início dos 60's)

Cor

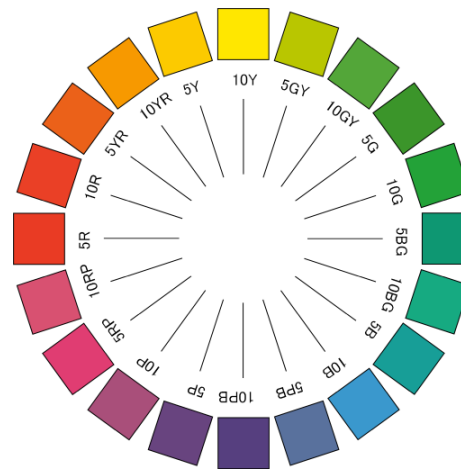
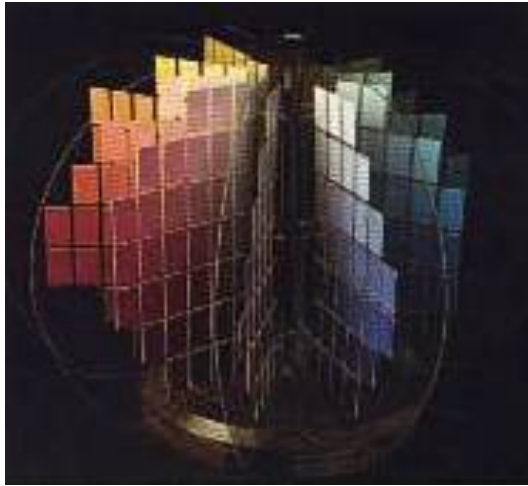
70

Munsell Book of Colors

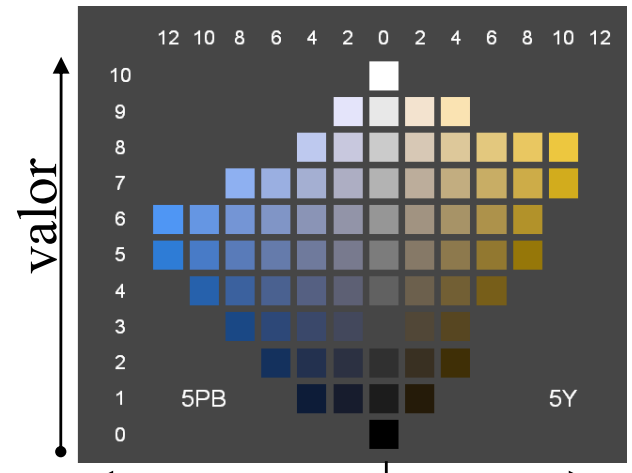


☆1858 †1918

Albert Henry Munsell



matiz (*hue*)
Cor



saturação (*chroma*)

Sistema de cor de Munsell

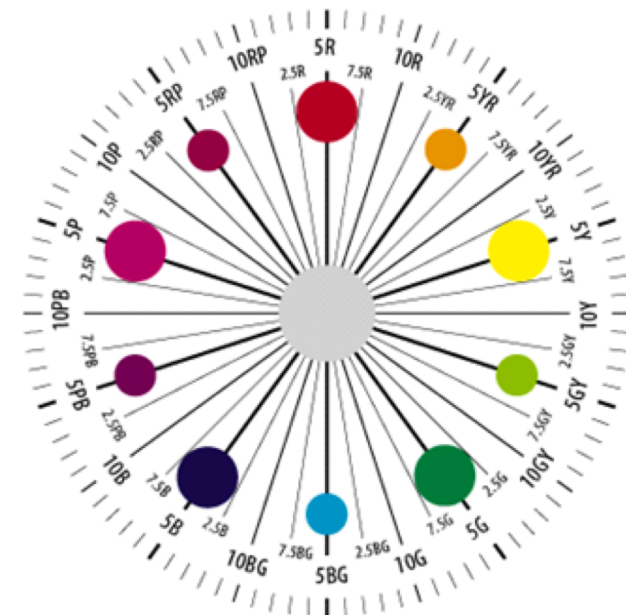
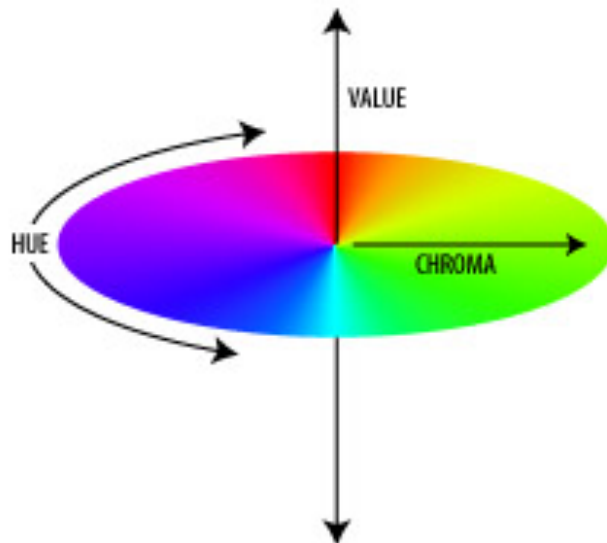
Passos iguais perceptualmente em Matiz, Valor e Cromo.

Matiz(*Hue*): R, YR, Y, GY, G, BG, B, PB, P, RP
(cada um subdividido em 10)

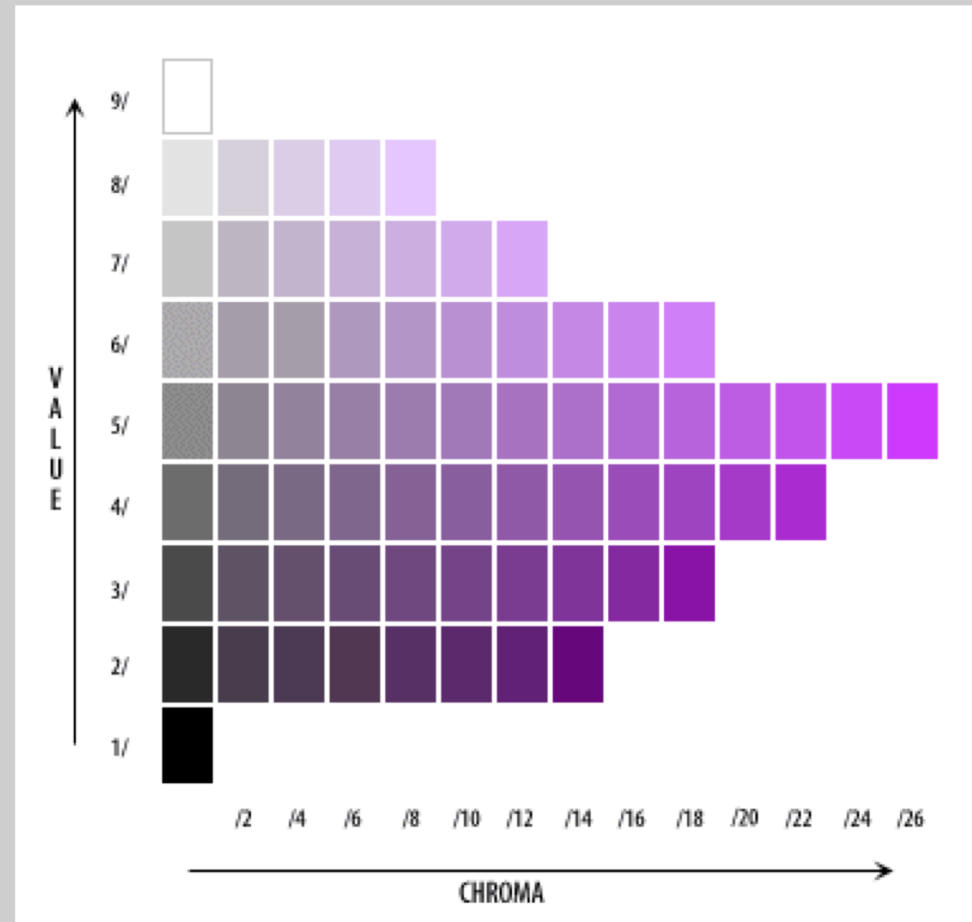
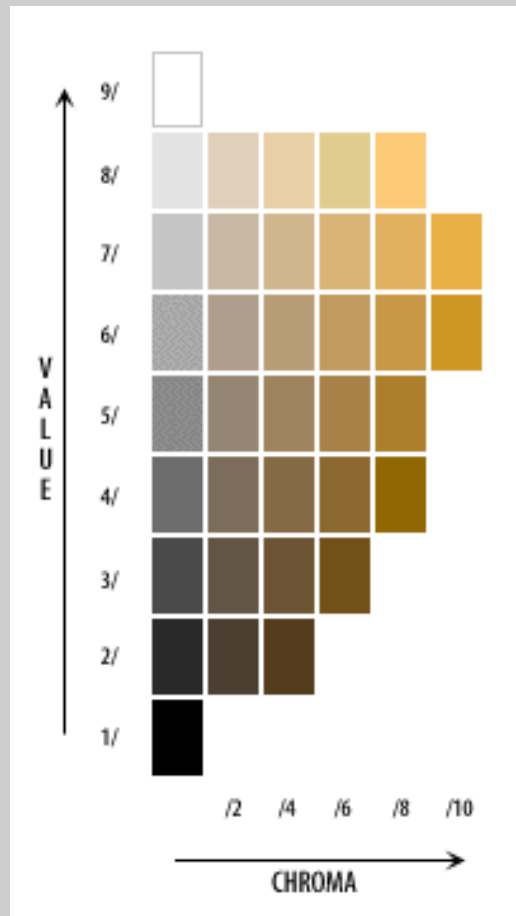
Valor(*Value*): 0 ... 10 (escuro ... branco)

Croma(*Chroma*): 0 ... 20 (neutro ... saturado)

Exemplo:
5YR 8/4



Munsell Book of Colors



PANTONE



Cor

7

PANTONE

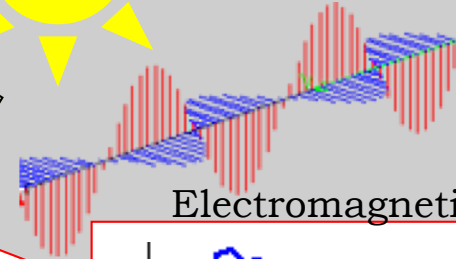
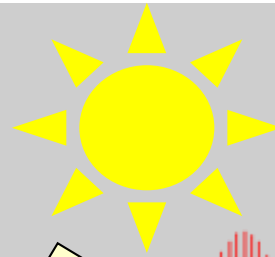
Pantone: Blue Iris



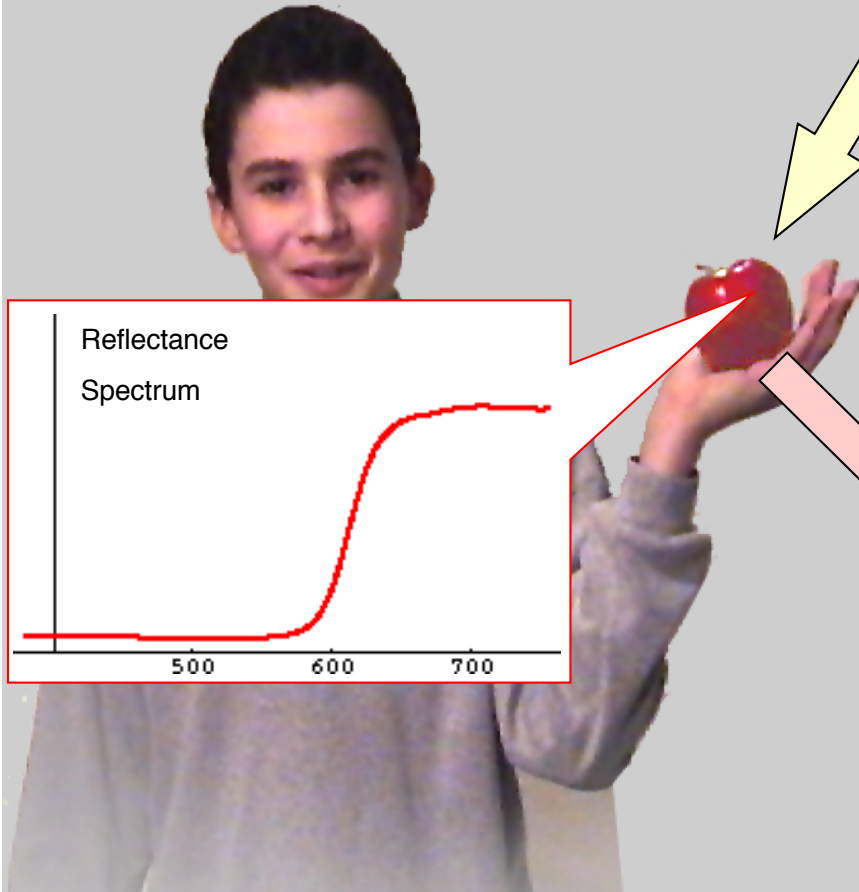
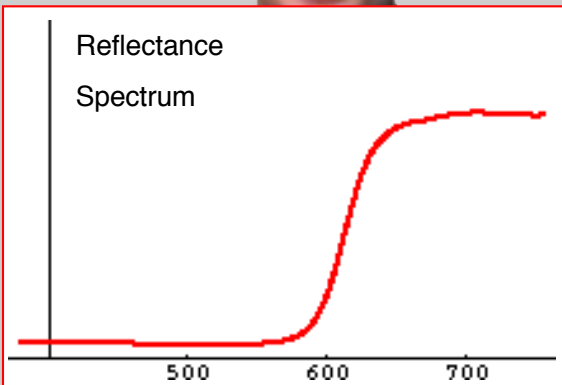
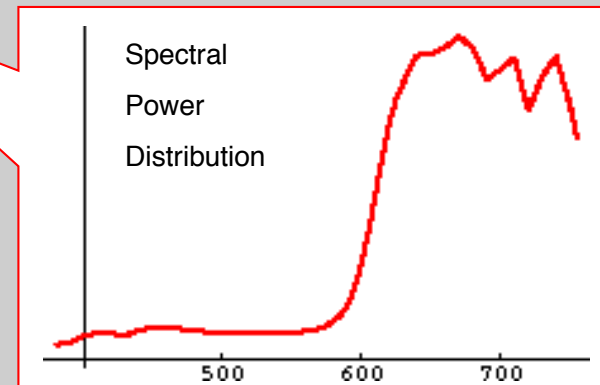
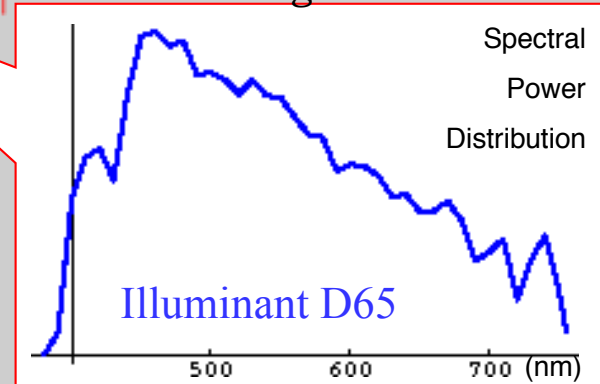
HEX: #506EB2 **RGB: 80, 110, 178**

valores

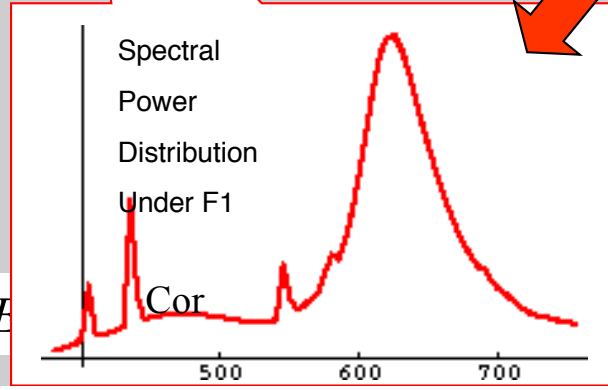
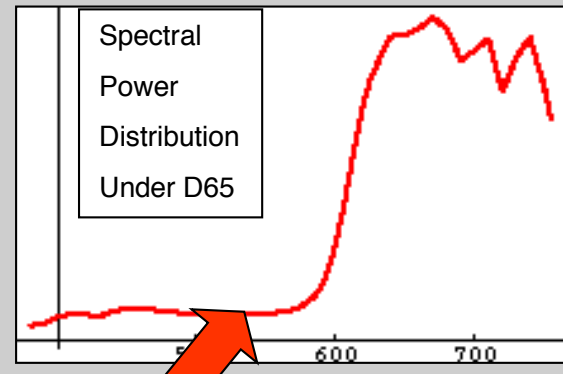
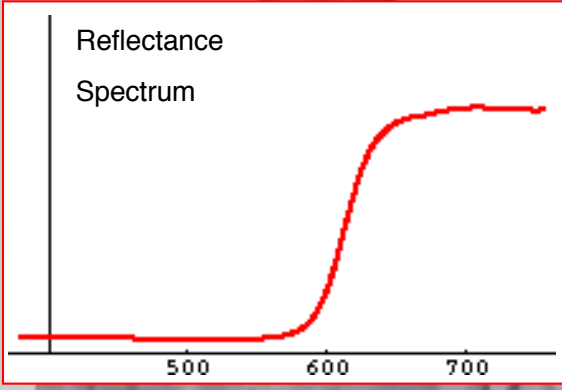
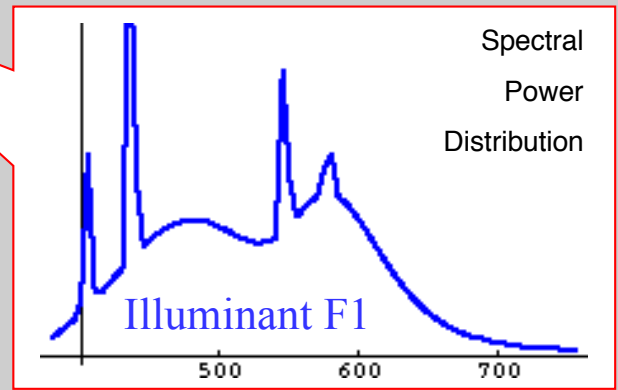
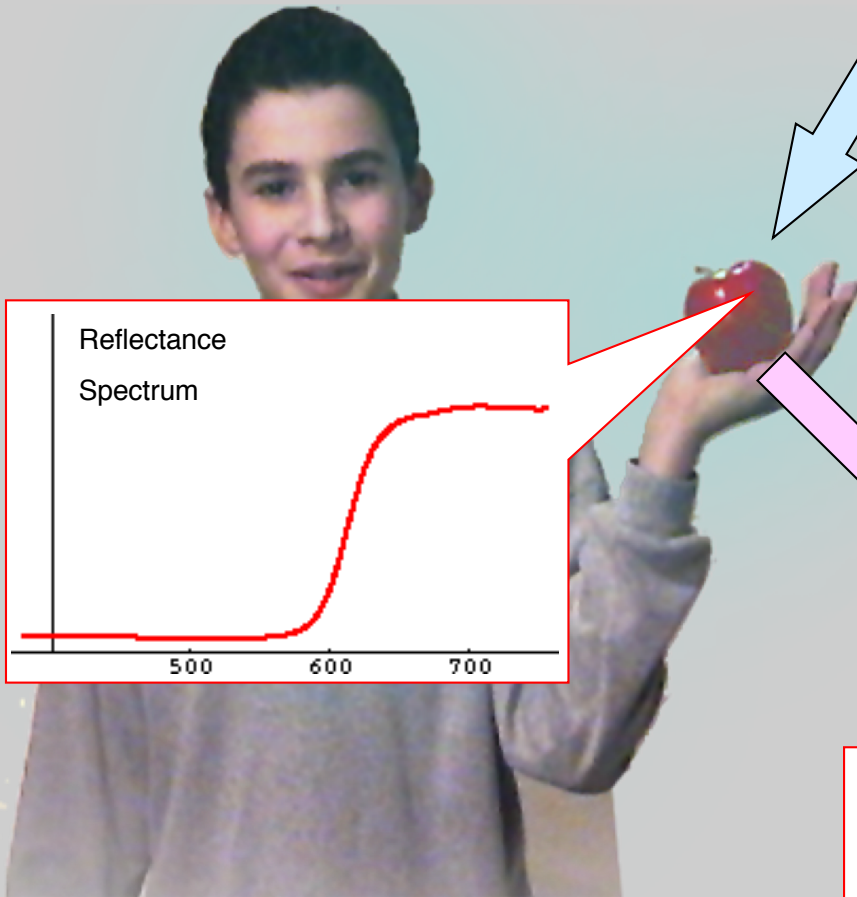
Interação da fonte com as superfícies



Electromagnetic Wave



Interação da fonte com as superfícies



Mesma foto. Diferentes luzes

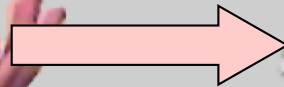
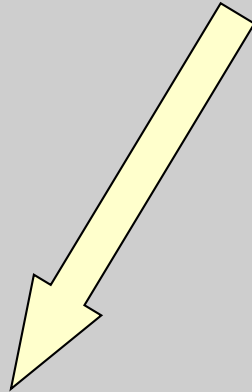
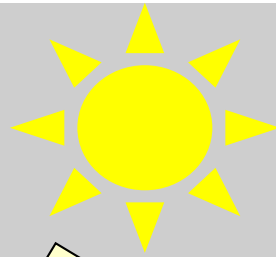




Cor

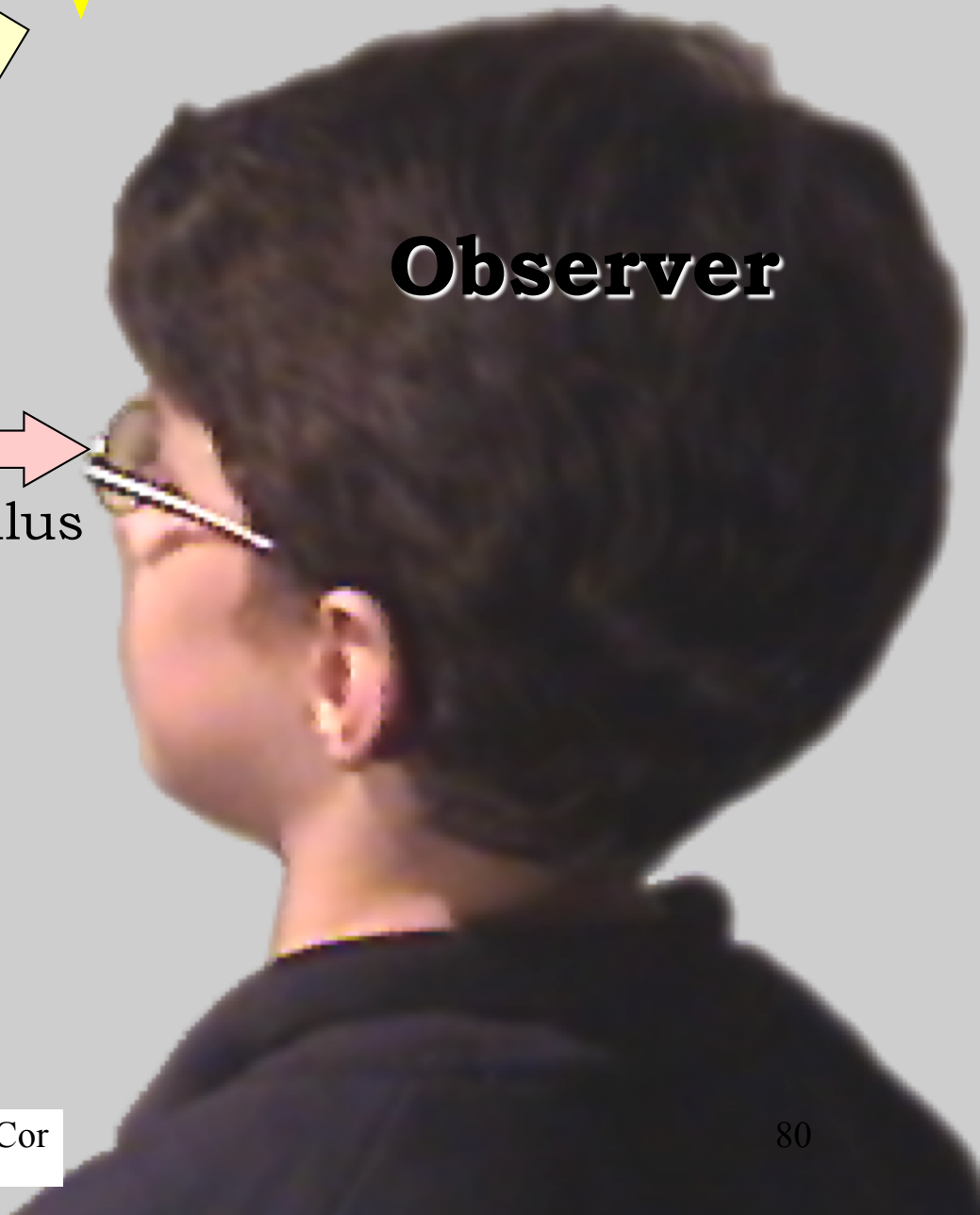
“Uma sensação humana”

What is Color?

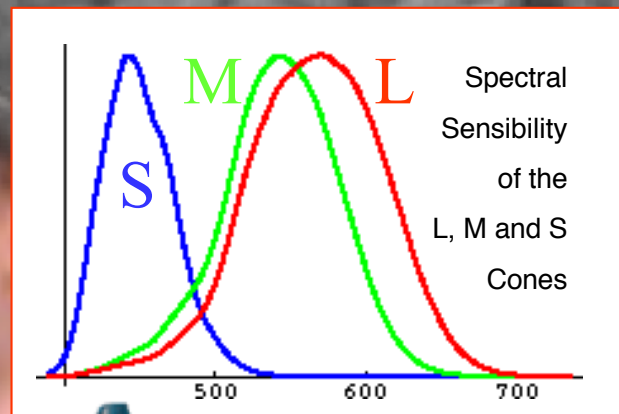
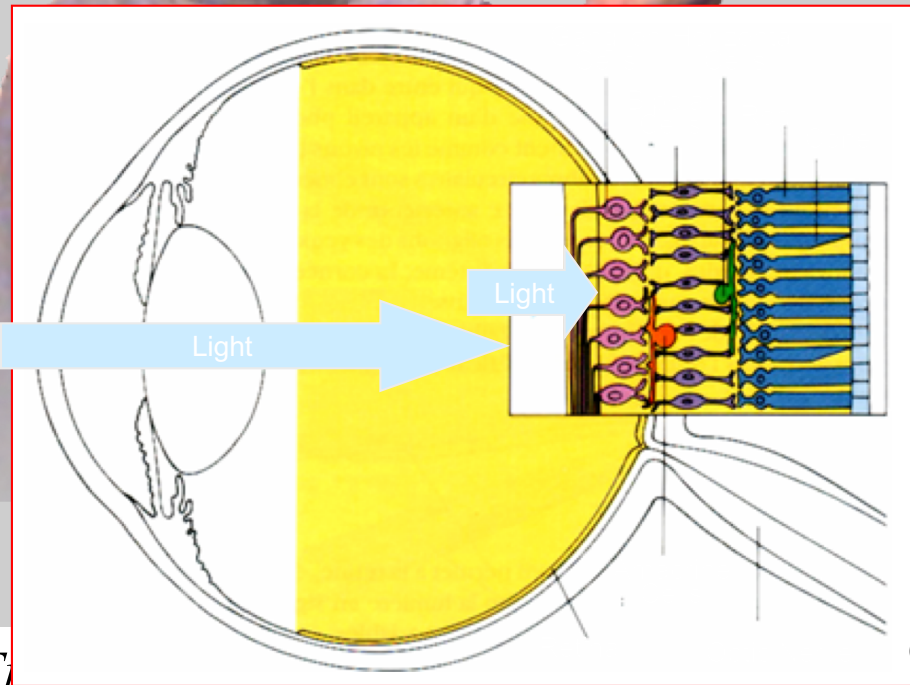
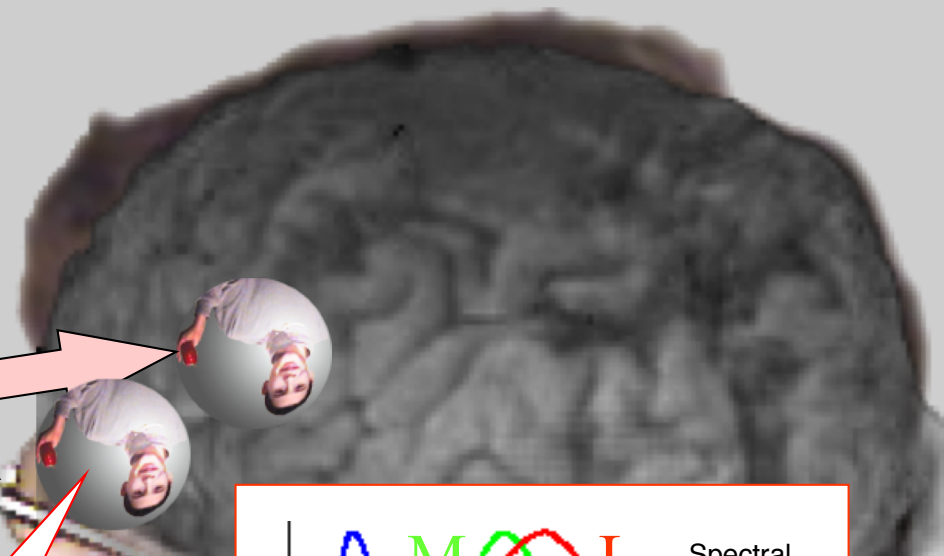
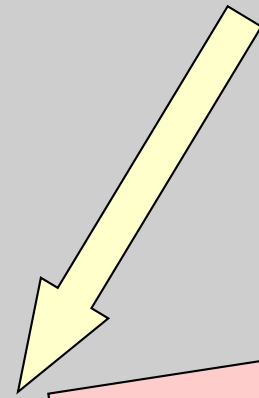
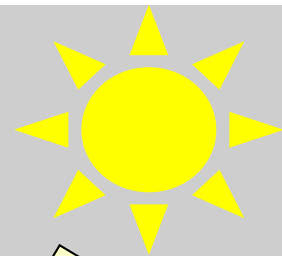


Stimulus

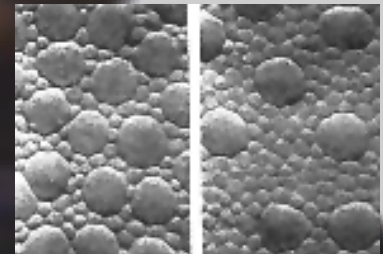
Observer



What is Color?

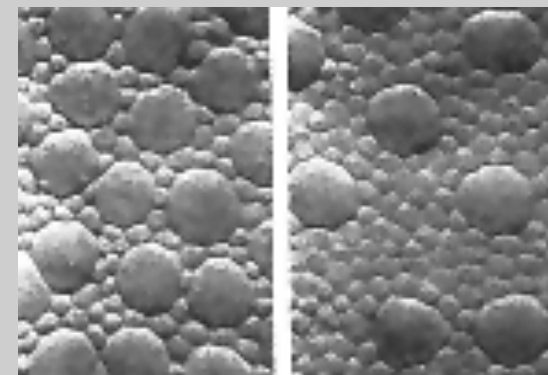
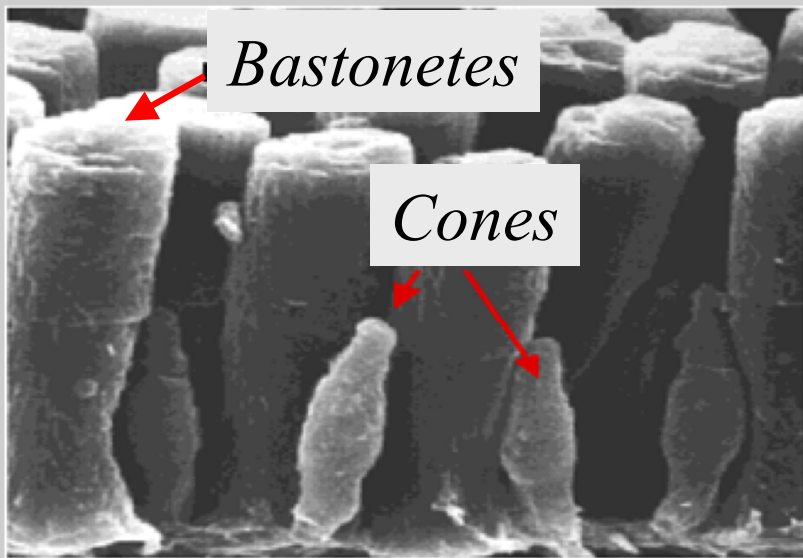
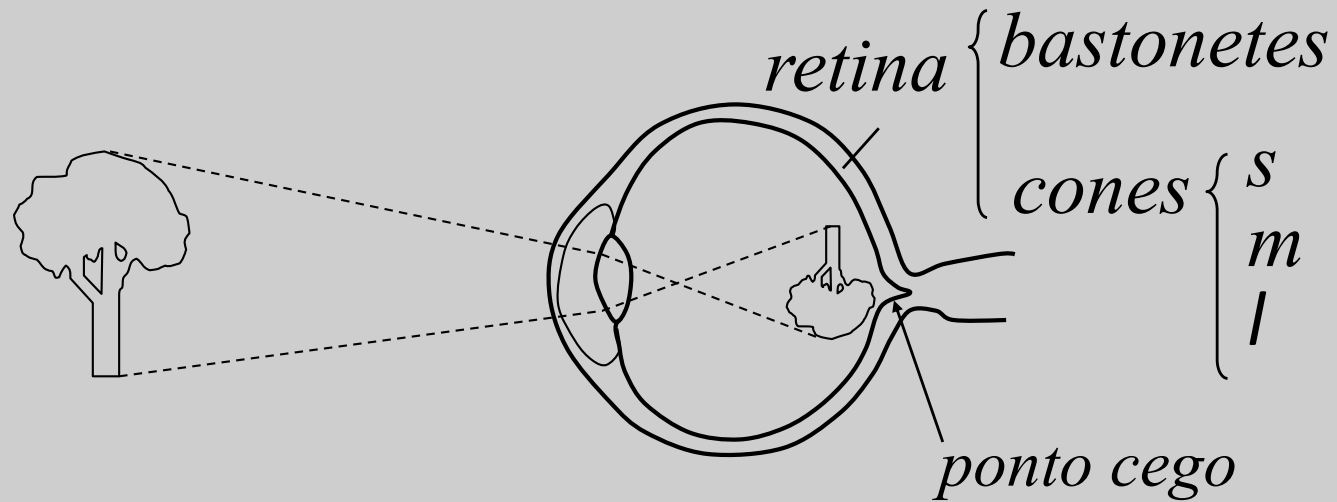


Rods Cones



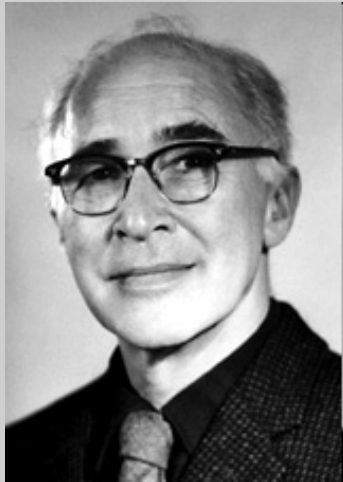
Distribution of Cones and Rods

Anatomia simplificada do olho humano



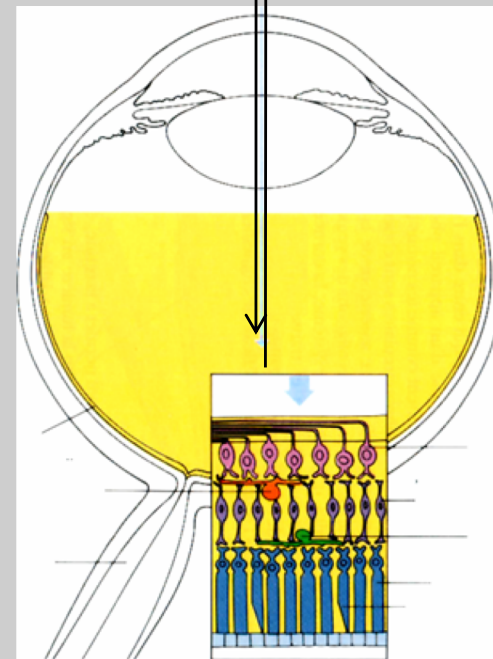
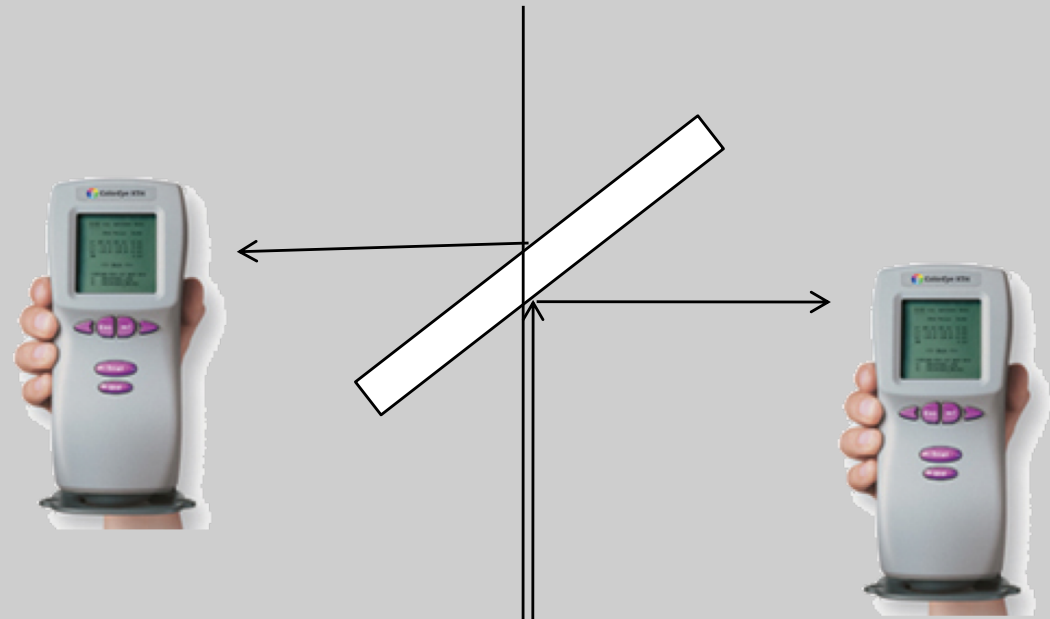
fóvea
10%

What is Color?



☆1906 †1997

George Wald
The Nobel Prize 1967



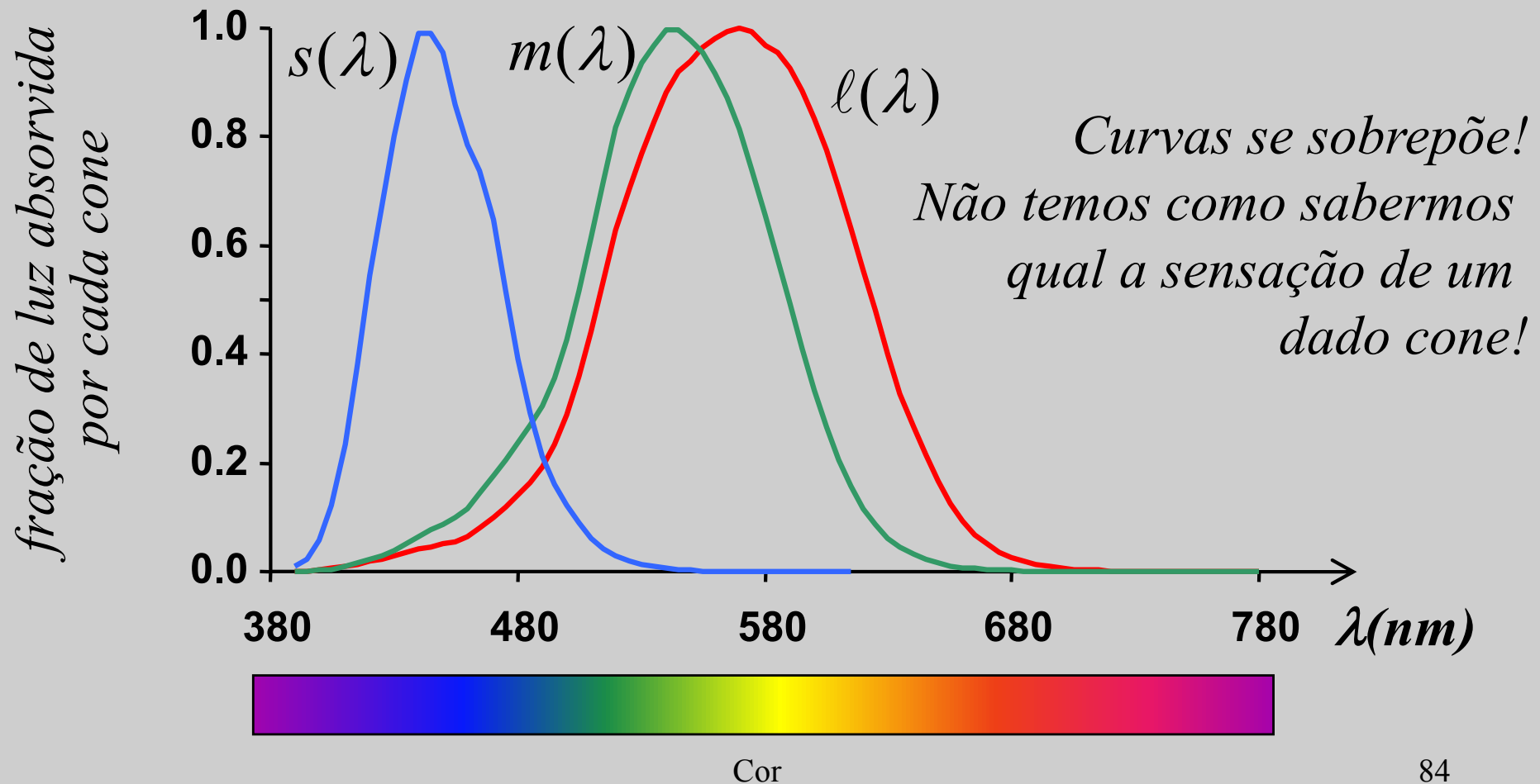
Cor

83

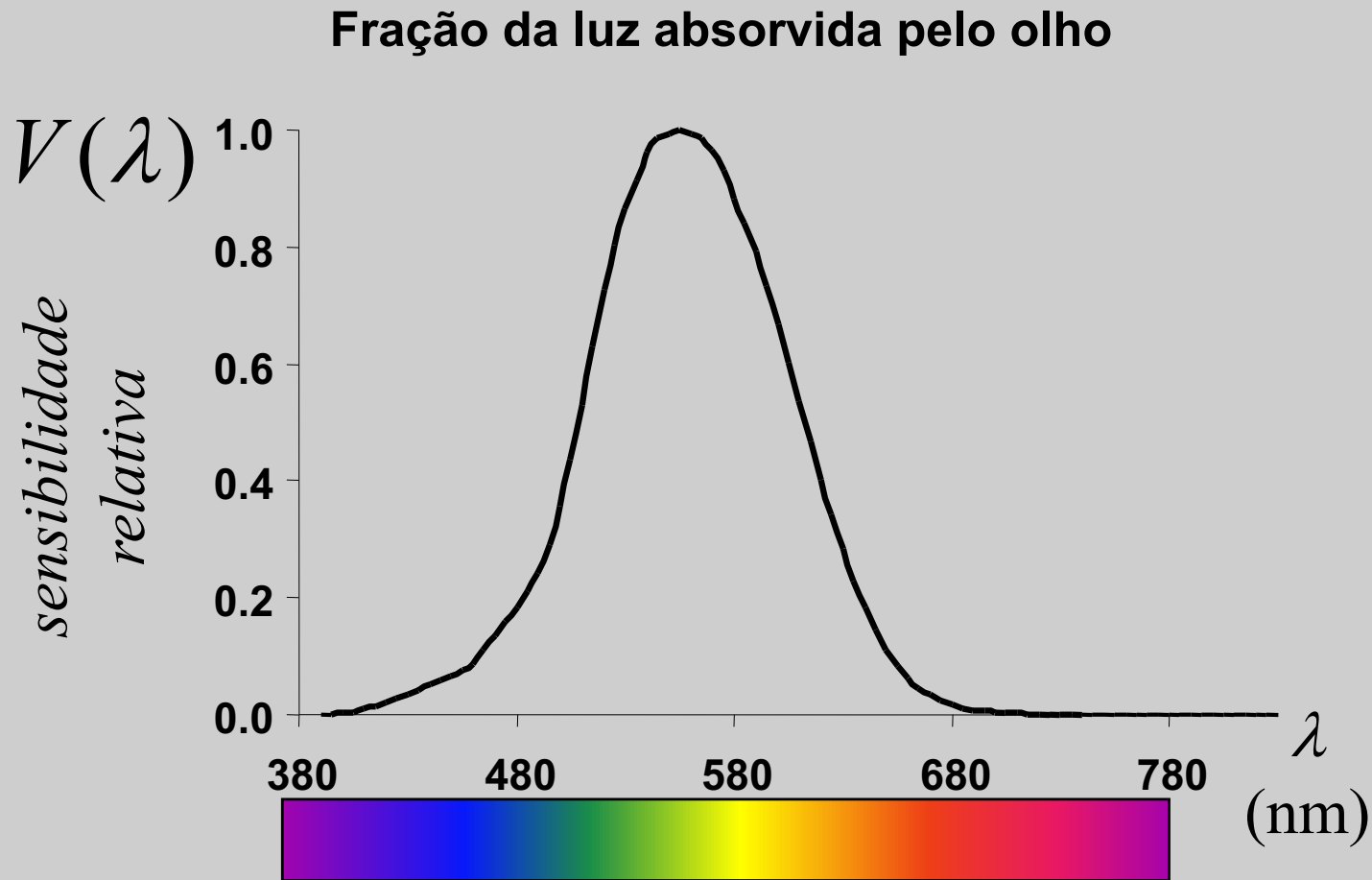
Sensibilidade dos cones do olho humano



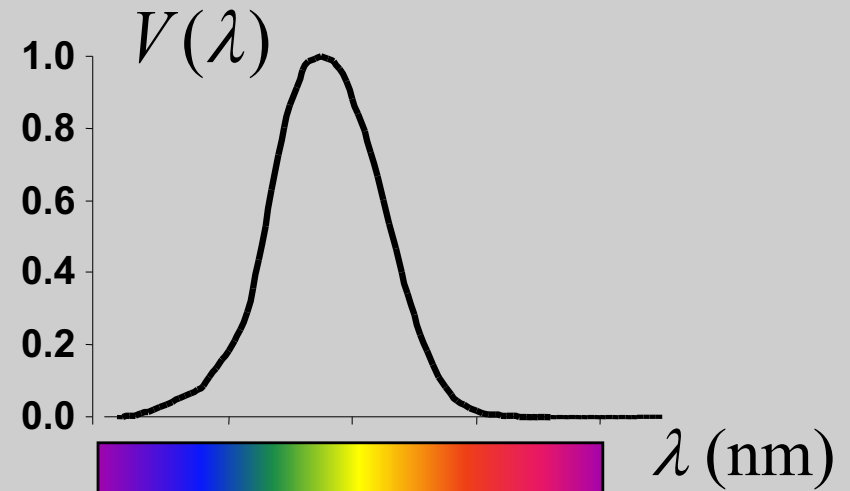
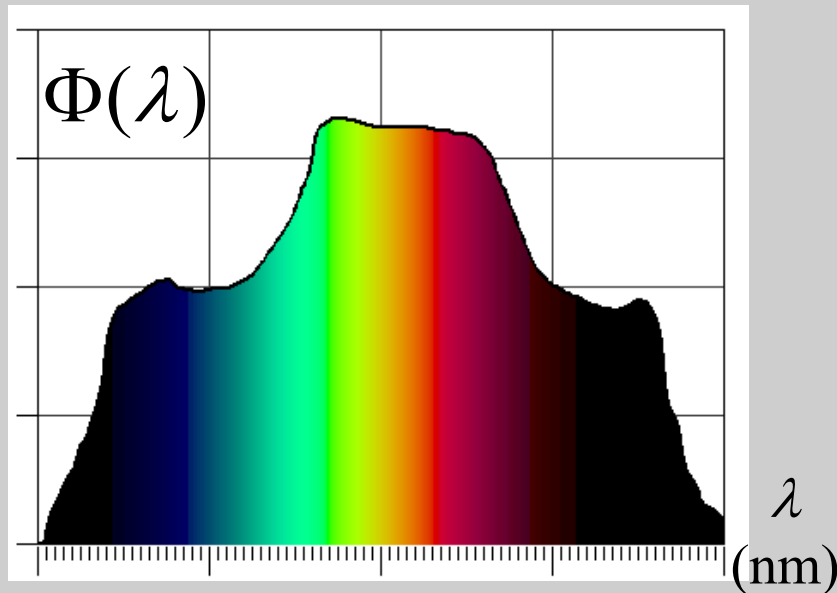
Olho humano: Cones (SML) e Bastonetes (cegos para cor)



Sensibilidade do olho em função do comprimento de onda



Brilho × Luminosidade

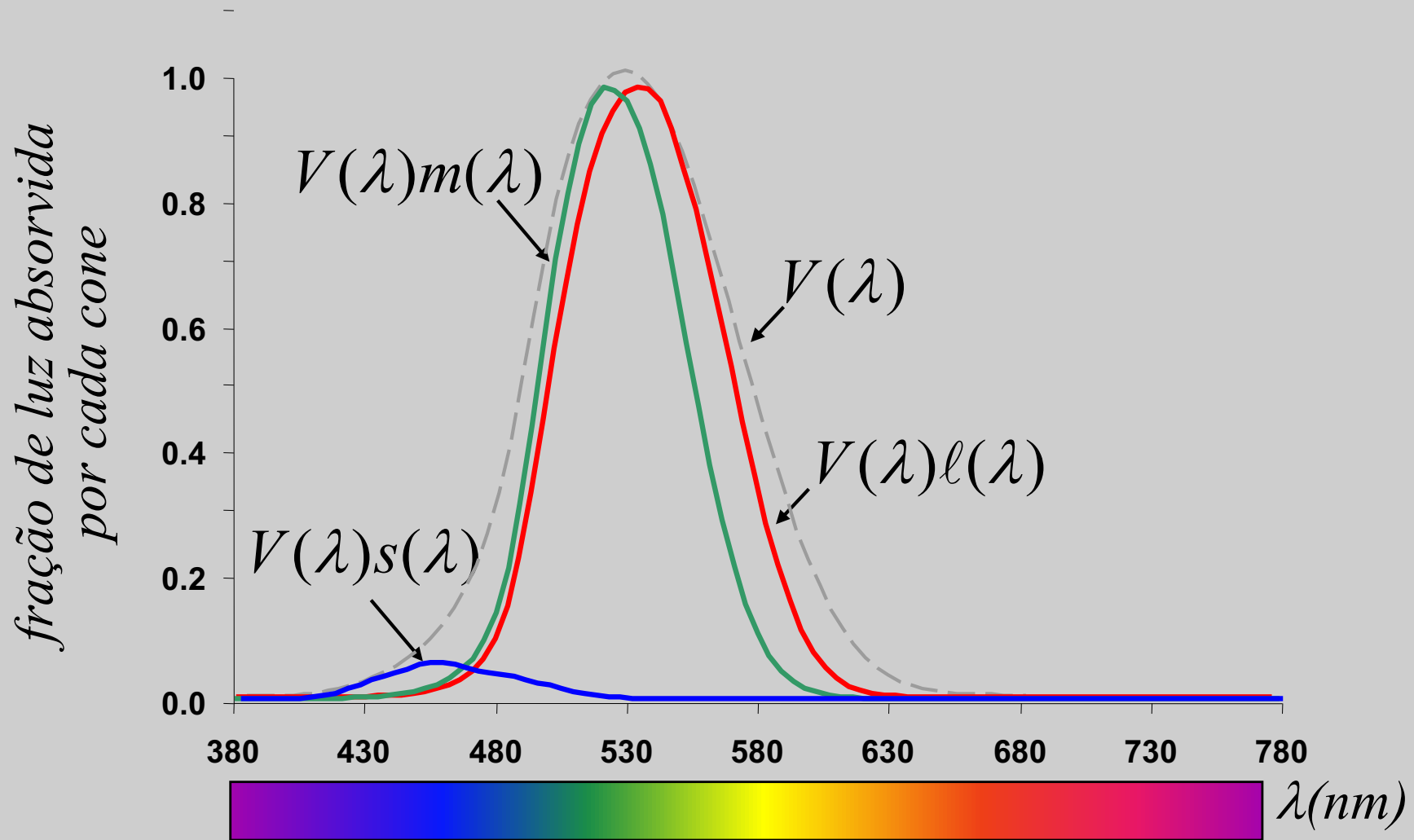


Brilho: $B = \int \Phi(\lambda) d\lambda$ (em Watts)

Luminosidade: $Y = k_m \int V(\lambda) \Phi_\lambda(\lambda) d\lambda$ (em lumens)

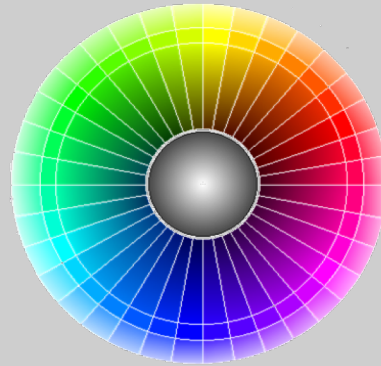
Cor $k_m = 680 \text{ lumes/watt}$

Sensibilidade relativa dos cones



Cor

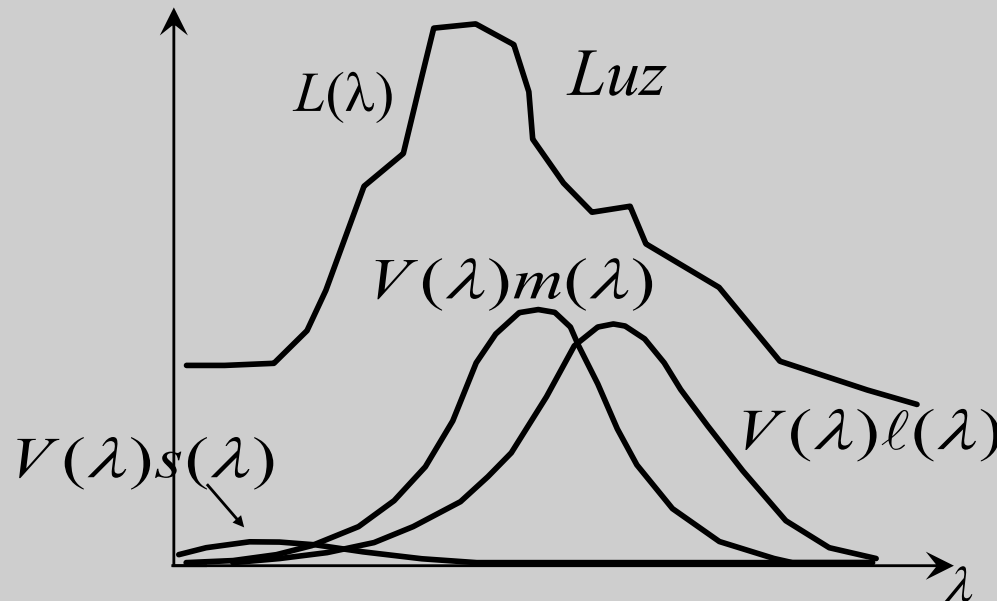
87



Colorimetria

“Medida da sensação de cor”

Medida da sensação de cor e o princípio da tri-cromaticidade

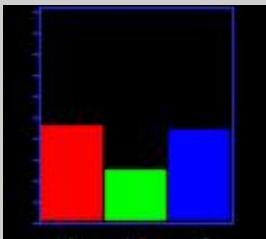


$$\bar{s} = \int L(\lambda)V(\lambda)s(\lambda)d\lambda$$

$$\bar{m} = \int L(\lambda)V(\lambda)m(\lambda)d\lambda$$

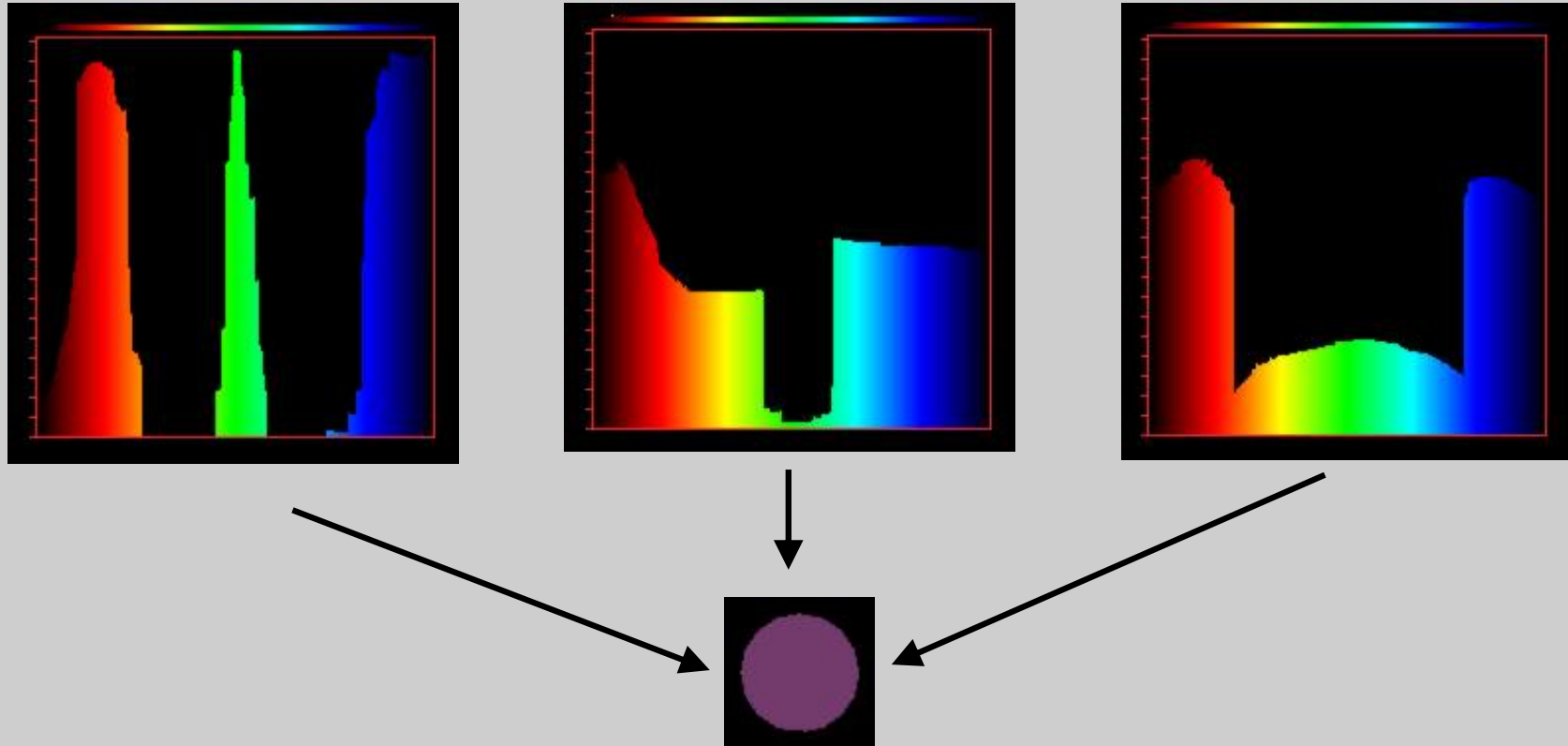
$$\bar{l} = \int L(\lambda)V(\lambda)l(\lambda)d\lambda$$

não é assim! mas...



Tri-cromaticidade: qualquer espectro pode ser representado por três números sem perda de informação para os sistema visual humano

Princípios do metamerismo



Metamerismo: todos os espectros que produzem as mesmas respostas tri-cromáticas são indistinguíveis.

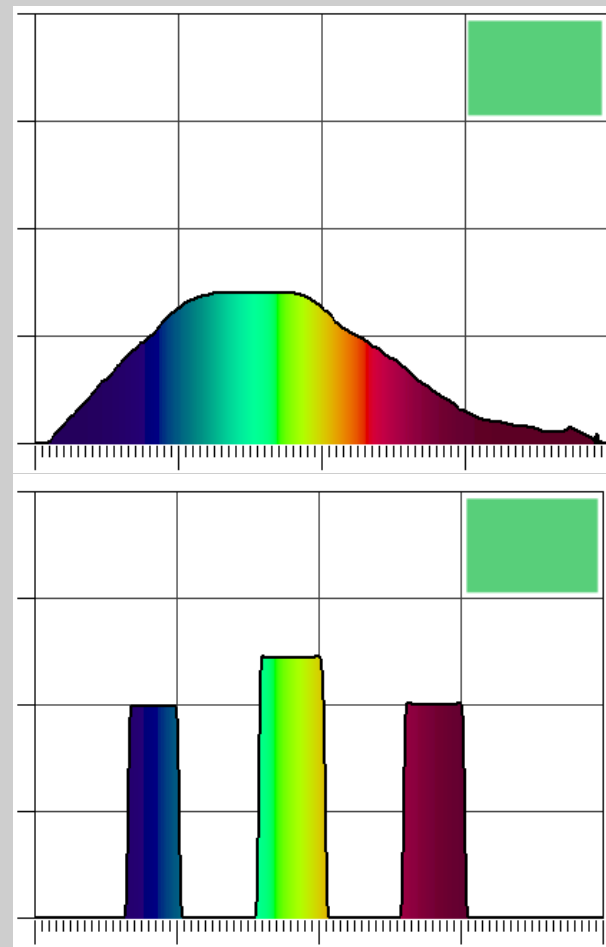
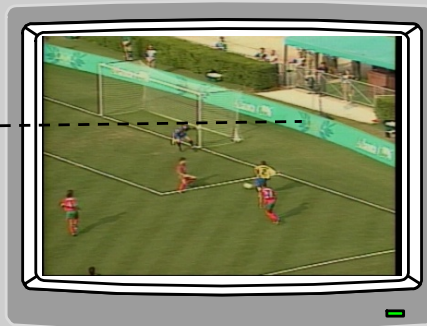
Metamerismo e reprodução de cor em CG

Mundo Real



objetivo: produzir a mesma sensação de cor

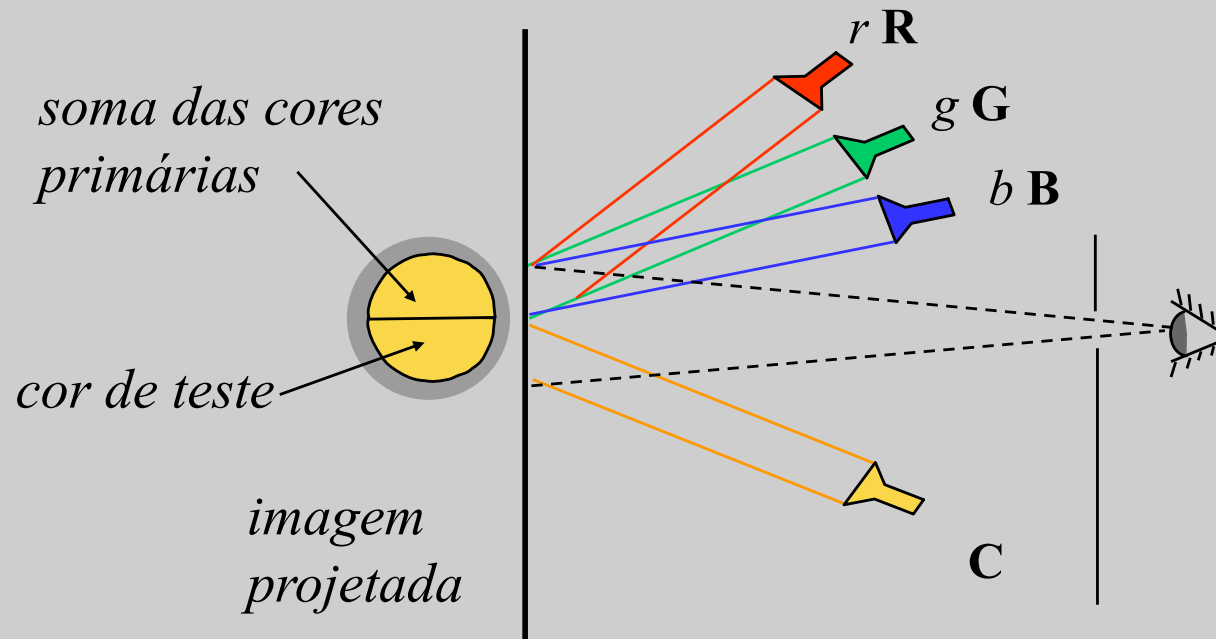
Espaço Virtual



olho só distingue 400 mil cores ($< 2^{19}$)_{Cor} \Rightarrow 19 bits deveriam ser suficientes

1ª Lei de Grassmann

A sensação de cor de qualquer espectro pode ser obtida da mistura de três cores primárias (tri-cromaticidade).

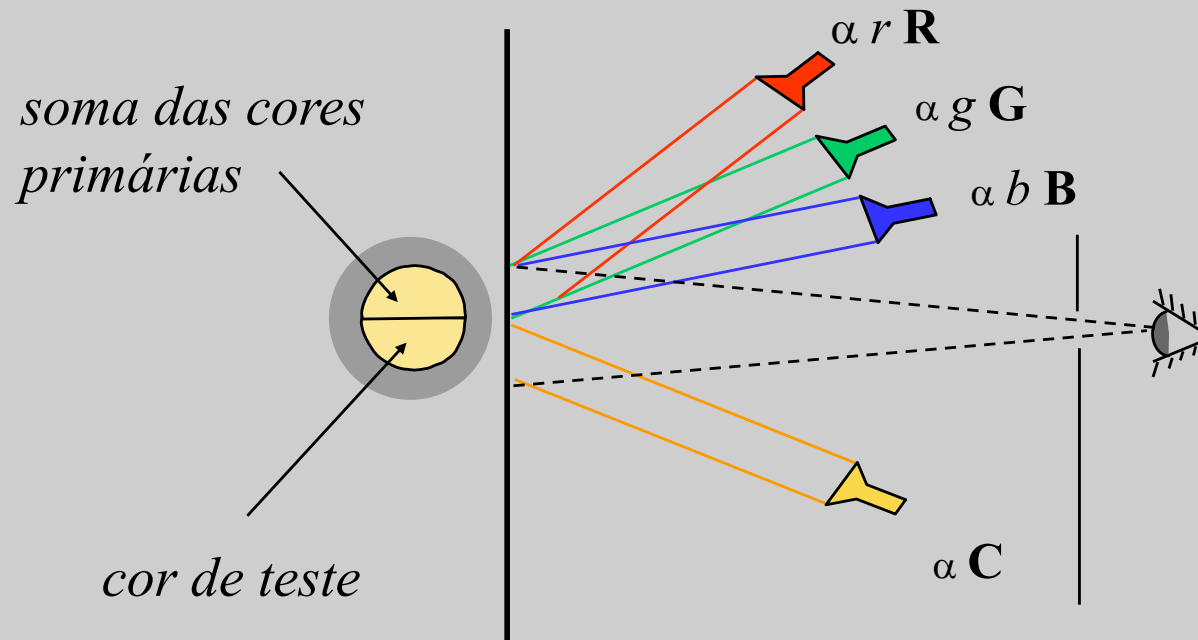


$$\mathbf{C} = r \mathbf{R} + g \mathbf{G} + b \mathbf{B}$$

Cor

2ª Lei de Grassmann

Se os espectros das luzes são intensificadas por um mesmo fator o metamerismo permanece



$$\alpha \mathbf{C} = \alpha r \mathbf{R} + \alpha g \mathbf{G} + \alpha b \mathbf{B}$$

3ª Lei de Grassmann

Se:

$$\mathbf{C}_1 = r_1 \mathbf{R} + g_1 \mathbf{G} + b_1 \mathbf{B}$$

e

$$\mathbf{C}_2 = r_2 \mathbf{R} + g_2 \mathbf{G} + b_2 \mathbf{B}$$

então

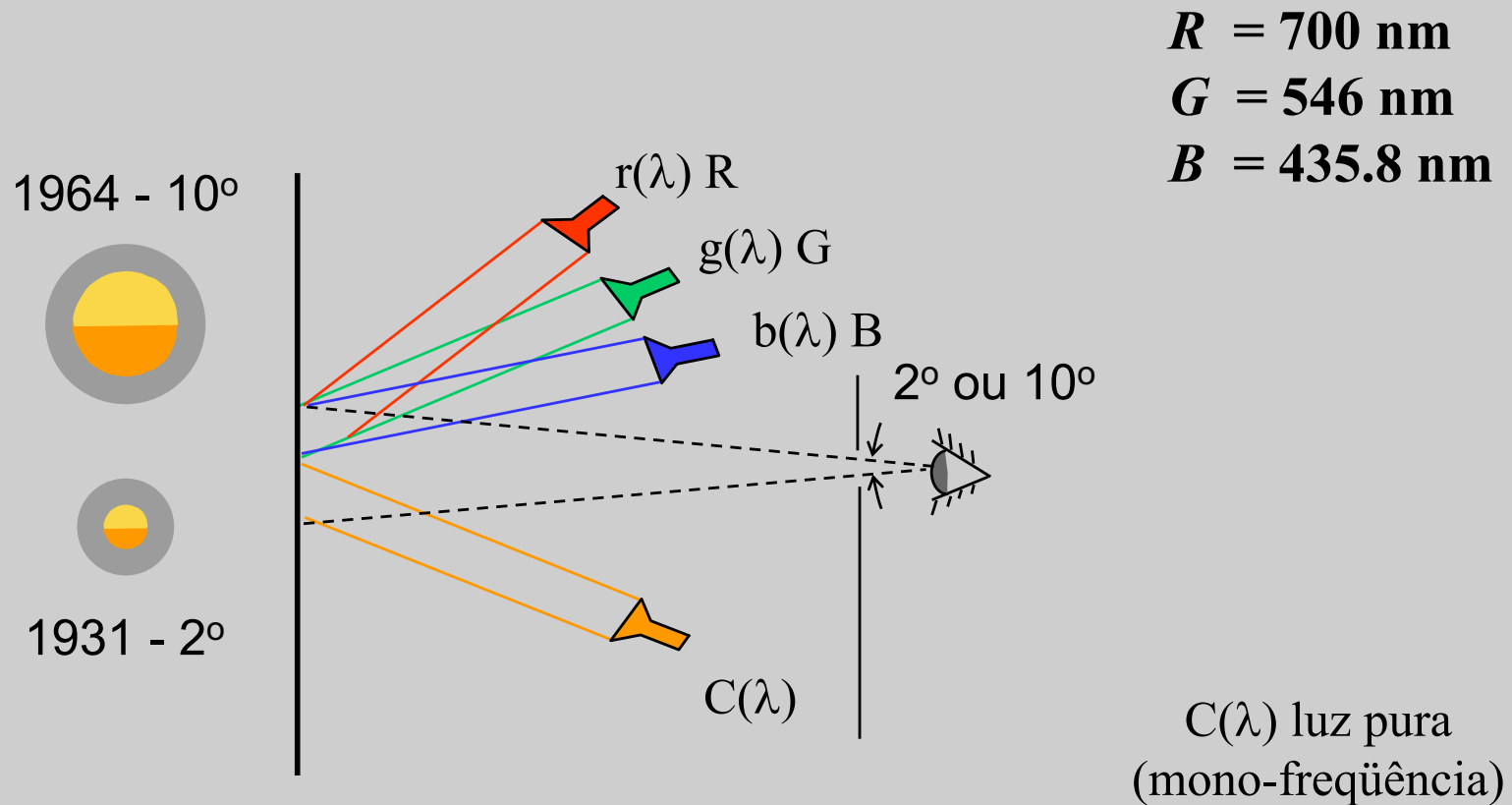
$$\mathbf{C}_1 + \mathbf{C}_2 = (r_1 + r_2) \mathbf{R} + (g_1 + g_2) \mathbf{G} + (b_1 + b_2) \mathbf{B}$$

Sistemas de Cor

Colorimetria e Sistemas de Cores

- Sistemas numéricos absolutos
 - CIE RGB
 - CIE XYZ
 - CIE xyY
 - CIE $L_u^*v^*$
 - $L_a^*b^*$
- Sistemas por exumeração
 - Munsell
 - Pantone
- Sistemas dependentes de dispositivos
 - mRGB
 - CMY
 - CMYK
- Sistemas para especificação interativa
 - HSV
 - HLS

Representação perceptual da cor CIE RGB



$$\mathbf{C}(\lambda) = r(\lambda)\mathbf{R} + g(\lambda)\mathbf{G} + b(\lambda)\mathbf{B}$$

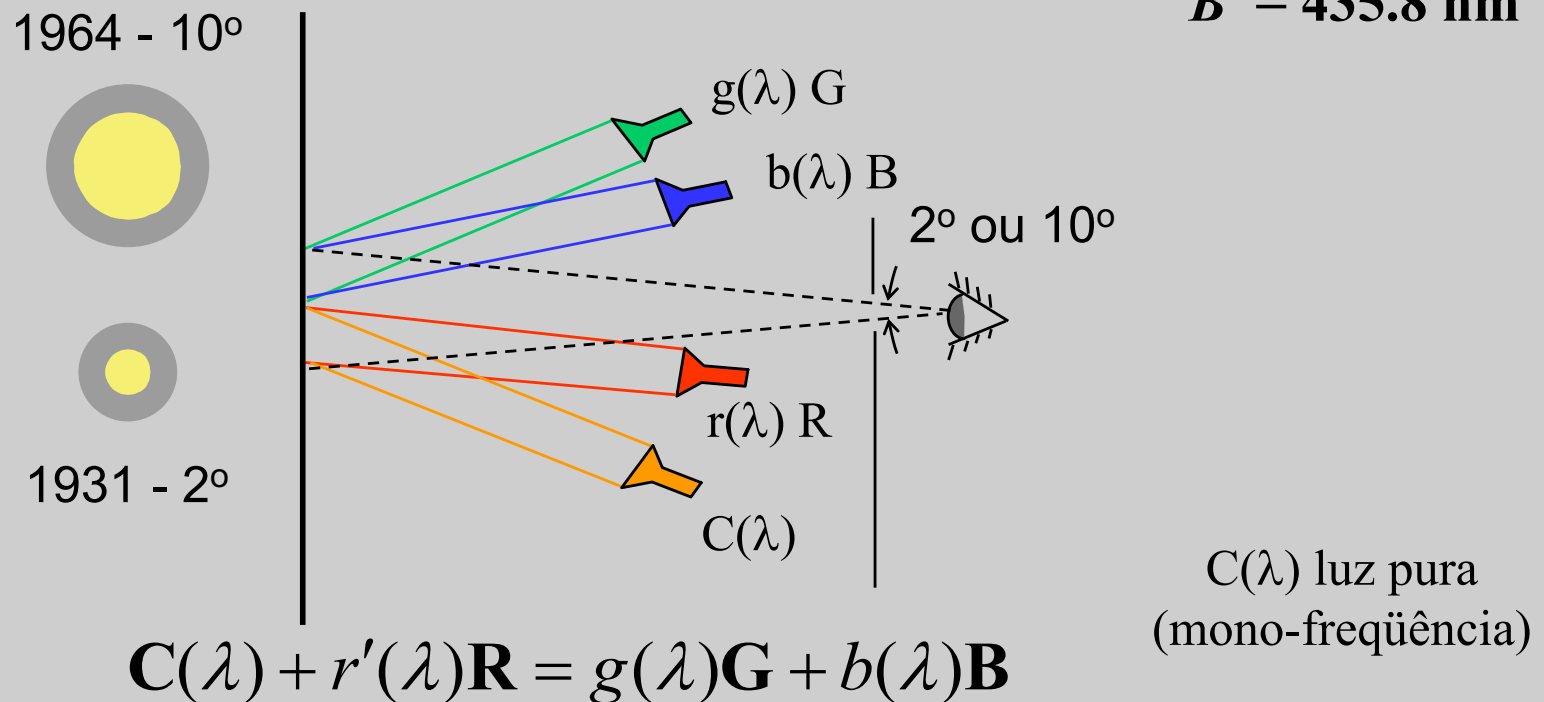
Problema:

Não consegue se representar todas as ^{Cor} cores visíveis (falta saturação)

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Artifício para “subtrair” uma componente

$R = 700 \text{ nm}$
 $G = 546 \text{ nm}$
 $B = 435.8 \text{ nm}$

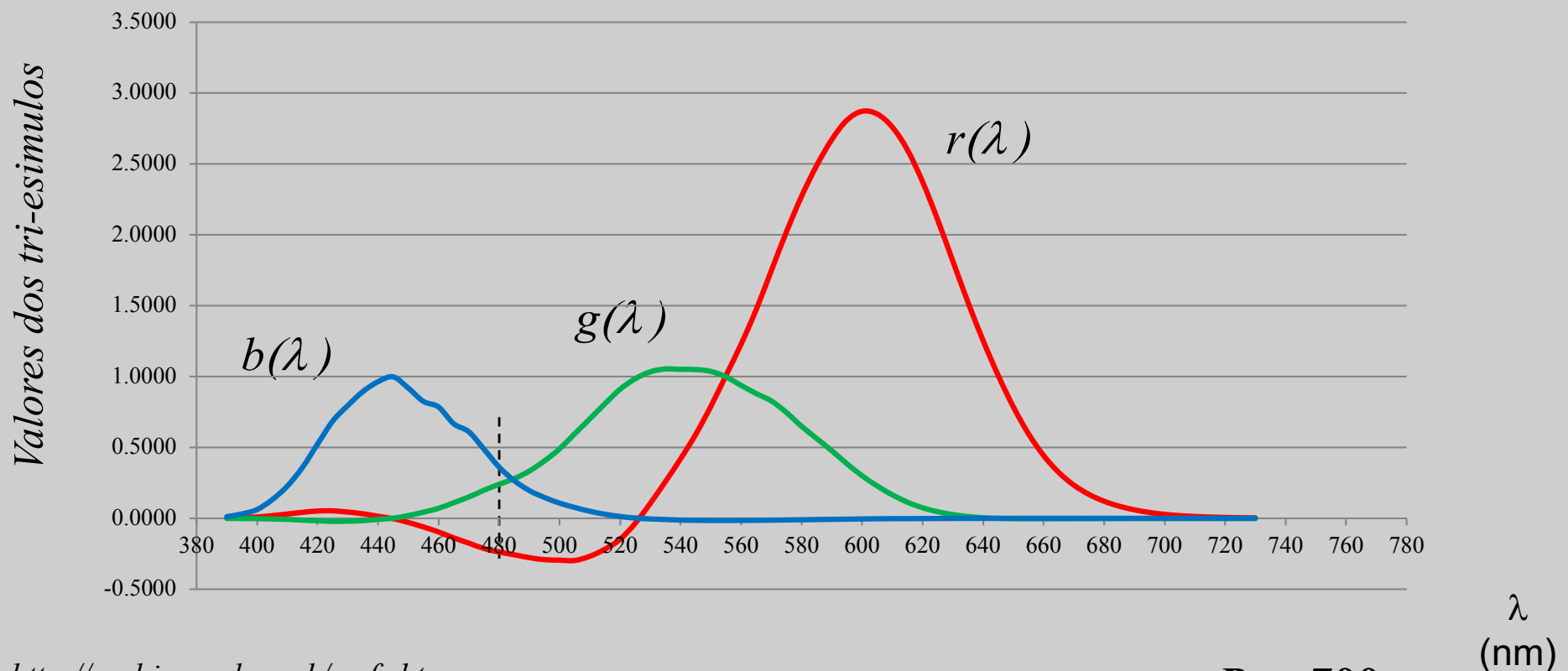


$$C(\lambda) = r(\lambda)\mathbf{R} + g(\lambda)\mathbf{G} + b(\lambda)\mathbf{B}, \quad \text{onde: } r(\lambda) = -r'(\lambda)$$

Cor

Componentes das cores monocromáticas - CIE RGB -

$$C(\lambda) = r(\lambda) R + g(\lambda) G + b(\lambda) B$$



<http://cvrl.ioo.ucl.ac.uk/cmfs.htm>

Combinação de três cores (RGB) para reproduzir as cores espectrais

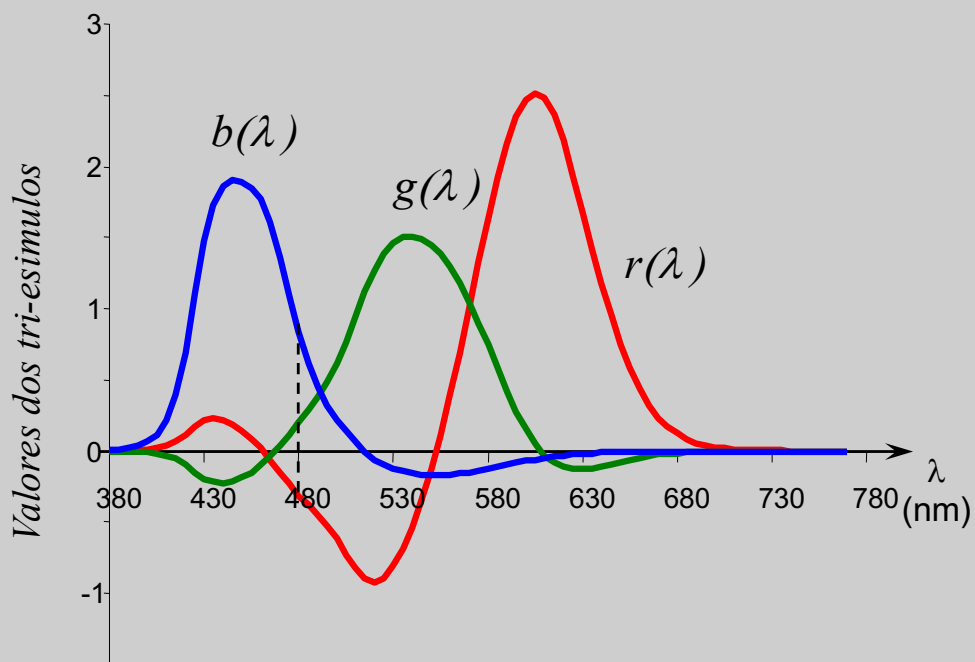
Cor

R = 700 nm

G = 546.1 nm

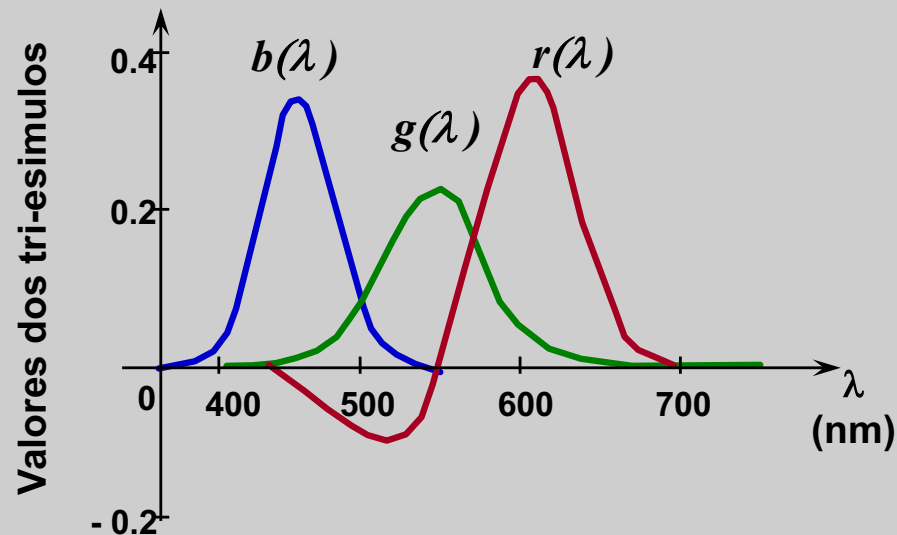
B = 435.8 nm

CIE RGB 2º 1931



λ	\bar{r}	\bar{g}	\bar{b}	λ	\bar{r}	\bar{g}	\bar{b}
390	0.0018	-0.0005	0.0122	565	1.4727	0.8804	-0.0138
395	0.0046	-0.0010	0.0311	570	1.7476	0.8284	-0.0127
400	0.0096	-0.0022	0.0624	575	2.0214	0.7469	-0.0114
405	0.0190	-0.0044	0.1316	580	2.2724	0.6493	-0.0099
410	0.0308	-0.0072	0.2275	585	2.4896	0.5632	-0.0084
415	0.0425	-0.0126	0.3590	590	2.6725	0.4768	-0.0070
420	0.0517	-0.0167	0.5240	595	2.8093	0.3848	-0.0057
425	0.0528	-0.0212	0.6859	600	2.8717	0.3007	-0.0043
430	0.0443	-0.0199	0.7960	605	2.8525	0.2285	-0.0029
435	0.0322	-0.0161	0.8946	610	2.7601	0.1658	-0.0023
440	0.0148	-0.0073	0.9640	615	2.5989	0.1137	-0.0020
445	-0.0023	0.0014	0.9981	620	2.3743	0.0747	-0.0015
450	-0.0291	0.0196	0.9188	625	2.1054	0.0465	-0.0009
455	-0.0607	0.0435	0.8249	630	1.8145	0.0263	-0.0006
460	-0.0962	0.0710	0.7855	635	1.5247	0.0127	-0.0003
465	-0.1376	0.1102	0.6672	640	1.2543	0.0045	-0.0001
470	-0.1749	0.1509	0.6110	645	1.0076	0.0001	0.0000
475	-0.2126	0.1979	0.4883	650	0.7864	-0.0020	0.0001
480	-0.2378	0.2404	0.3620	655	0.5966	-0.0026	0.0002
485	-0.2567	0.2799	0.2663	660	0.4432	-0.0026	0.0002
490	-0.2773	0.3335	0.1959	665	0.3241	-0.0023	0.0002
495	-0.2913	0.4052	0.1473	670	0.2346	-0.0019	0.0002
500	-0.2950	0.4906	0.1075	675	0.1688	-0.0014	0.0001
505	-0.2971	0.5967	0.0767	680	0.1209	-0.0011	0.0001
510	-0.2676	0.7018	0.0502	685	0.0858	-0.0008	0.0000
515	-0.2173	0.8085	0.0288	690	0.0603	-0.0006	0.0000
520	-0.1477	0.9108	0.0133	695	0.0415	-0.0004	0.0000
525	-0.0352	0.9848	0.0021	700	0.0281	-0.0003	0.0000
530	0.1061	1.0339	-0.0042	705	0.0191	-0.0002	0.0000
535	0.2598	1.0538	-0.0083	710	0.0133	-0.0001	0.0000
540	0.4198	1.0512	-0.0122	715	0.0094	-0.0001	0.0000
545	0.5926	1.0498	-0.0140	720	0.0065	-0.0001	0.0000
550	0.7900	1.0368	-0.0147	725	0.0045	0.0000	0.0000
555	1.0078	0.9983	-0.0149	730	0.0032	0.0000	0.0000
560	1.2283	0.9378	-0.0146				

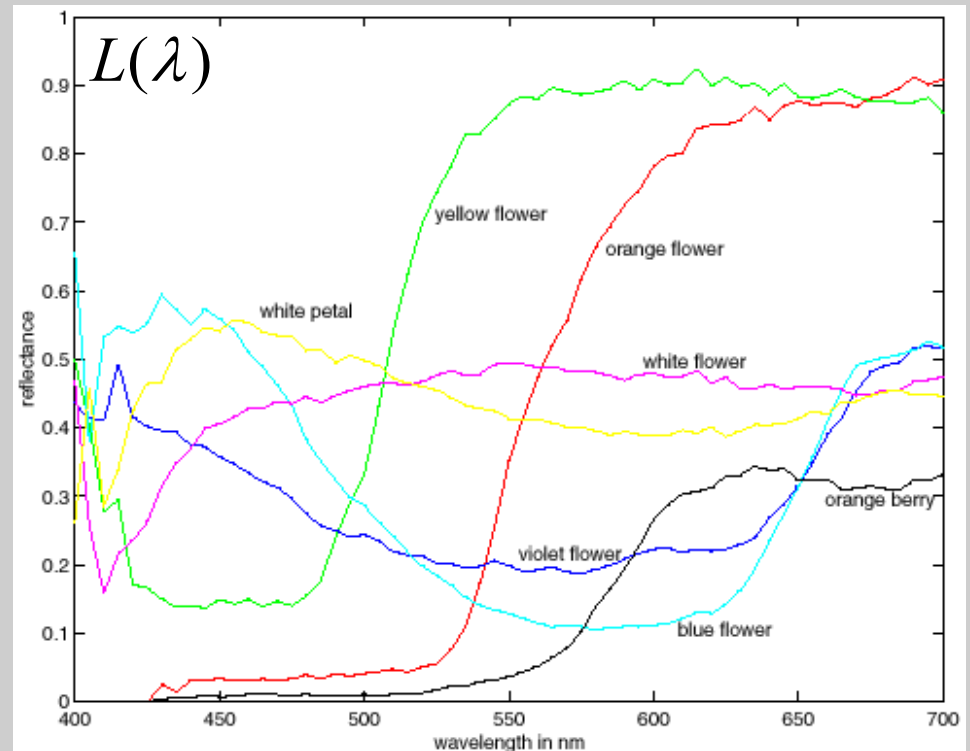
Componentes das cores monocromáticas - CIE RGB -



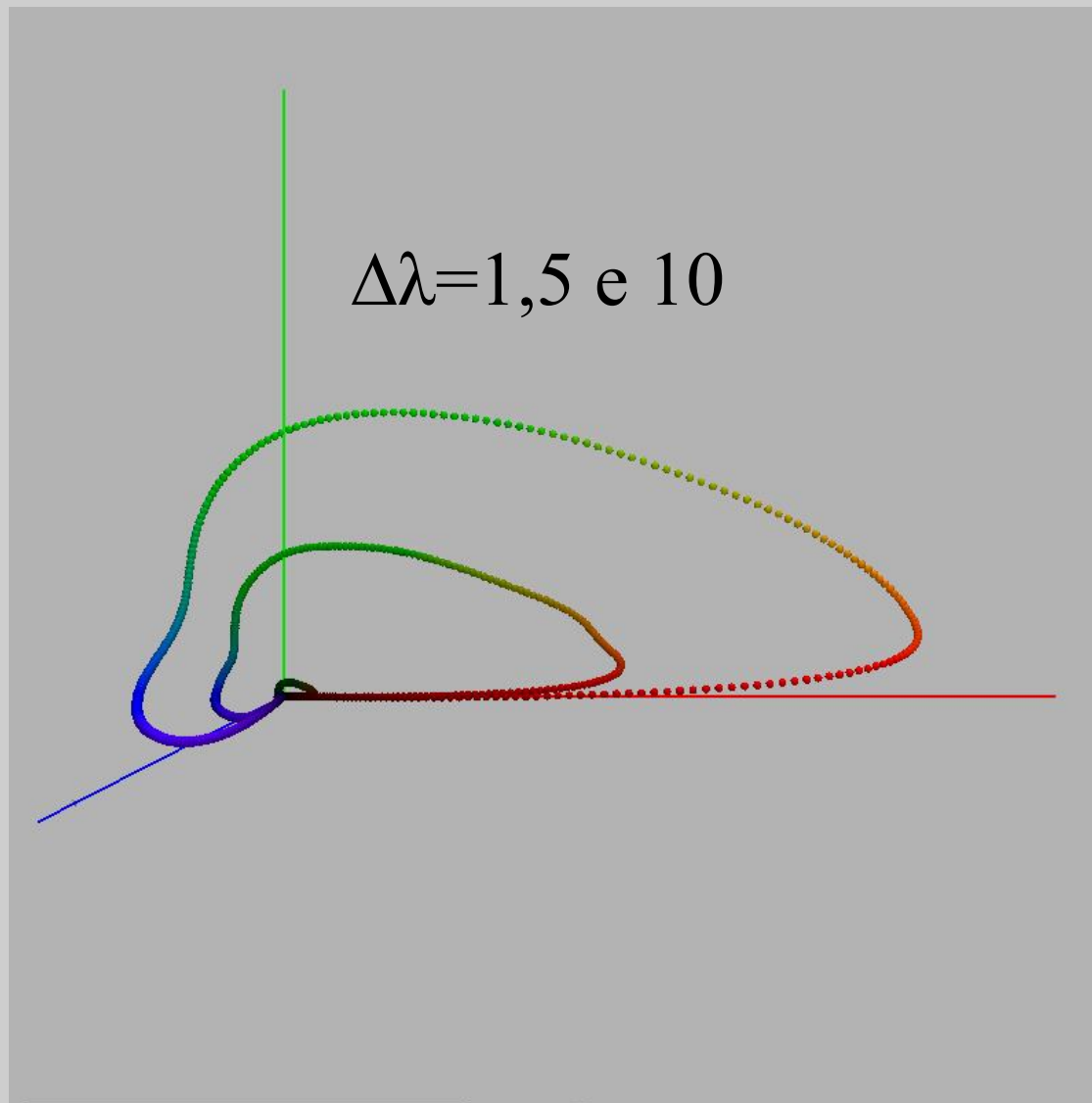
$$R = k \int \Phi(\lambda) r(\lambda) d\lambda$$

$$G = k \int \Phi(\lambda) g(\lambda) d\lambda$$

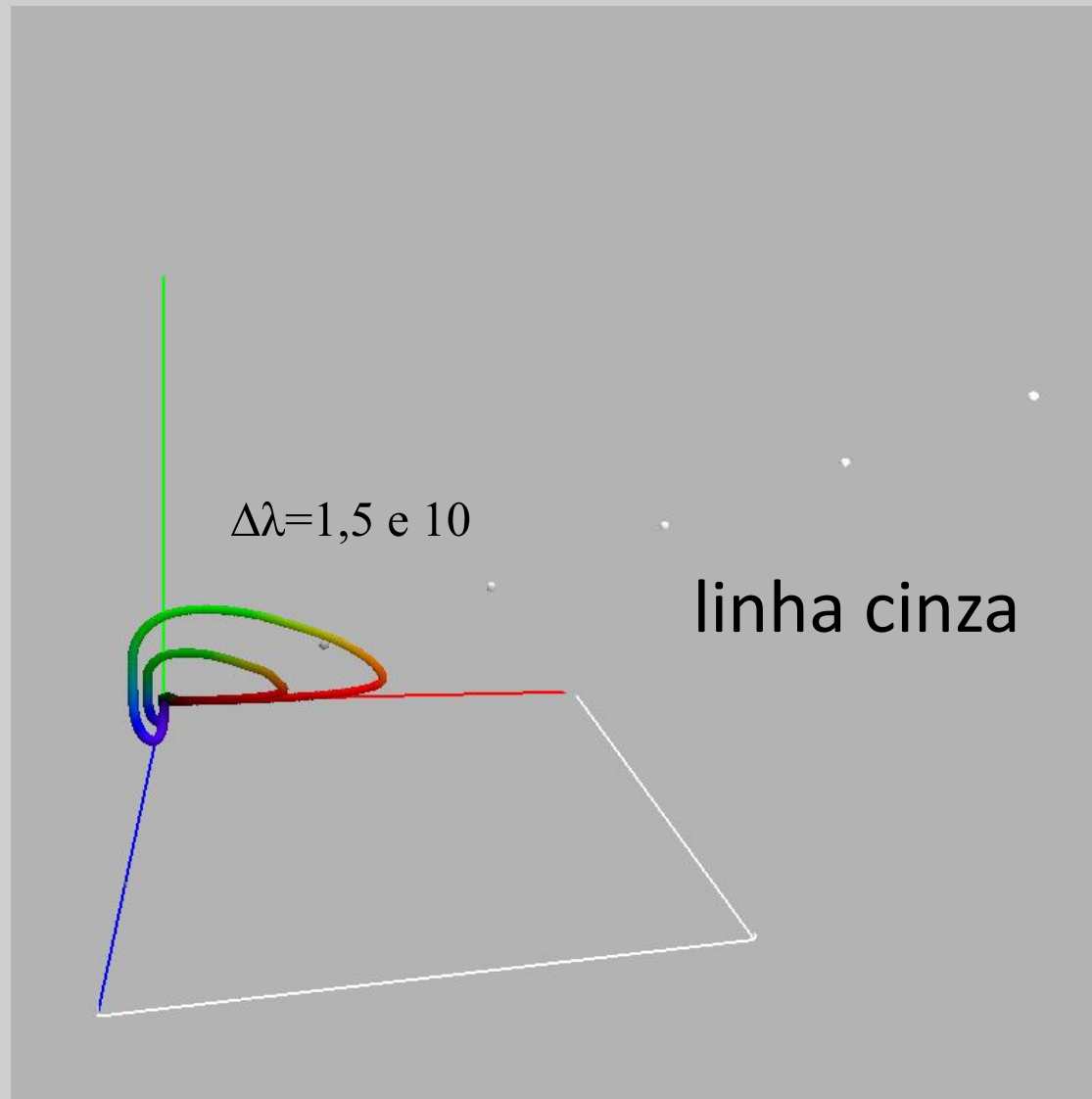
$$B = k \int \Phi(\lambda) b(\lambda) d\lambda$$



CIERGB curvas de saturação máxima

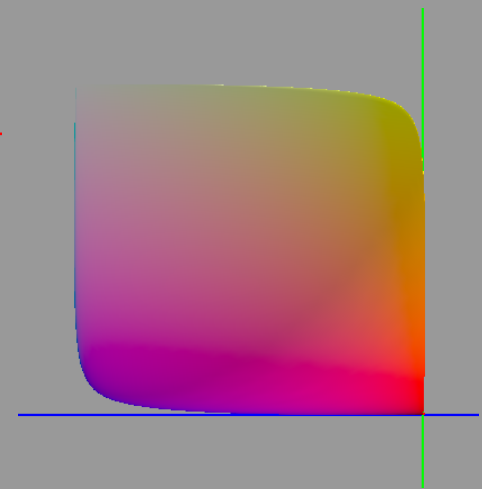
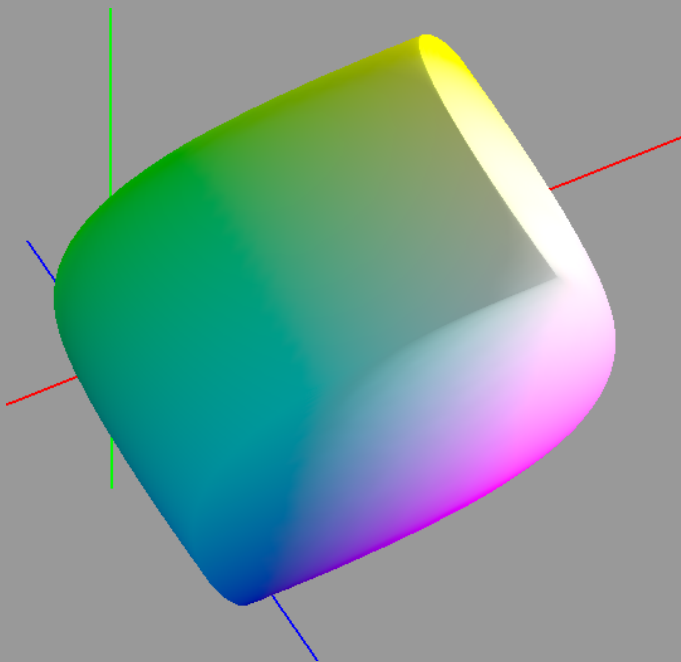
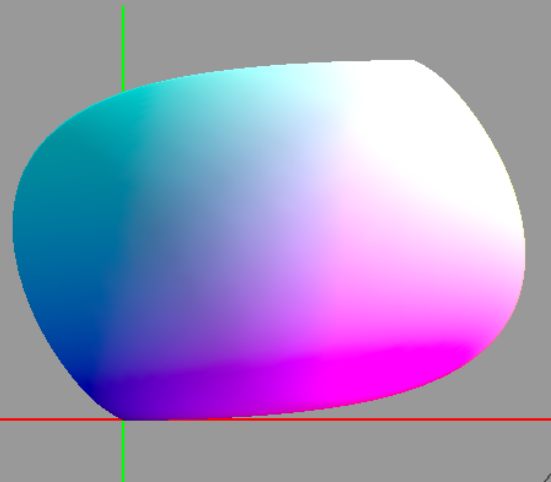
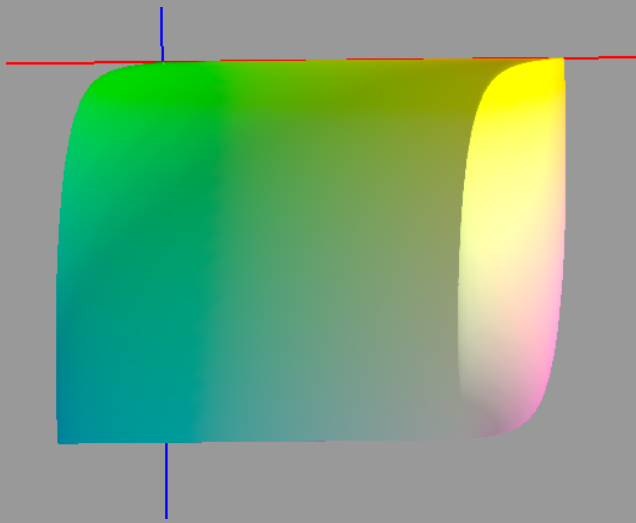


CIERGB curvas de saturação máxima



CIERGB com D65

Gamut de todas as superfícies visíveis

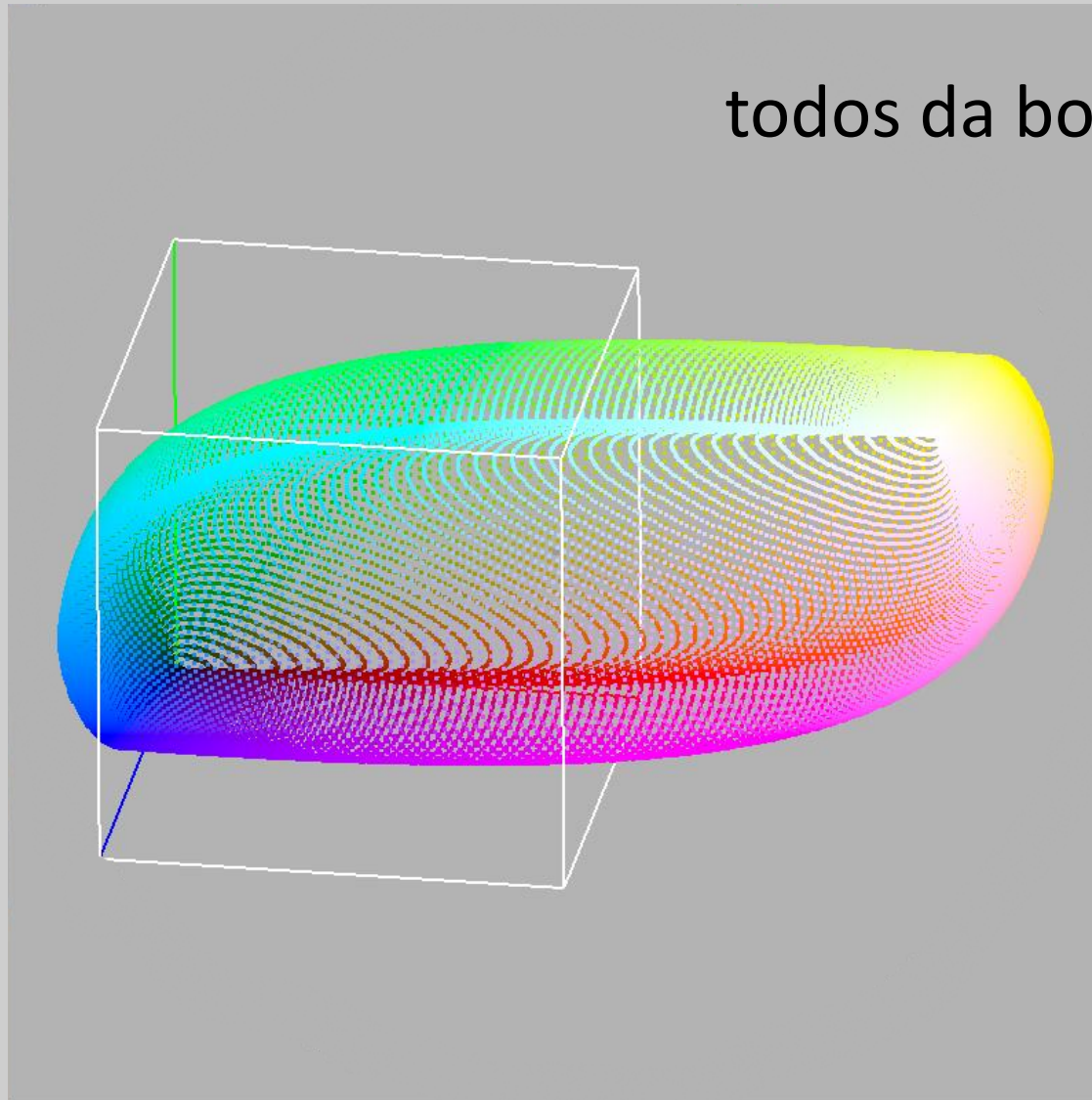


Cor

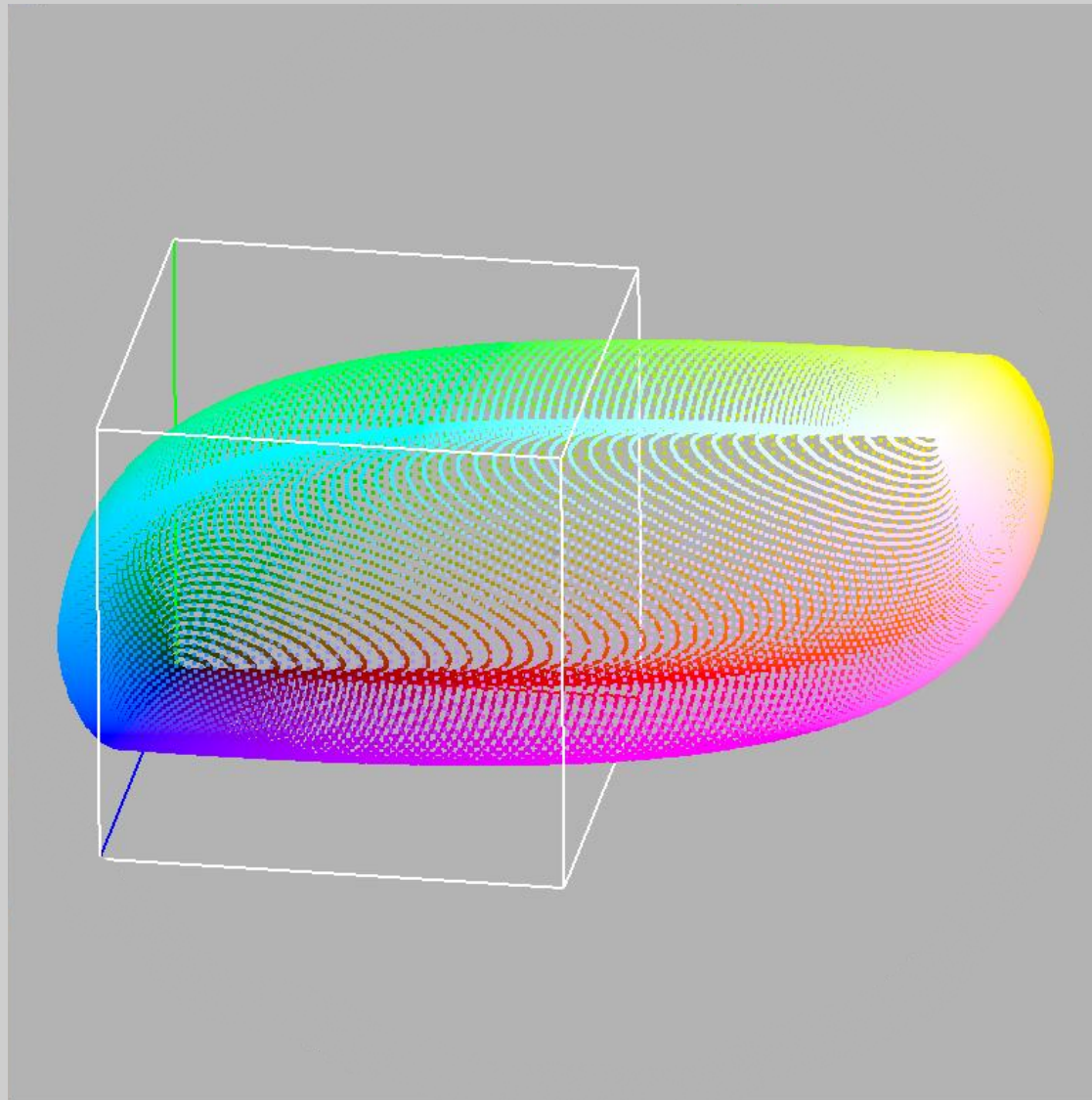
104

CIERGB com D65

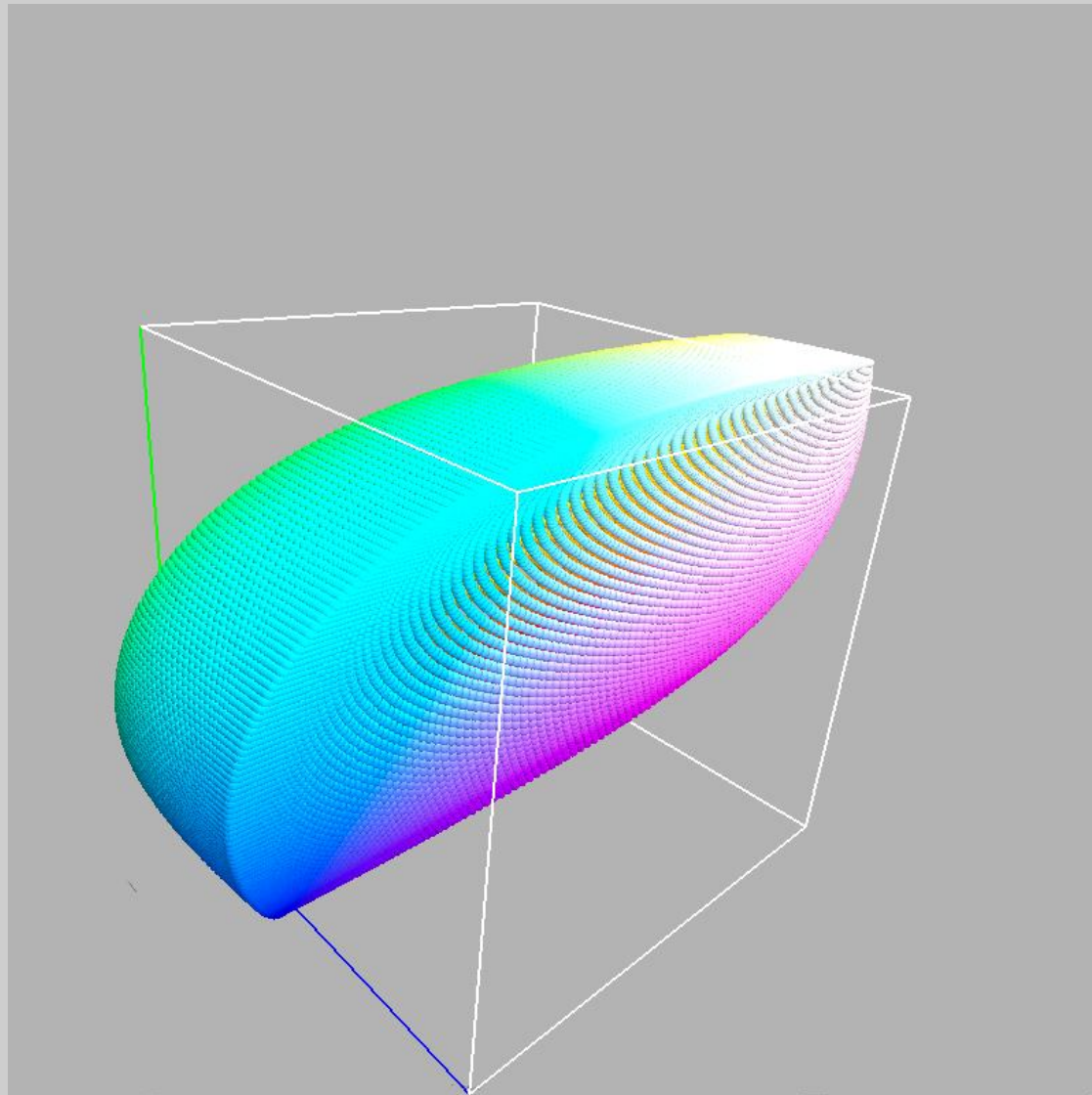
todos da borda



CIERGB com D65



CIERGB com D65



Transformação CIERGB para CIEXYZ

R=700.0 *nm*, **G**=546.1 *nm*, **B**=435.8 *nm*

CIE xyz				
	Red	Green	Blue	Equal E
<i>x</i>	0.73467	0.27376	0.16658	0.33333
<i>y</i>	0.26533	0.71741	0.00886	0.33333
<i>z</i>	0.00000	0.00833	0.82456	0.33333

Cor correspondente a um *RGB*

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R \\ Y_R \\ Z_R \end{pmatrix} R + \begin{pmatrix} X_G \\ Y_G \\ Z_G \end{pmatrix} G + \begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix} B$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Relação entre XYZ e xyz

$$x_R = \frac{X_R}{X_R + Y_R + Z_R} = \frac{X_R}{\Sigma_R}$$

$$y_R = \frac{Y_R}{X_R + Y_R + Z_R} = \frac{Y_R}{\Sigma_R}$$

$$z_R = \frac{Z_R}{X_R + Y_R + Z_R} = \frac{Z_R}{\Sigma_R}$$

$$X_R = x_R \Sigma_R$$

$$Y_R = y_R \Sigma_R$$

$$Z_R = z_R \Sigma_R$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} x_R \Sigma_R & x_G \Sigma_G & x_G \Sigma_B \\ y_R \Sigma_R & y_G \Sigma_G & y_G \Sigma_B \\ z_R \Sigma_R & z_G \Sigma_G & z_G \Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.73467 \Sigma_R & 0.27376 \Sigma_G & 0.16658 \Sigma_B \\ 0.26533 \Sigma_R & 0.71741 \Sigma_G & 0.00886 \Sigma_B \\ 0.00000 \Sigma_R & 0.00883 \Sigma_G & 0.82456 \Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Branco de referência D65

CIE	Equal E
x_w	0.333333
y_w	0.333333
z_w	0.333333

$$Y_W = 1.0$$

$$X_W = x_w \Sigma_W = 0.333333 \Sigma_W$$

$$Y_W = y_w \Sigma_W = 0.333333 \Sigma_W$$

$$Z_W = z_w \Sigma_W = 0.333333 \Sigma_W$$

$$\Sigma_W = \frac{1}{0.333333} = 3.00000$$

$$X_W = \frac{0.333333}{0.333333} = 1.00000$$

$$Z_W = \frac{0.333333}{0.333333} = 1.00000$$

Reprodução do branco D65

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.73467\Sigma_R & 0.27376\Sigma_G & 0.16658\Sigma_B \\ 0.26533\Sigma_R & 0.71741\Sigma_G & 0.00886\Sigma_B \\ 0.00000\Sigma_R & 0.00883\Sigma_G & 0.82456\Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \begin{bmatrix} 0.73467\Sigma_R & 0.27376\Sigma_G & 0.16658\Sigma_B \\ 0.26533\Sigma_R & 0.71741\Sigma_G & 0.00886\Sigma_B \\ 0.00000\Sigma_R & 0.00883\Sigma_G & 0.82456\Sigma_B \end{bmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

Resolvendo os Σ 's

$$\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \begin{bmatrix} 0.73467\Sigma_R & 0.27376\Sigma_G & 0.16658\Sigma_B \\ 0.26533\Sigma_R & 0.71741\Sigma_G & 0.00886\Sigma_B \\ 0.00000\Sigma_R & 0.00883\Sigma_G & 0.82456\Sigma_B \end{bmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} 1.0 \\ 1.0 \\ 1.0 \end{pmatrix} = \begin{bmatrix} 0.73467 & 0.27376 & 0.16658 \\ 0.26533 & 0.71741 & 0.00886 \\ 0.00000 & 0.00883 & 0.82456 \end{bmatrix} \begin{pmatrix} \Sigma_R \\ \Sigma_G \\ \Sigma_B \end{pmatrix}$$

$$\begin{pmatrix} \Sigma_R \\ \Sigma_G \\ \Sigma_B \end{pmatrix} = \begin{pmatrix} 0.66695 \\ 1.13241 \\ 1.20064 \end{pmatrix}$$

Cor

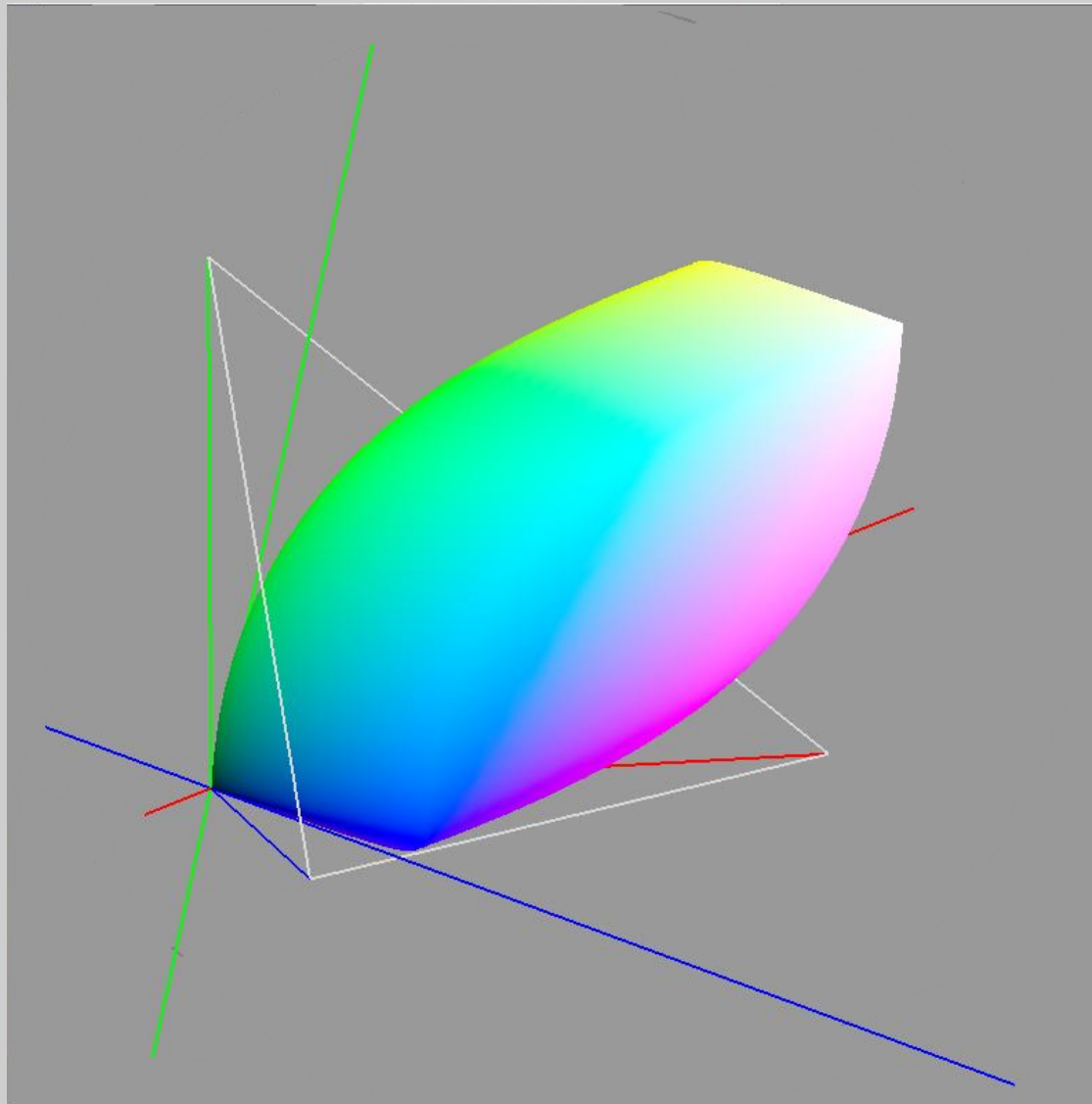
Relação entre CIE XYZ e CIE RGB

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

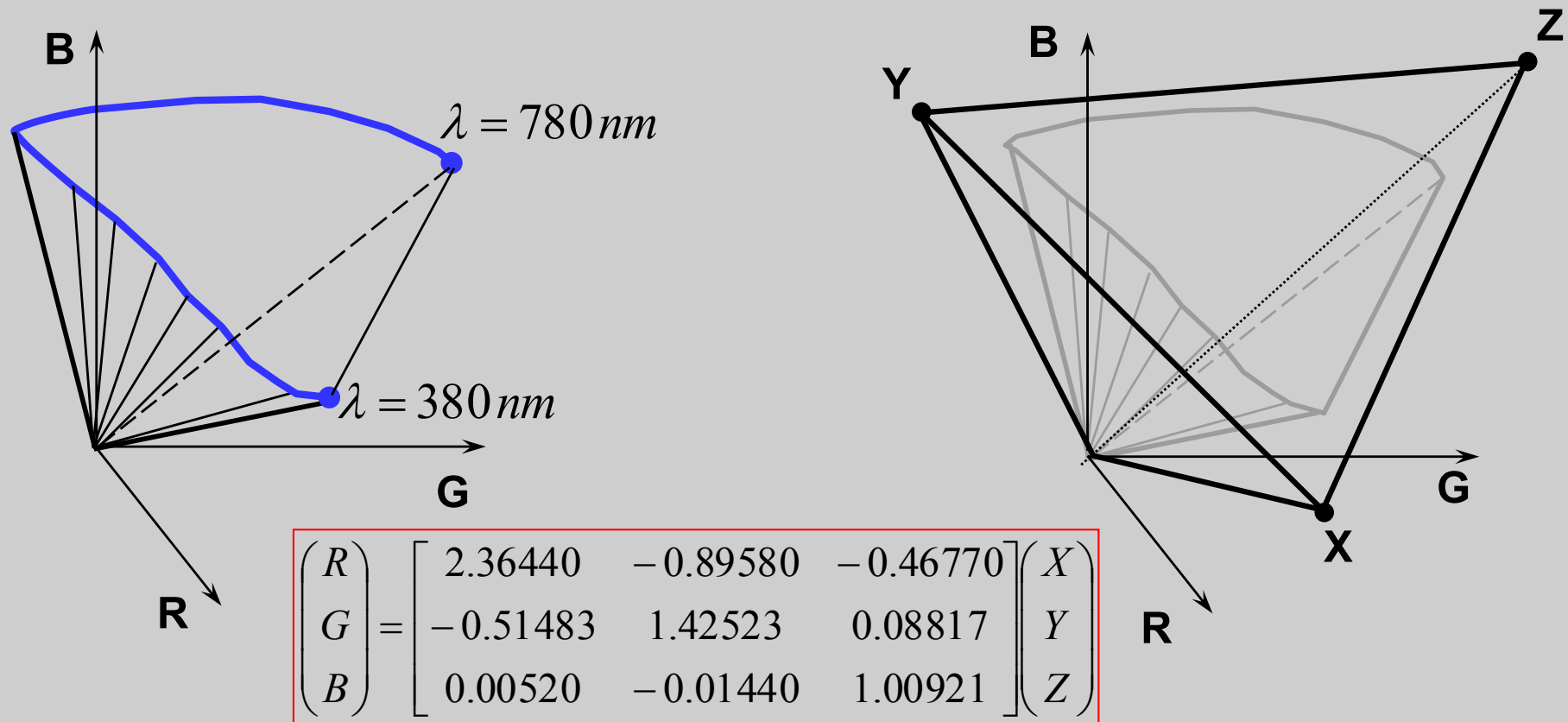
ou

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{bmatrix} 2.36440 & -0.89580 & -0.46770 \\ -0.51483 & 1.42523 & 0.08817 \\ 0.00520 & -0.01440 & 1.00921 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

CIERGB e base XYZ (D65)



Mudança de Base do Espaço de Cor



Conversão da base CIE RGB para CIE XYZ

$$\mathbf{C}(\lambda) = r(\lambda)\mathbf{R} + g(\lambda)\mathbf{G} + b(\lambda)\mathbf{B}$$

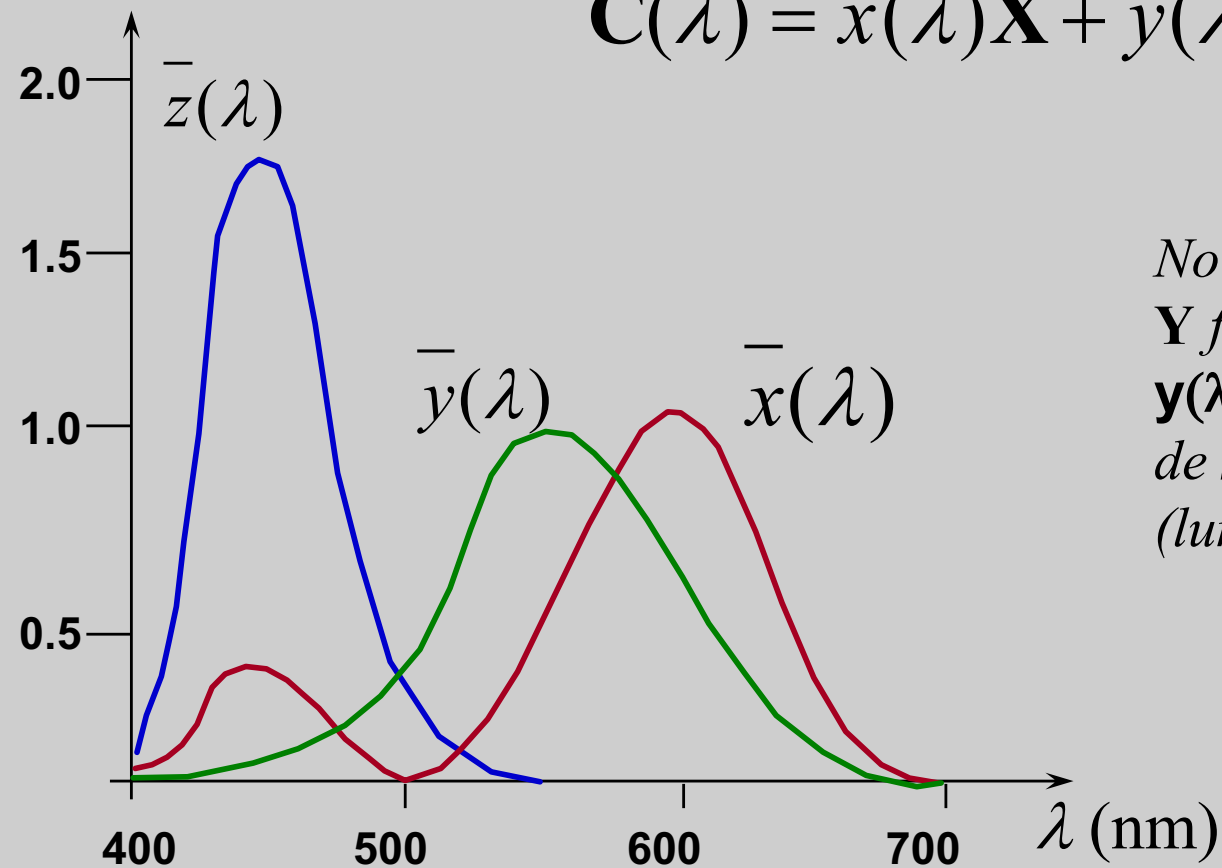
$$\begin{bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{bmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

$$\mathbf{C}(\lambda) = \bar{x}(\lambda)\mathbf{X} + \bar{y}(\lambda)\mathbf{Y} + \bar{z}(\lambda)\mathbf{Z}$$

Componentes das cores monocromáticas - CIE XYZ -

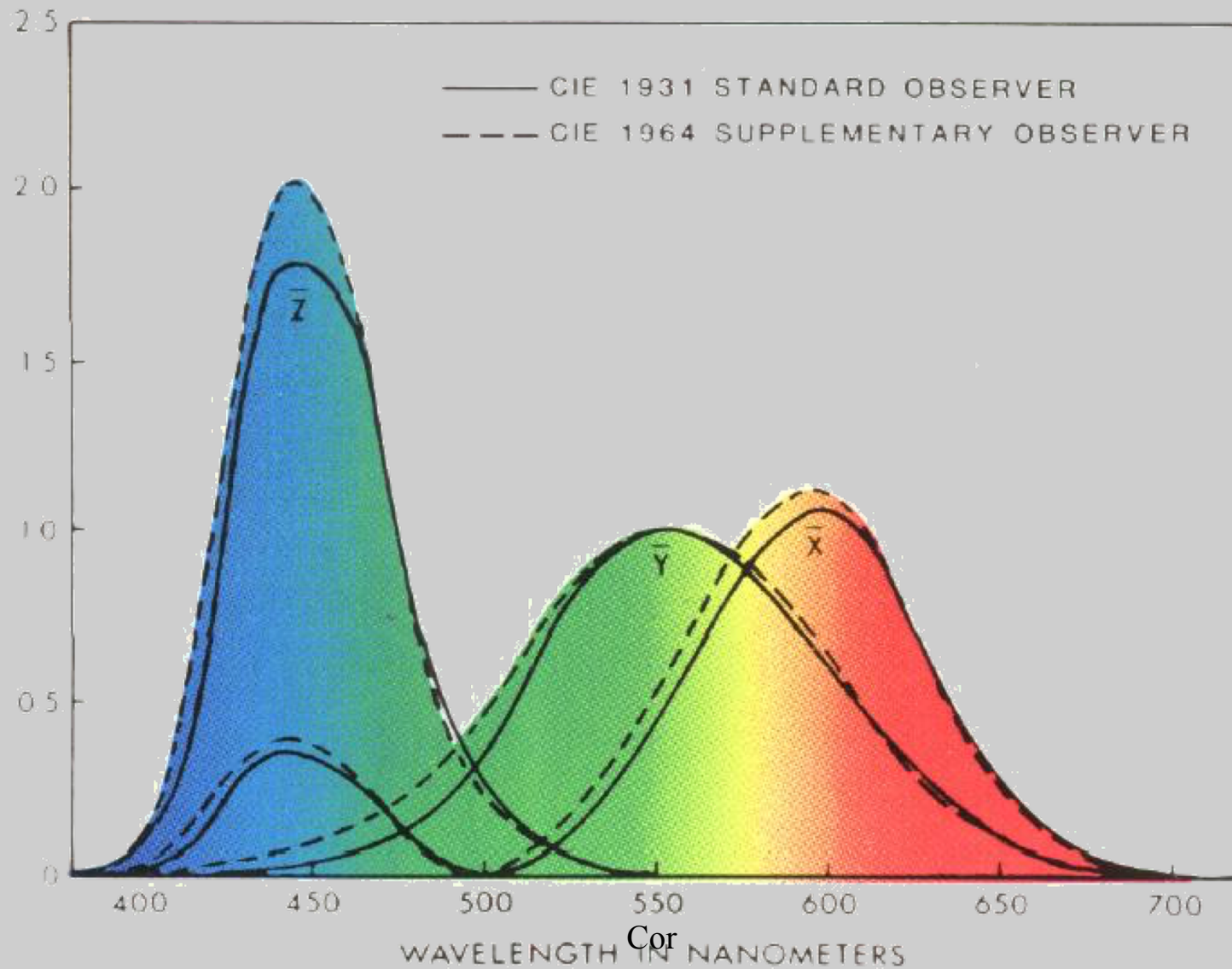
Cores Básicas do CIE 1931

$$C(\lambda) = \bar{x}(\lambda)X + \bar{y}(\lambda)Y + \bar{z}(\lambda)Z$$

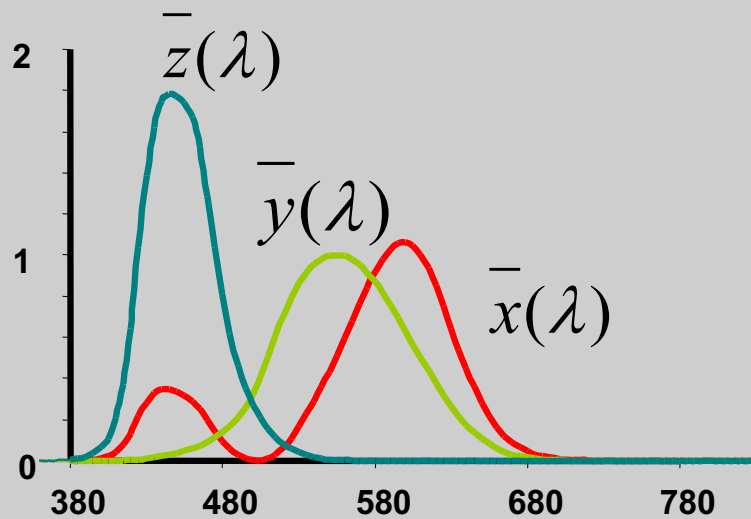


*Nota: No CIE 1931
Y foi escolhida de forma a
y(λ) ser semelhante à curva
de sensibilidade do olho
(luminância)*

CIE XYZ (2° e 10°)

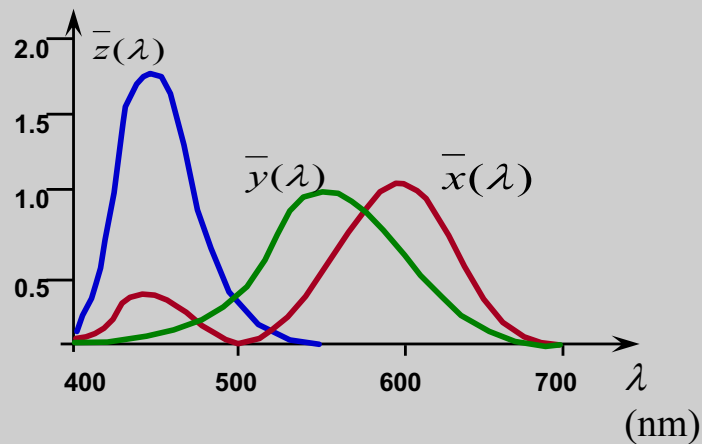
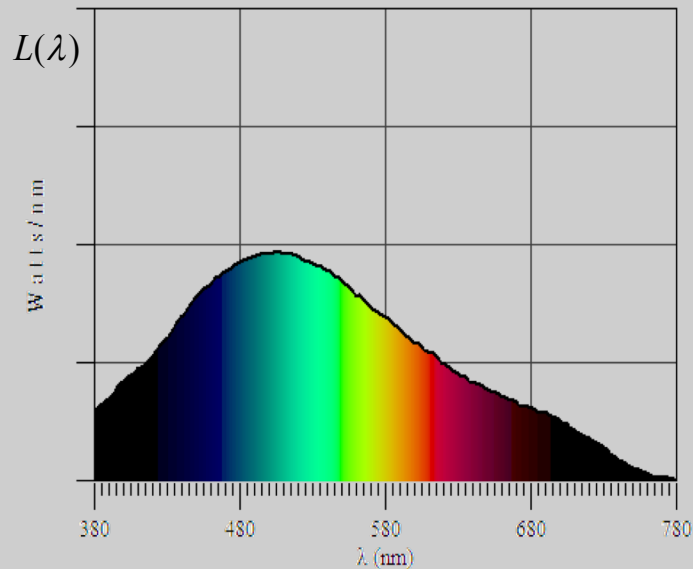


CIE XYZ 2° 1931



λ	\bar{x}	\bar{y}	\bar{z}	λ	\bar{x}	\bar{y}	\bar{z}
390	0.0042	0.0001	0.0201	565	0.6784	0.9786	0.0027
395	0.0077	0.0002	0.0362	570	0.7621	0.9520	0.0021
400	0.0143	0.0004	0.0679	575	0.8425	0.9154	0.0018
405	0.0232	0.0006	0.1102	580	0.9163	0.8700	0.0017
410	0.0435	0.0012	0.2074	585	0.9786	0.8163	0.0014
415	0.0776	0.0022	0.3713	590	1.0263	0.7570	0.0011
420	0.1344	0.0040	0.6456	595	1.0567	0.6949	0.0010
425	0.2148	0.0073	1.0391	600	1.0622	0.6310	0.0008
430	0.2839	0.0116	1.3856	605	1.0456	0.5668	0.0006
435	0.3285	0.0168	1.6230	610	1.0026	0.5030	0.0003
440	0.3483	0.0230	1.7471	615	0.9384	0.4412	0.0002
445	0.3481	0.0298	1.7826	620	0.8544	0.3810	0.0002
450	0.3362	0.0380	1.7721	625	0.7514	0.3210	0.0001
455	0.3187	0.0480	1.7441	630	0.6424	0.2650	0.0000
460	0.2908	0.0600	1.6692	635	0.5419	0.2170	0.0000
465	0.2511	0.0739	1.5281	640	0.4479	0.1750	0.0000
470	0.1954	0.0910	1.2876	645	0.3608	0.1382	0.0000
475	0.1421	0.1126	1.0419	650	0.2835	0.1070	0.0000
480	0.0956	0.1390	0.8130	655	0.2187	0.0816	0.0000
485	0.0580	0.1693	0.6162	660	0.1649	0.0610	0.0000
490	0.0320	0.2080	0.4652	665	0.1212	0.0446	0.0000
495	0.0147	0.2586	0.3533	670	0.0874	0.0320	0.0000
500	0.0049	0.3230	0.2720	675	0.0636	0.0232	0.0000
505	0.0024	0.4073	0.2123	680	0.0468	0.0170	0.0000
510	0.0093	0.5030	0.1582	685	0.0329	0.0119	0.0000
515	0.0291	0.6082	0.1117	690	0.0227	0.0082	0.0000
520	0.0633	0.7100	0.0782	695	0.0158	0.0057	0.0000
525	0.1096	0.7932	0.0573	700	0.0114	0.0041	0.0000
530	0.1655	0.8620	0.0422	705	0.0081	0.0029	0.0000
535	0.2257	0.9149	0.0298	710	0.0058	0.0021	0.0000
540	0.2904	0.9540	0.0203	715	0.0041	0.0015	0.0000
545	0.3597	0.9803	0.0134	720	0.0029	0.0010	0.0000
550	0.4334	0.9950	0.0087	725	0.0020	0.0007	0.0000
555	0.5121	1.0000	0.0057	730	0.0014	0.0005	0.0000
560	0.5945	0.9950	0.0039	735	0.0010	0.0004	0.0000

CIE XYZ a partir do espectro de uma fonte



$$X = k \int_{380}^{780} L(\lambda) \bar{x}(\lambda) d\lambda$$

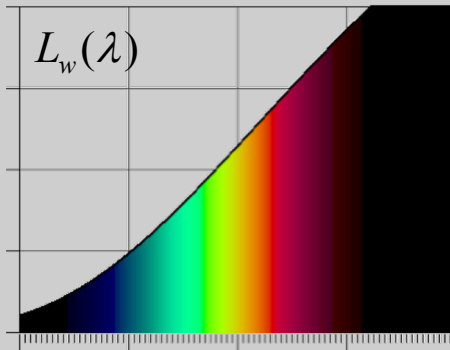
$$Y = k \int_{380}^{780} L(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int_{380}^{780} L(\lambda) \bar{z}(\lambda) d\lambda$$

$$k = \frac{100}{\int_{380}^{780} L_w(\lambda) \bar{y}(\lambda) d\lambda}$$

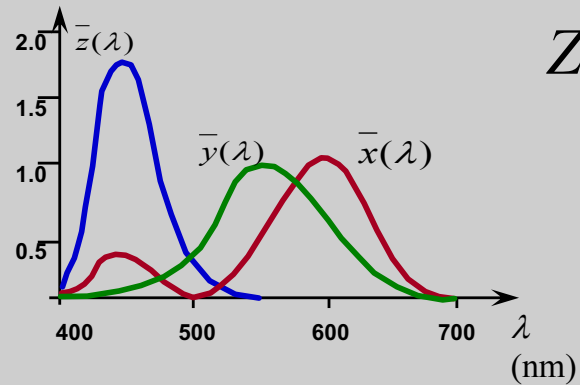
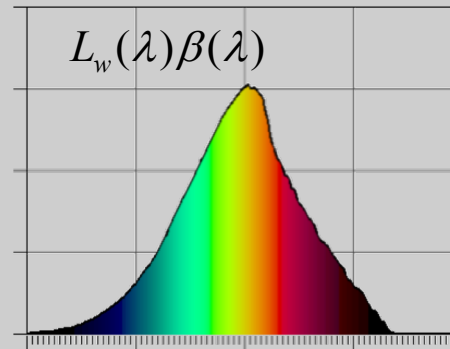
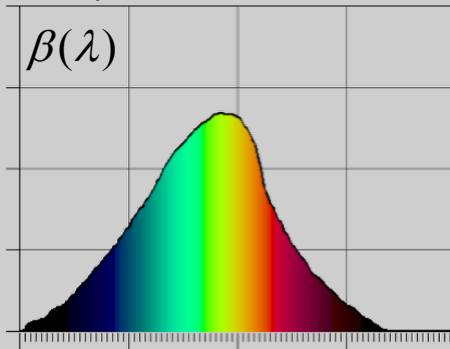
Cor de uma superfície no CIE XYZ

iluminante



×

reflexão do material



$$X = k \int_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{z}(\lambda) d\lambda$$

$$k = \frac{100}{\int_{380}^{780} L_w(\lambda) \bar{y}(\lambda) d\lambda}$$

Cor

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Cor de uma superfície no CIE XYZ

$$X = k \sum_{308}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda)$$

$$Y = k \sum_{308}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda)$$

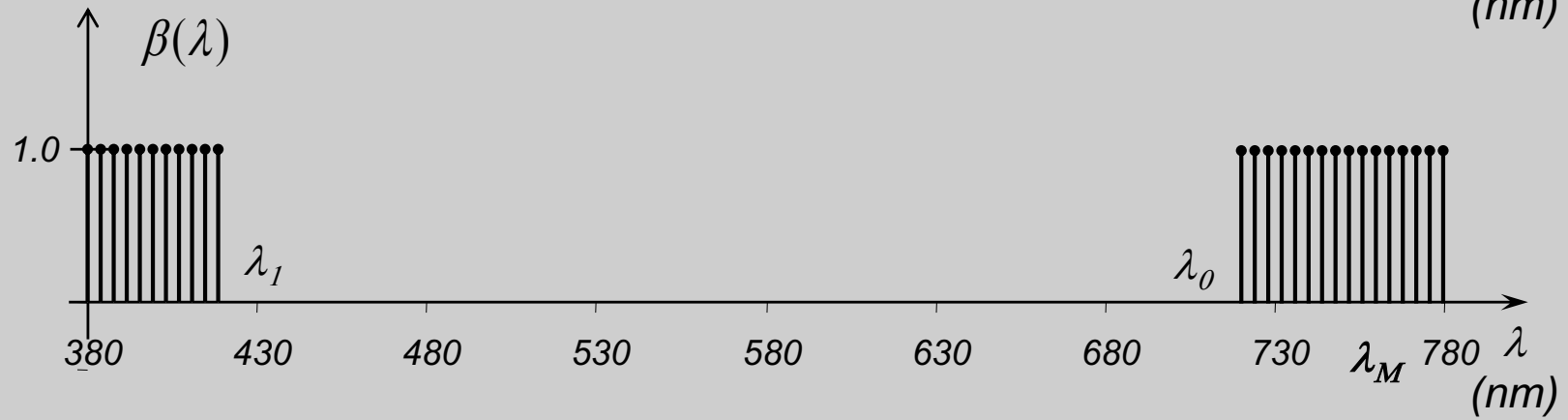
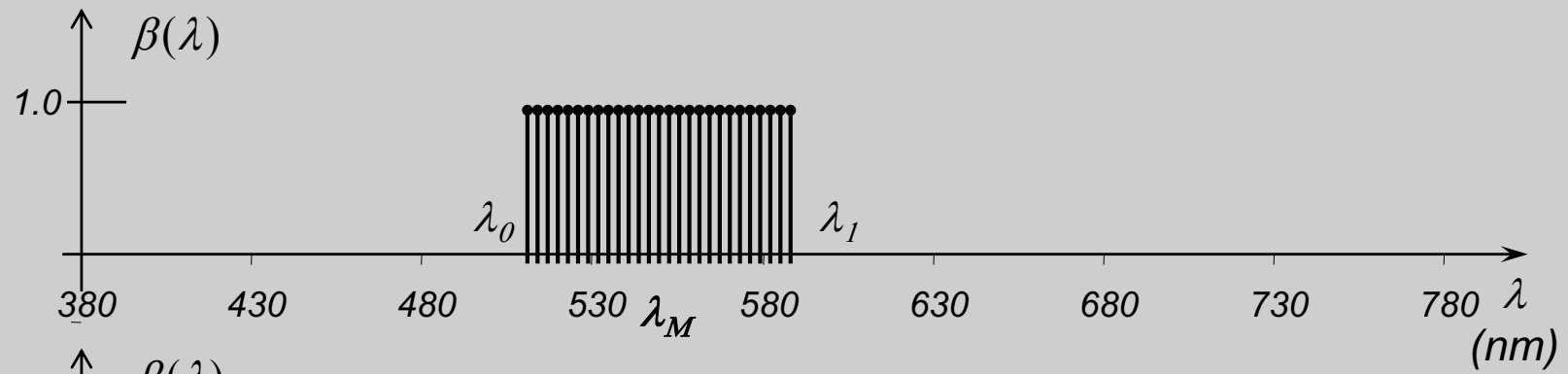
$$Z = k \sum_{308}^{780} L_w(\lambda) \beta(\lambda) \bar{z}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{z}(\lambda)$$

$$X_w = k \sum_{380}^{780} L_w(\lambda) \bar{x}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{x}(\lambda)$$

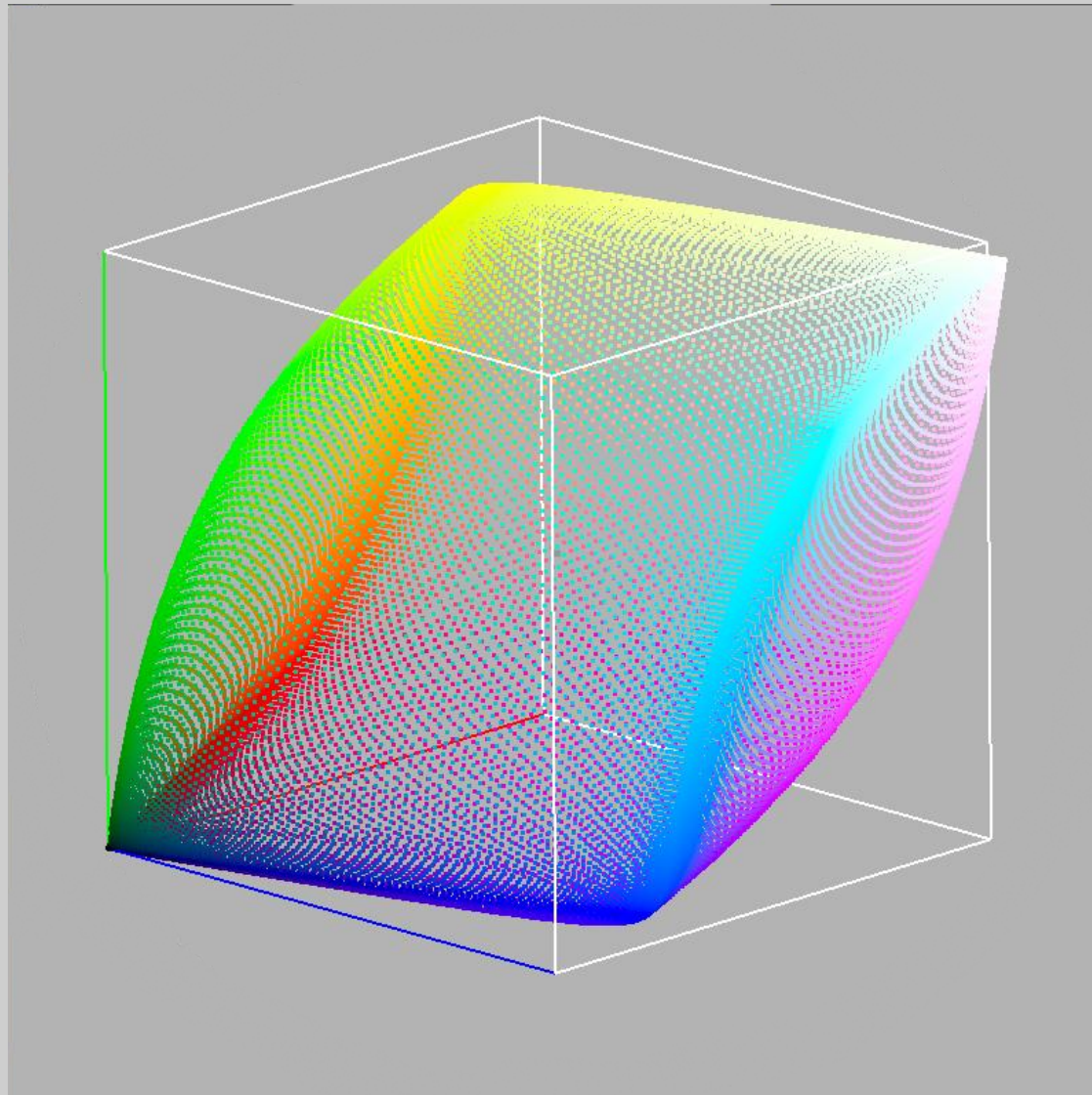
$$Y_w = k \sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda) = 1.0$$

$$Z_w = k \sum_{380}^{780} L_w(\lambda) \bar{z}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{z}(\lambda)$$

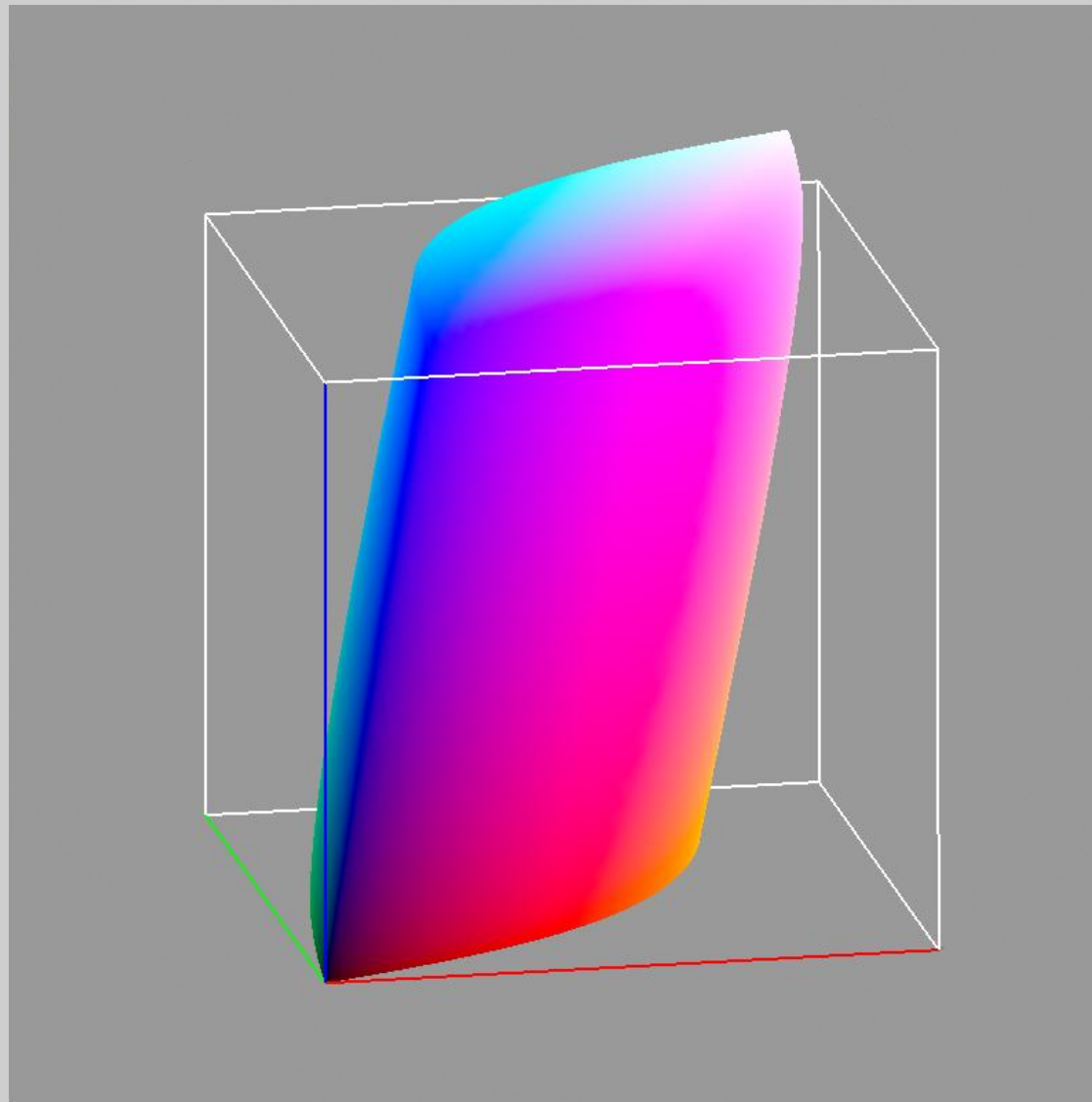
$$k = \frac{1}{\Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda)}$$



CIEXYZ com D65



CIEXYZ com D65



Cor de uma superfície no CIE XYZ

$$X = k \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda)$$

$$Y = k \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda)$$

$$Z = k \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{z}(\lambda) \Delta\lambda = k \Delta\lambda \sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{z}(\lambda)$$

$$x = \frac{\sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{x}(\lambda)}{\sum_{380}^{780} L_w(\lambda) \beta(\lambda) (\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))}$$

$$y = \frac{\sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda)}{\sum_{380}^{780} L_w(\lambda) \beta(\lambda) (\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))}$$

Luminância da cor

reflexão da superfície branca

$$\beta_w(\lambda) = 1.0$$

$$Y_w = k\Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda) = 1.0$$

$$k = \frac{1}{\Delta\lambda \sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda)}$$

$$Y = \frac{\sum_{380}^{780} L_w(\lambda) \beta(\lambda) \bar{y}(\lambda)}{\sum_{380}^{780} L_w(\lambda) \bar{y}(\lambda)}$$

$$Y = 1.0$$

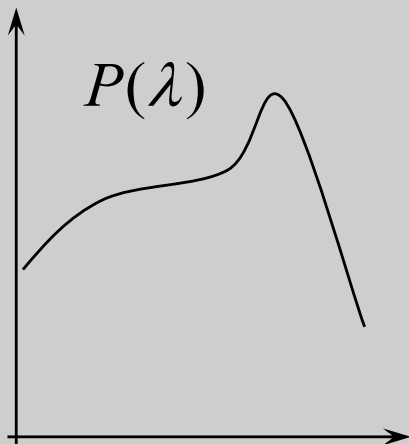
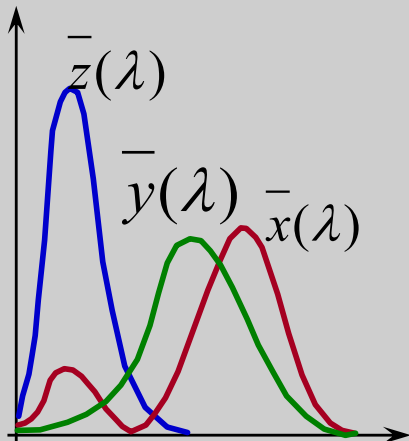


Cor



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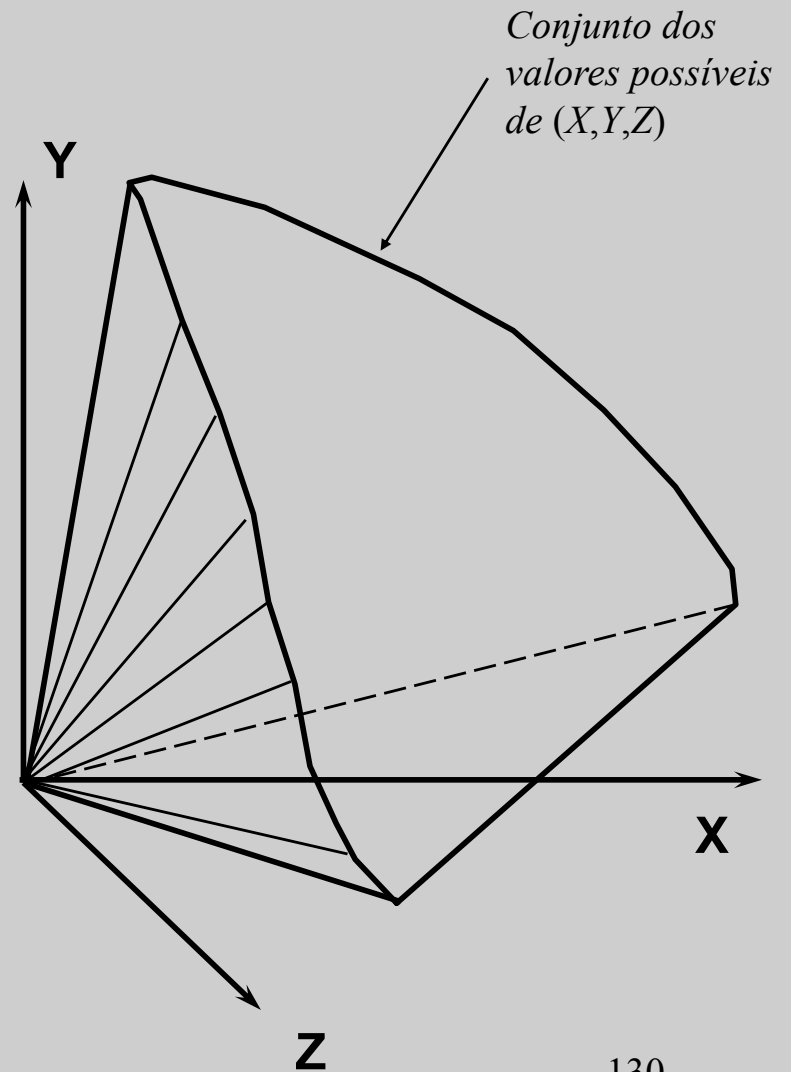
Cores visíveis representadas no sistema CIE XYZ



$$X = k \int_{380}^{780} L(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int_{380}^{780} L(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int_{380}^{780} L(\lambda) \bar{z}(\lambda) d\lambda$$



Retirando a luminosidade ou brilho da definição da cor em CIE XYZ

- *Um parenteses sobre luminosidade ou brilho*

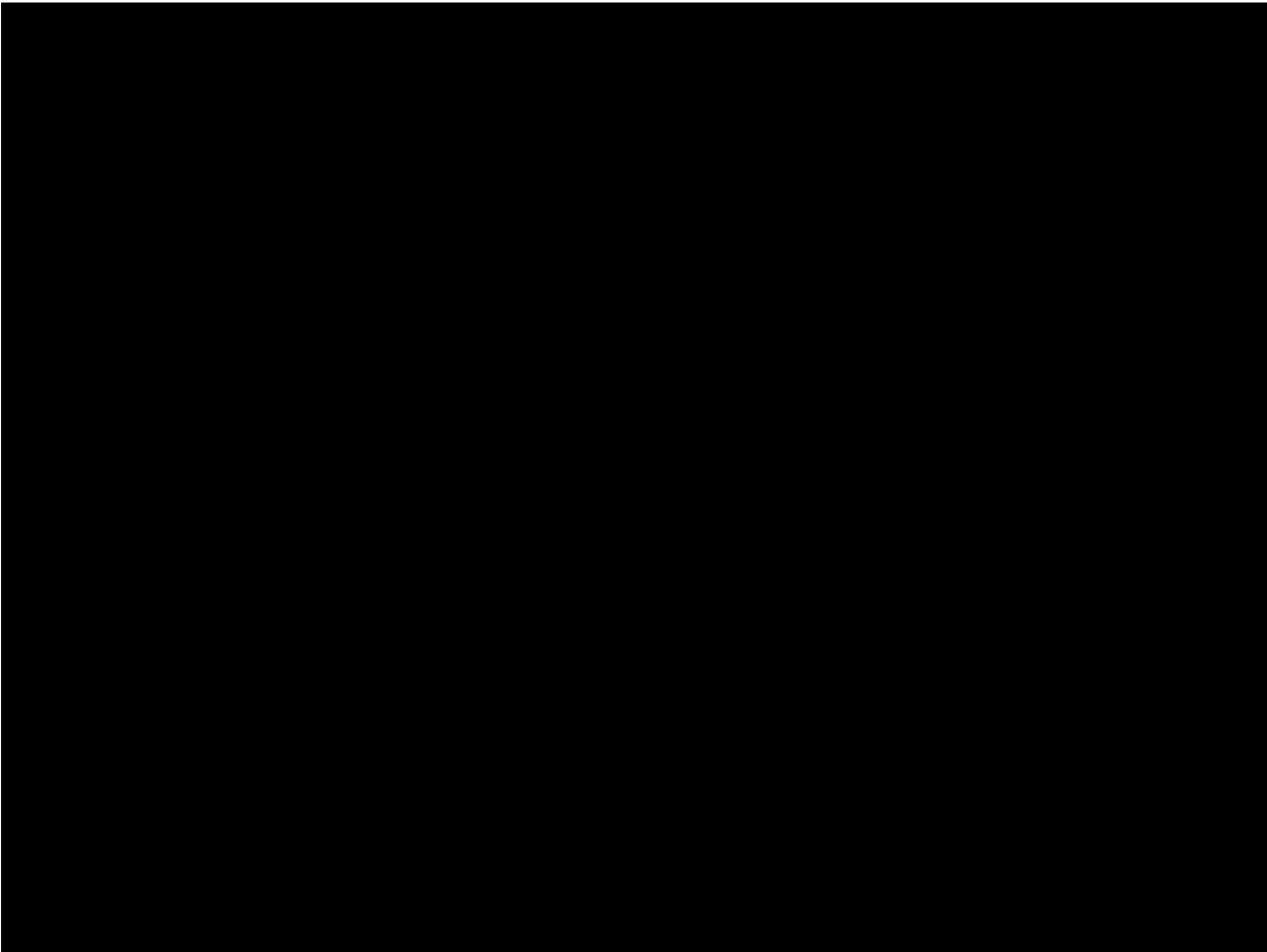
Valores típicos de luminosidade de um de uma superfície

Modo	Valores (<i>lux</i>)
Luz do dia (máximo)	100 000
Luz de dia sombrio	10 000
Interior próximo a janela	1 000
Minimo p/ trabalho	100
Lua cheia	0.2
Luz das estrelas	0.0003

... e o olho se acomoda!

Cor







Kokos
nuss
1,95

Grapefruit
Stück 1,20

Türkei I
Kranz-
Feigen
1,65

Tunesien I
Datteln
1,30
Pkg

Kebun Ben
Passionsfrucht
1,45

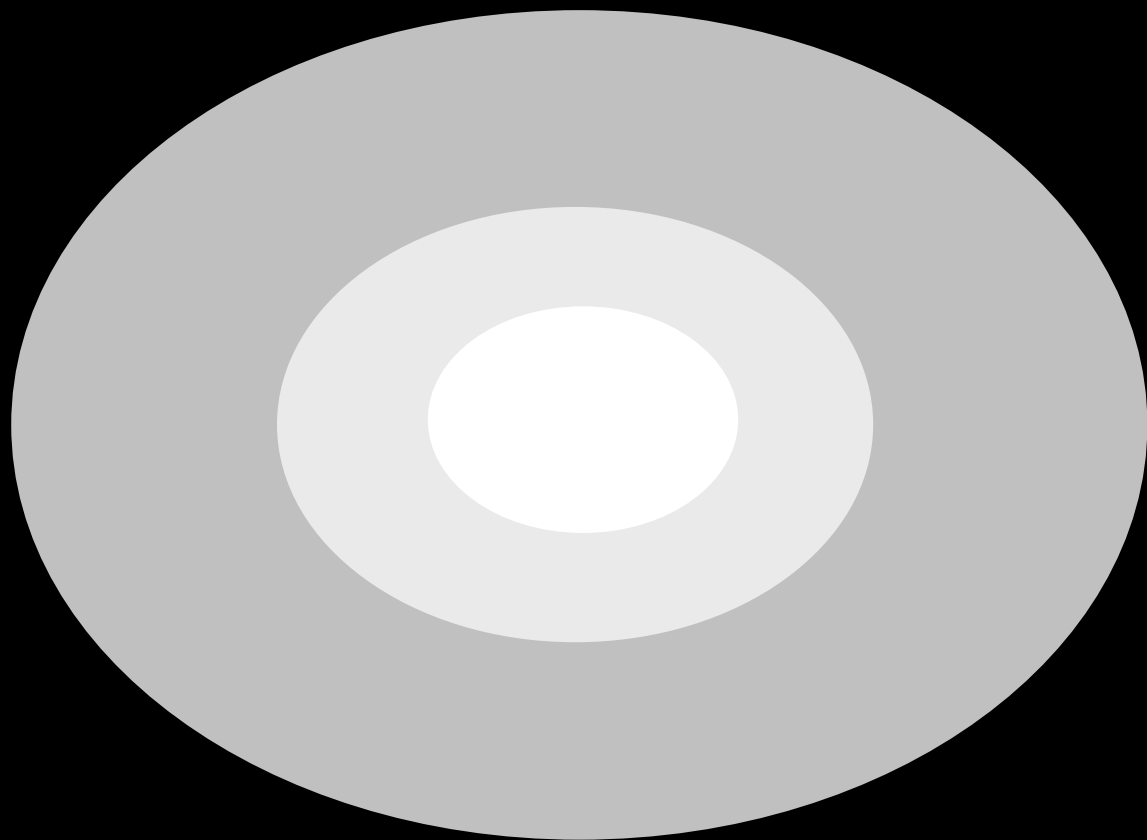
Kestane
2,95
kg

Indonesien I
Maka
1,70



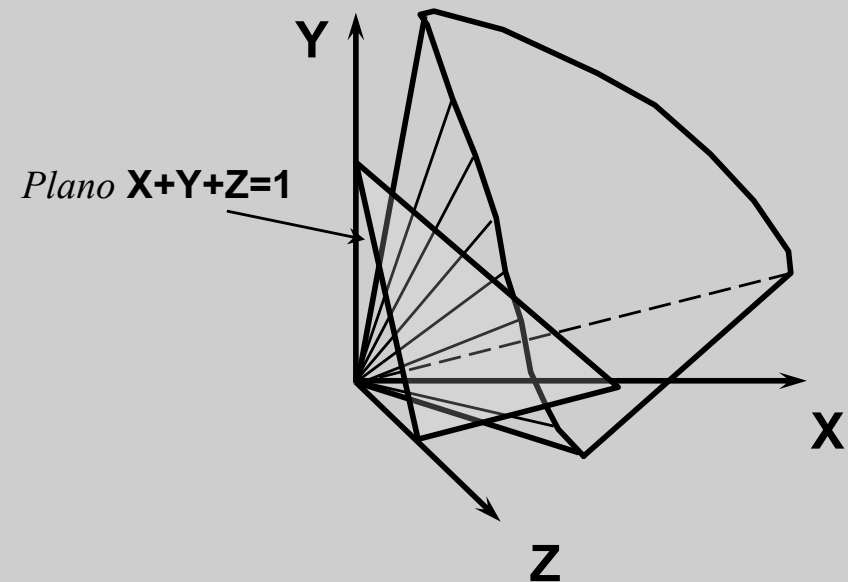


Adaptção cromática



Retirando a luminosidade ou brilho da definição da cor em CIE XYZ

- *Retirar o fator luminosidade ou brilho projetando no plano $X+Y+Z=1$*

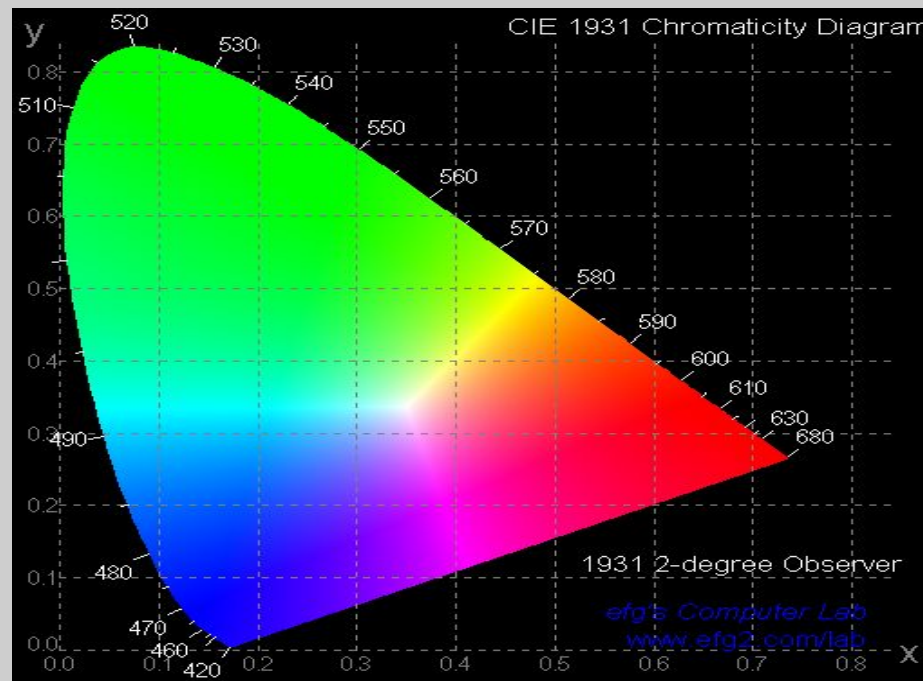
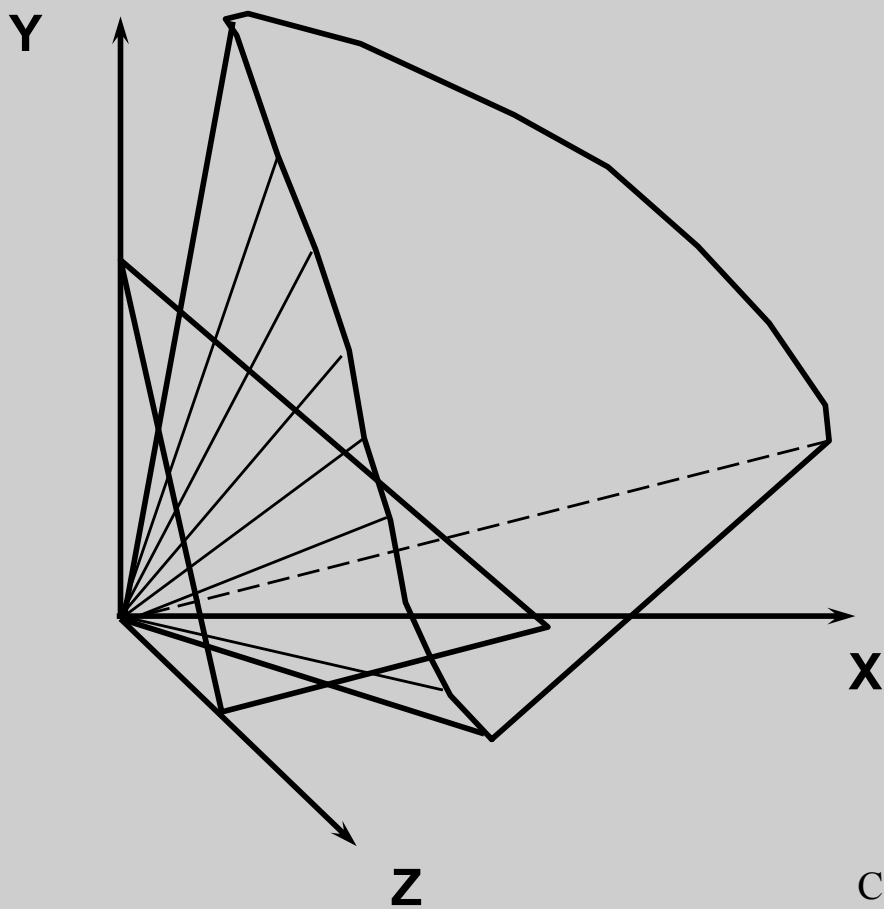


$$\begin{aligned}x &= X/(X+Y+Z) \\y &= Y/(X+Y+Z) \\z &= Z/(X+Y+Z)\end{aligned}$$

note que
 $x+y+z = 1$

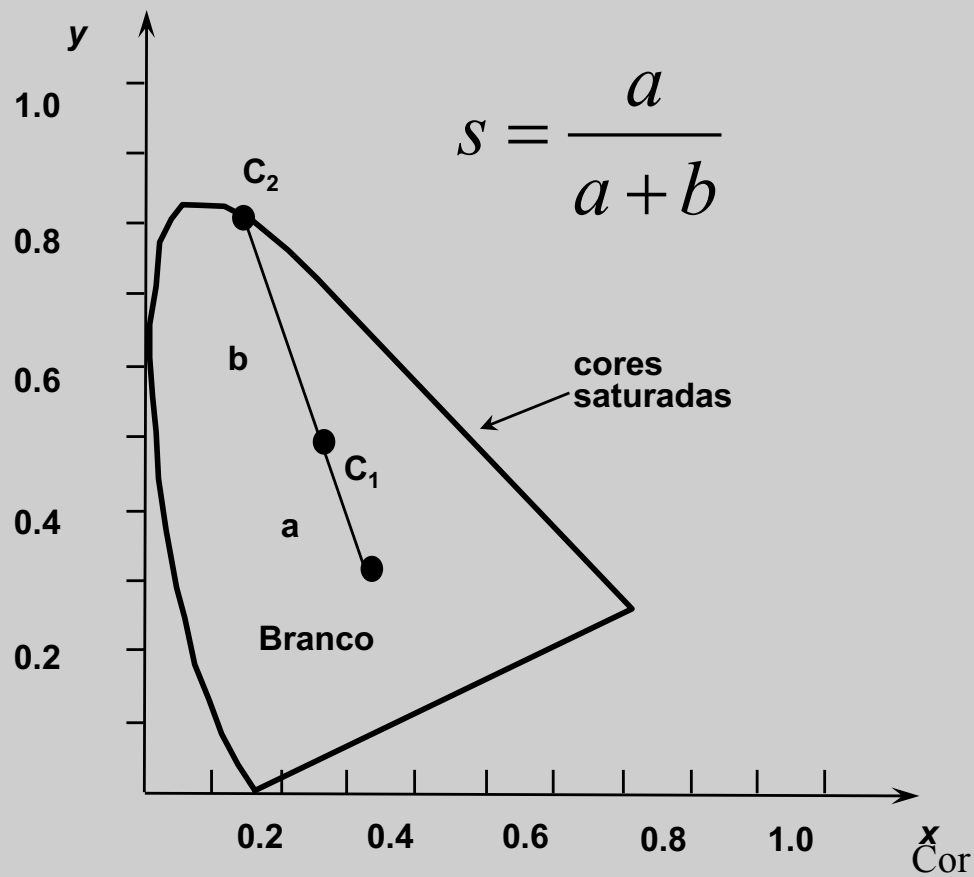
$$\begin{aligned}X &= (x / y) Y \\Y &= Y \\Z &= (1-x-y) Y / y\end{aligned}$$

Cores visíveis representadas no sistema CIE xyY

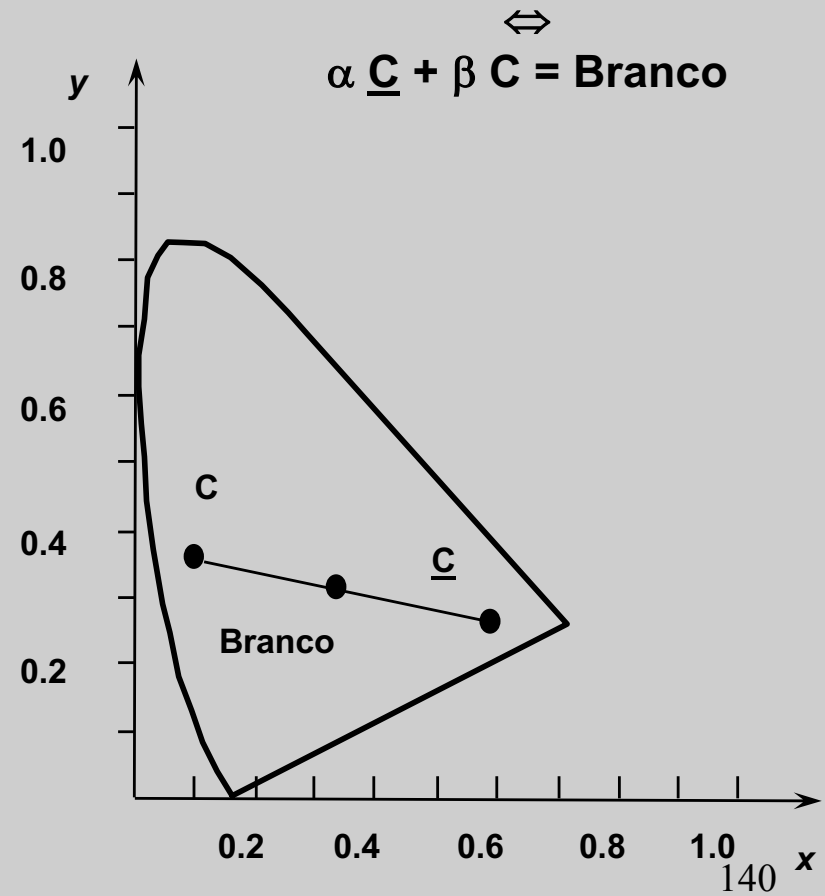


Saturação e cor complementar no diagrama de cromaticidade xy

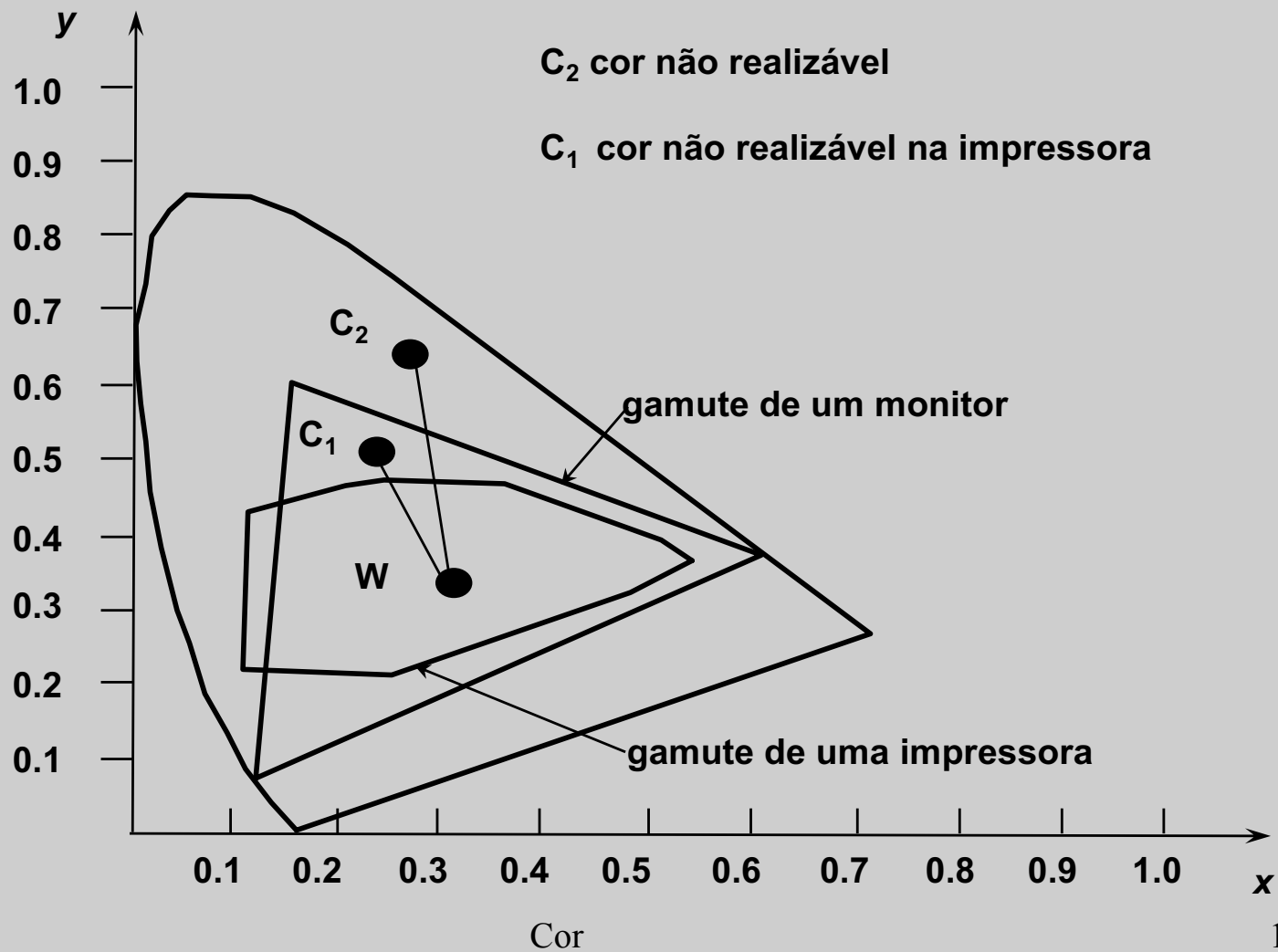
saturação de C_1



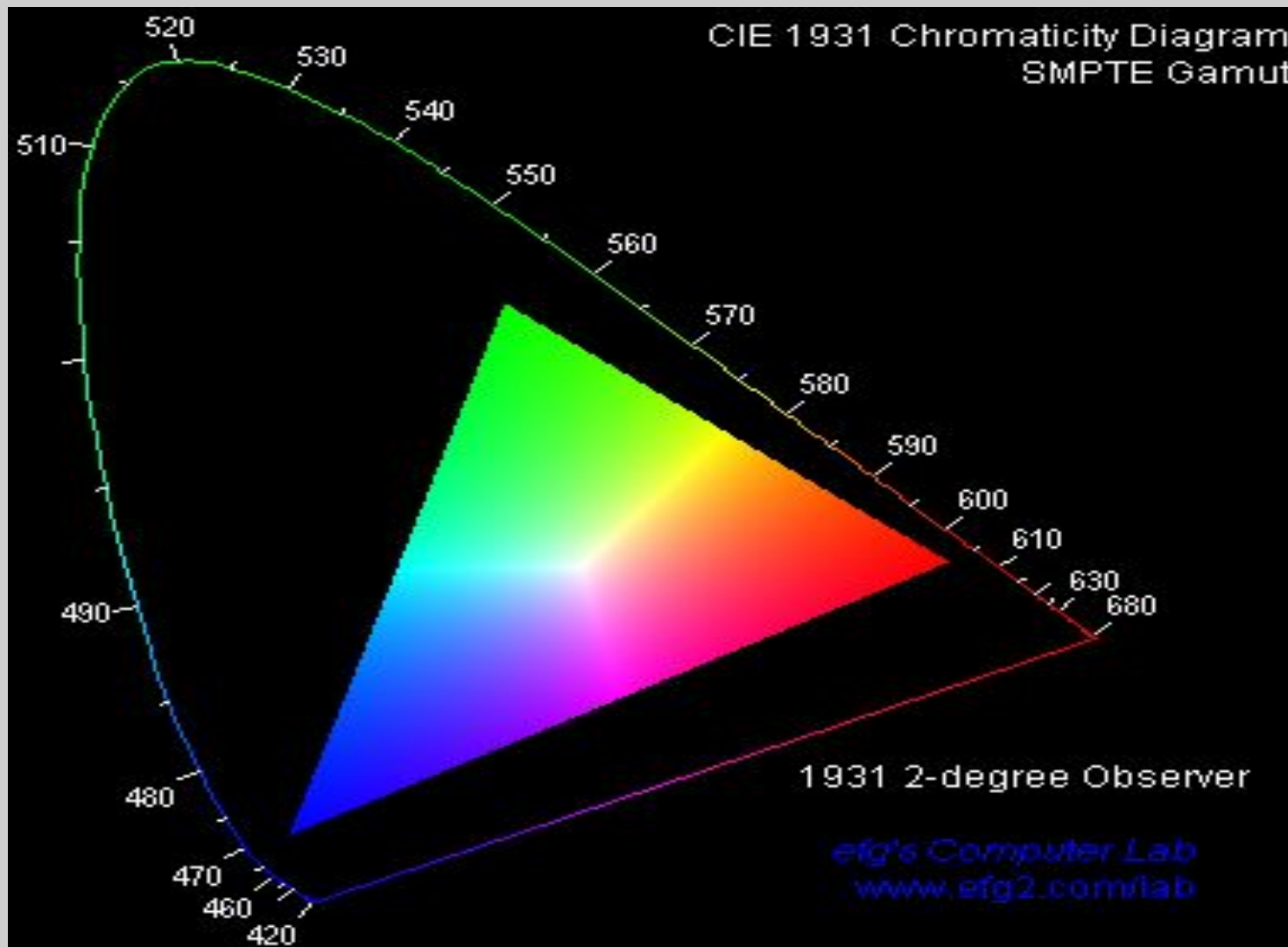
\underline{C} é complementar a C



Gamute de cromaticidade de dispositivos



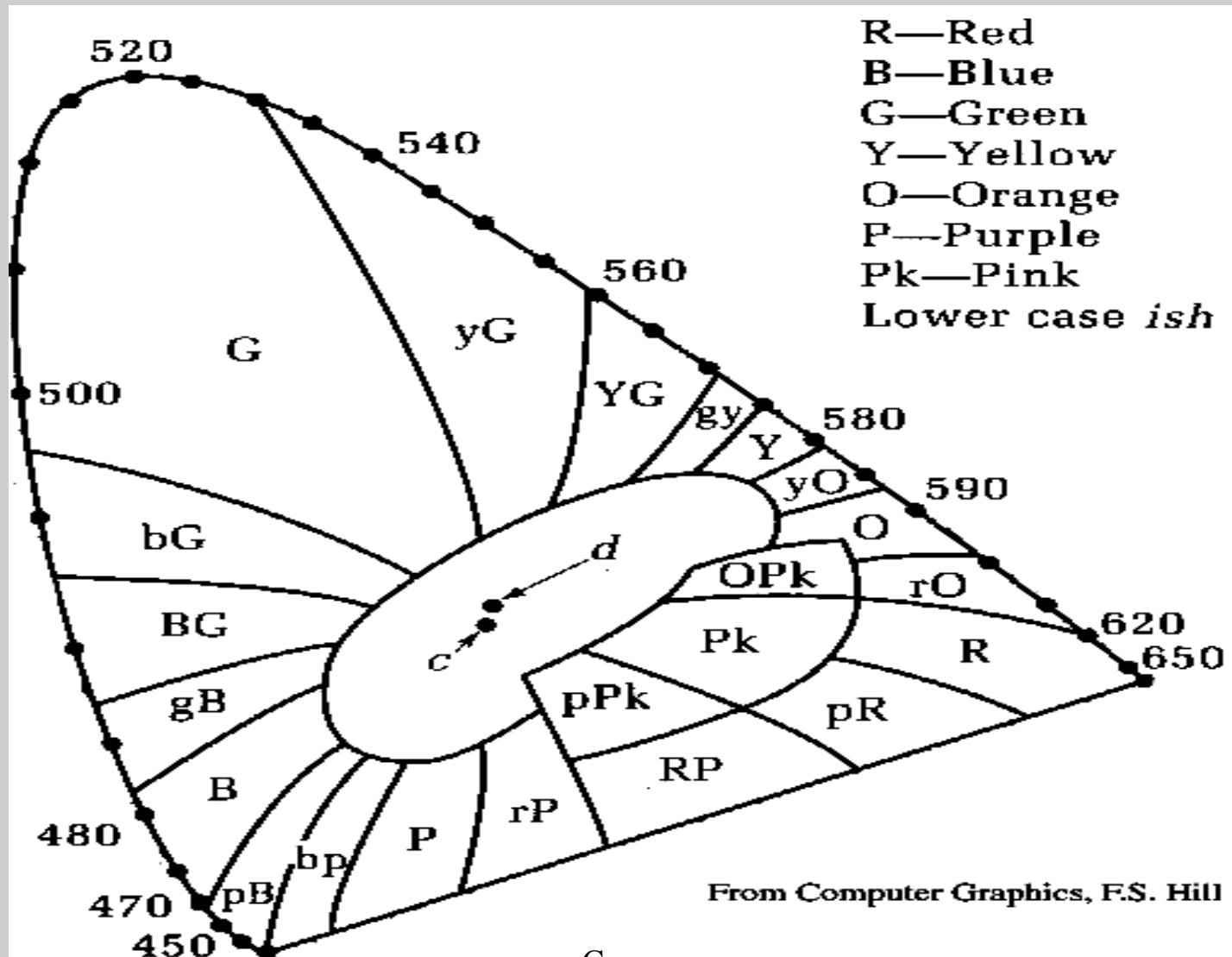
Gamut de cores de um monitor RGB



Cor

142

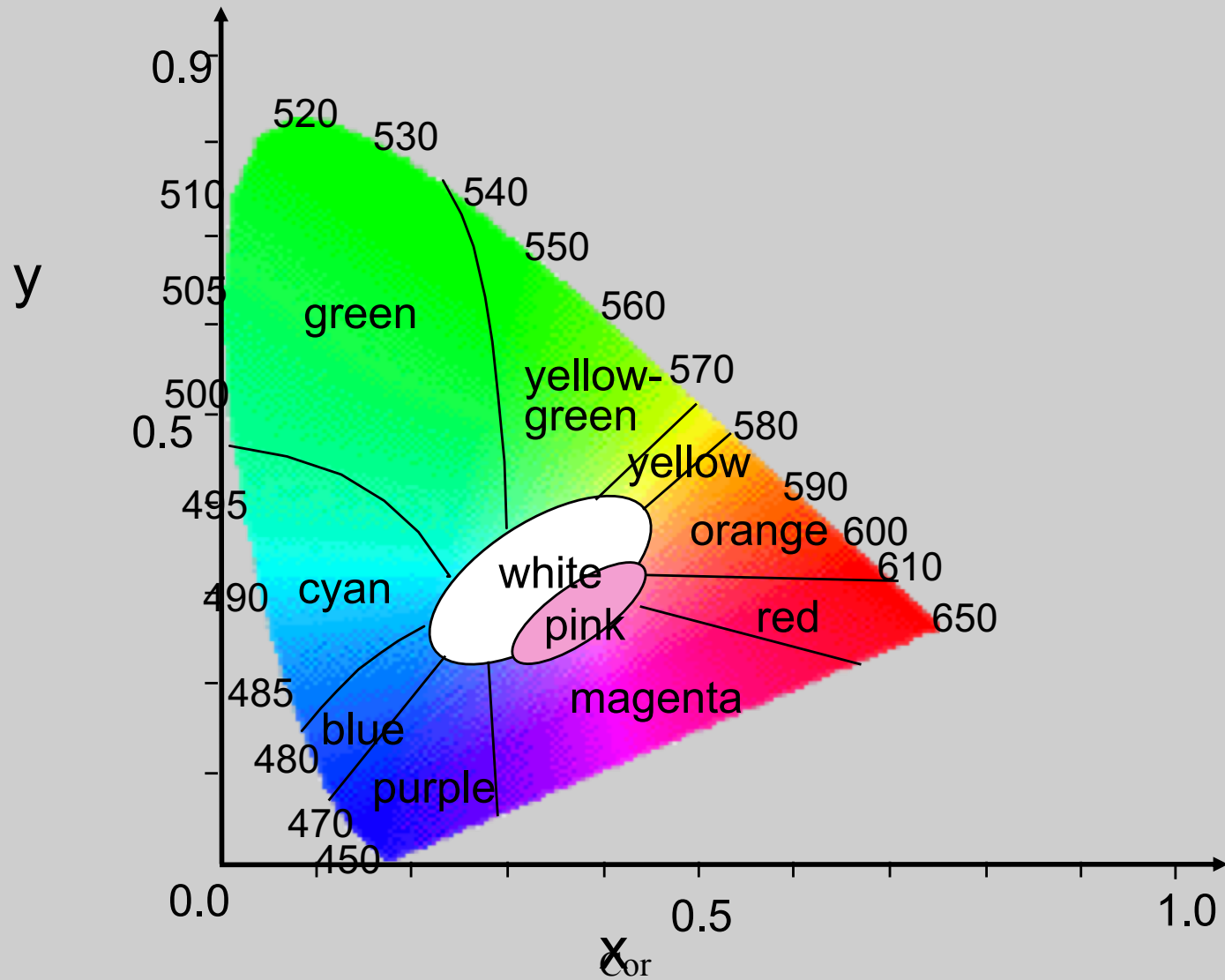
Nome das cores



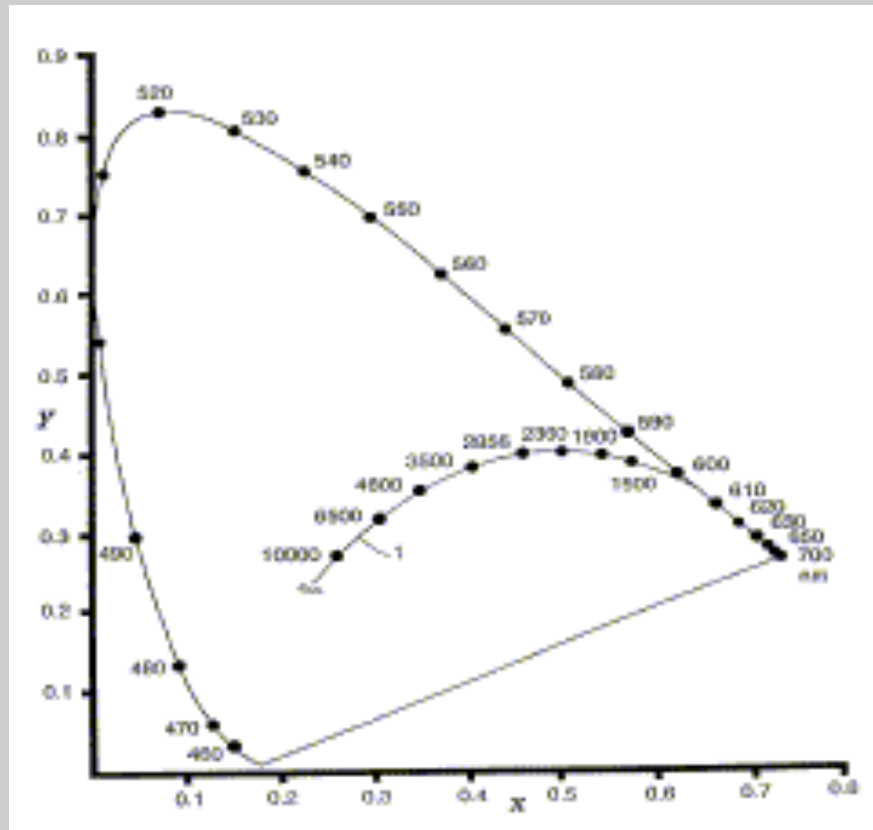
Cor

143

Nome das cores



Planckian locus



U.S. Patent

Nov. 3, 1908

Sheet 3 of 14

5,831,686

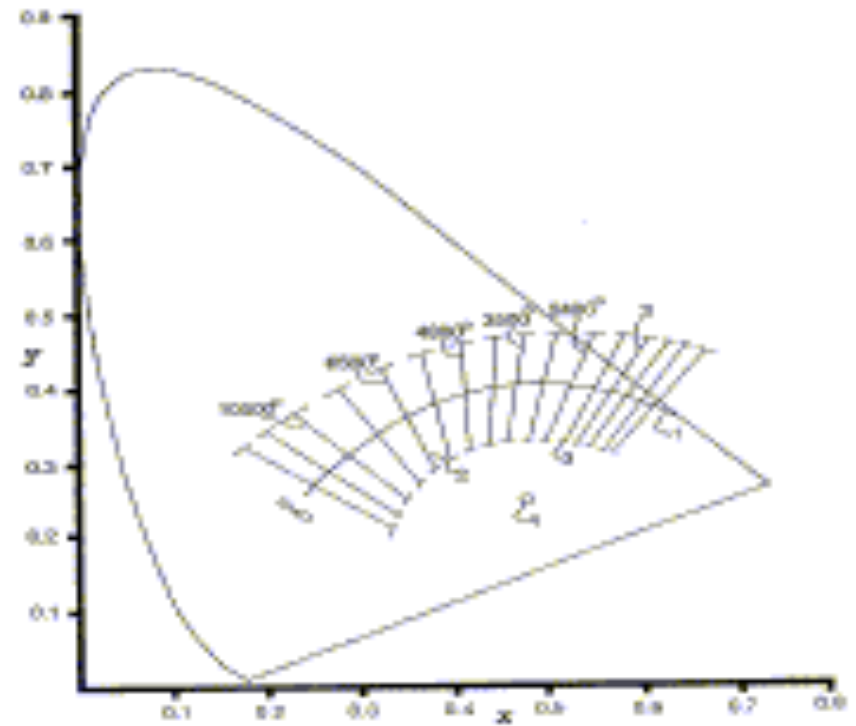
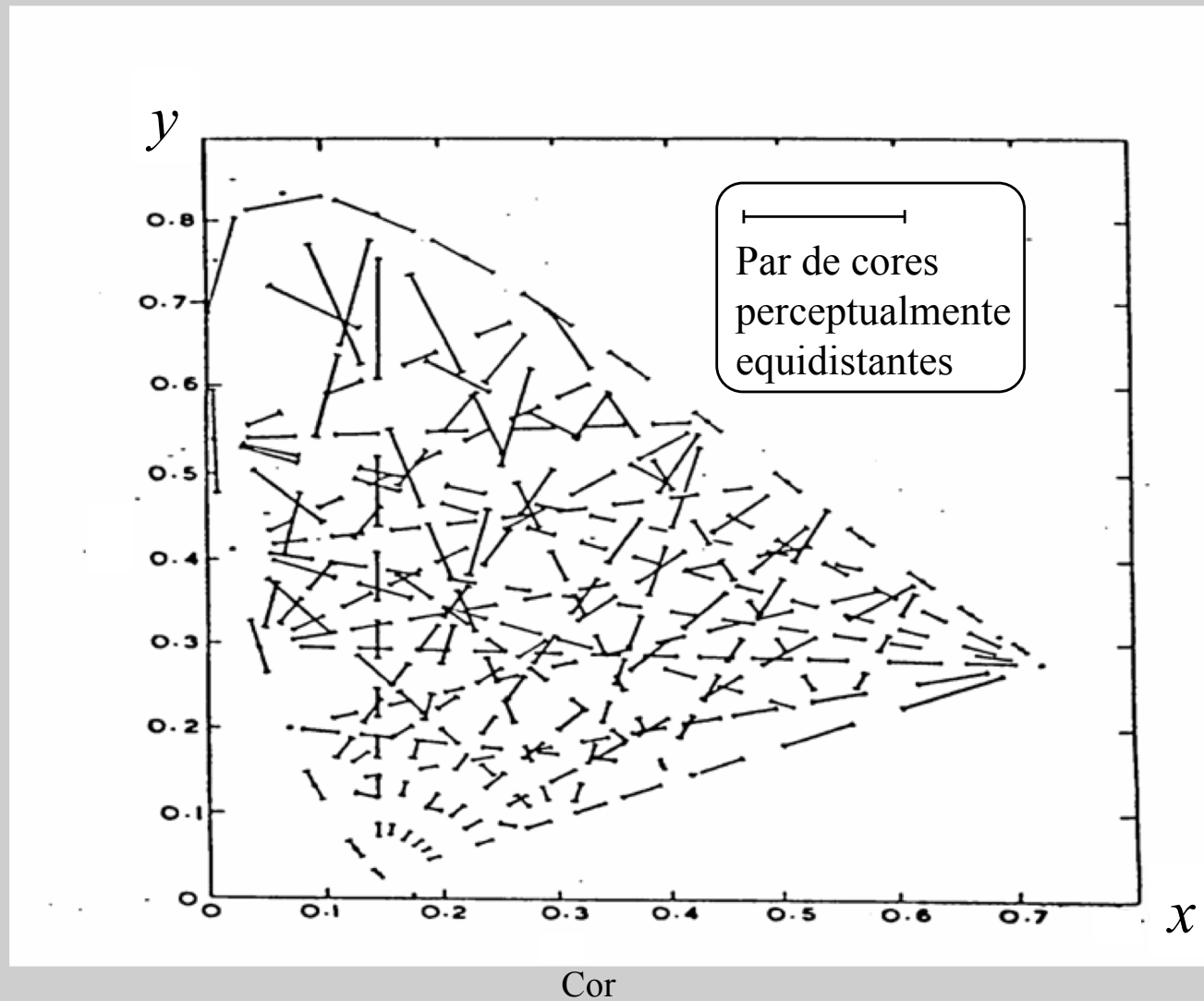


FIG. 4

Cores perceptualmente equidistantes representadas no sistema CIE xyY

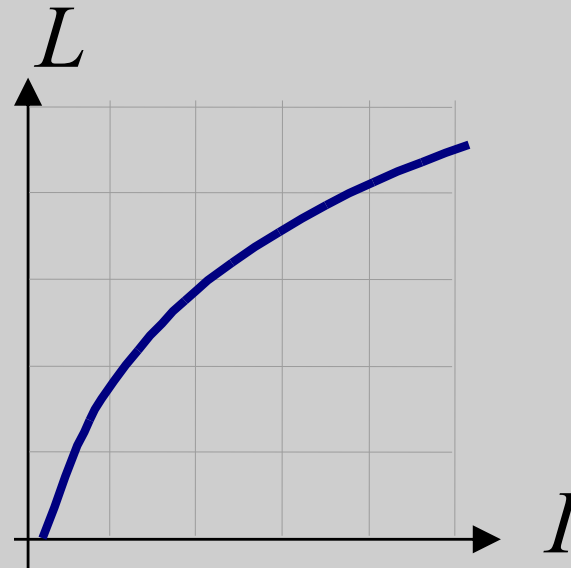


Weber's law

- The change in a stimulus that will be just noticeable (JND) is a constant ratio of the original stimulus.

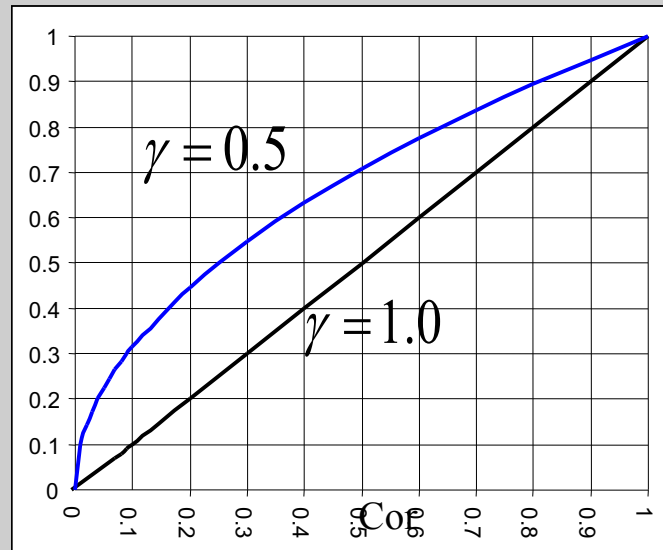
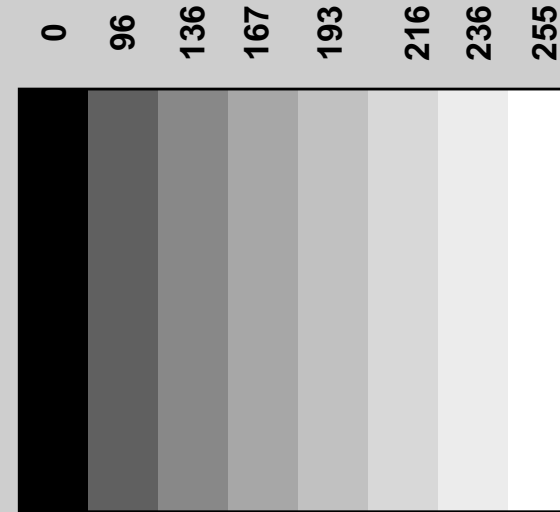
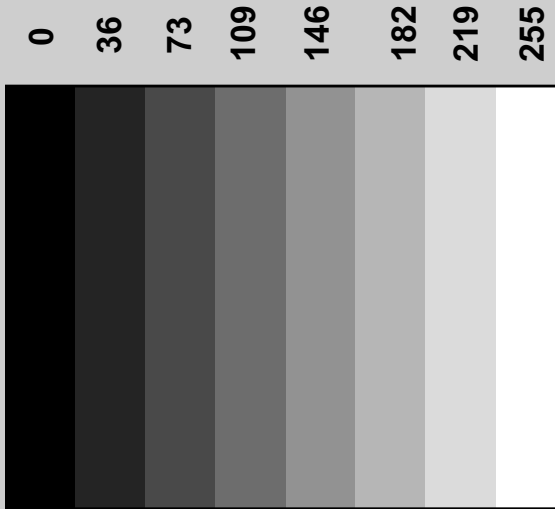
$$\Delta L \propto \frac{\Delta I}{I}$$

$$L \propto \log(I)$$



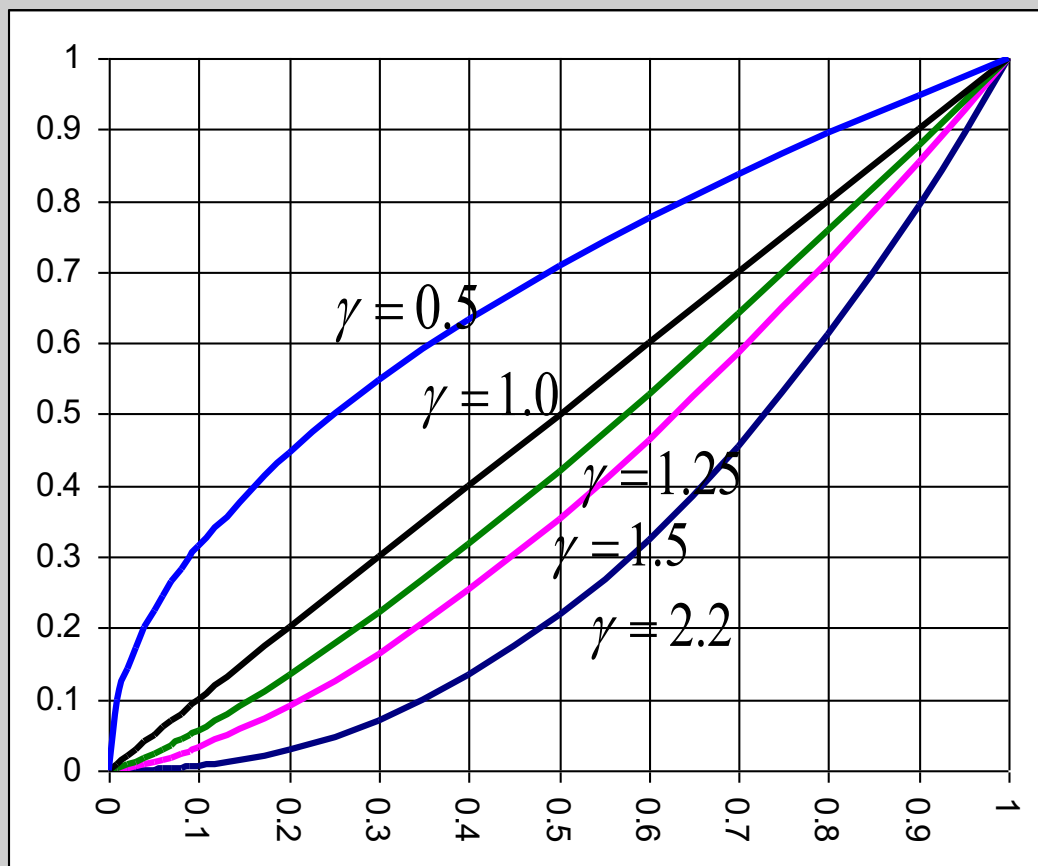
E. H. Weber, in 1834

Que ajuste adotar?



Correção Gama

Correção Gama



$$y = x^{\gamma_1}$$

$$g = y^{\gamma_2}$$

$$g = \left(x^{\gamma_1}\right)^{\gamma_2}$$

$$g = x^{\gamma_1\gamma_2}$$

Efeito da correção gana



$\gamma = 4$

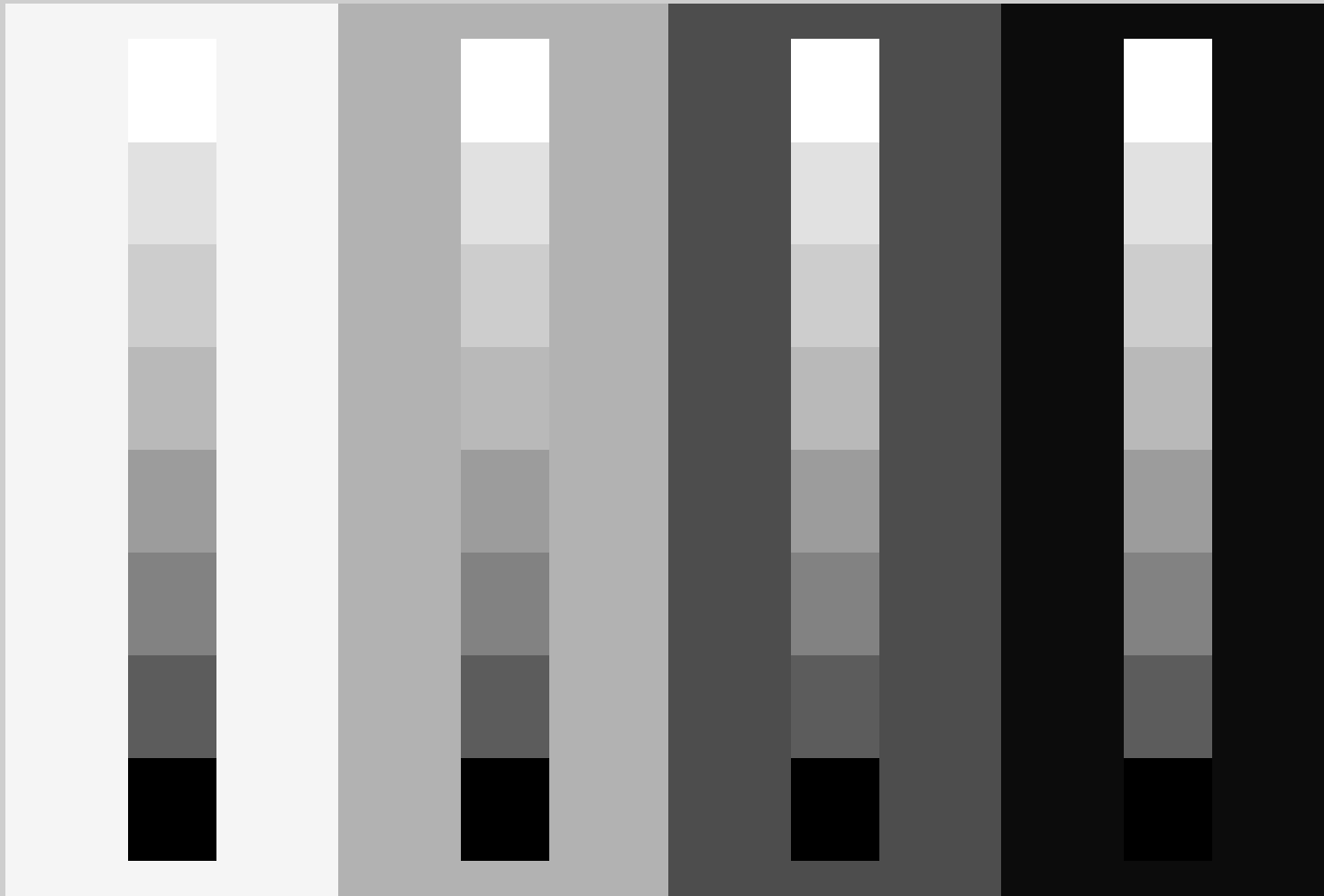
$\gamma = 2$

$\gamma = 1$

$\gamma = 0.5$

$\gamma = 0.25$

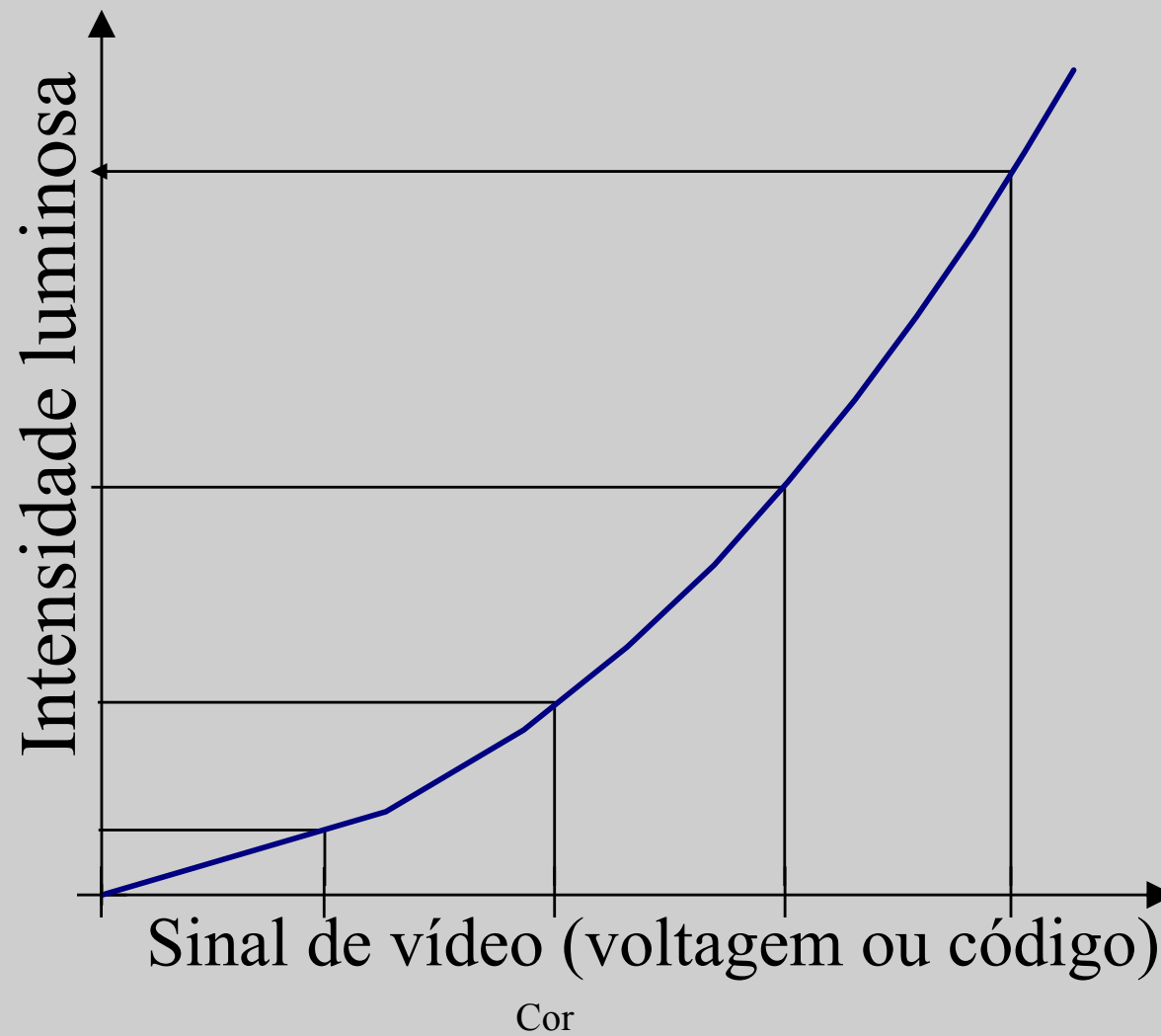
Correção gama depende das condições do ambiente



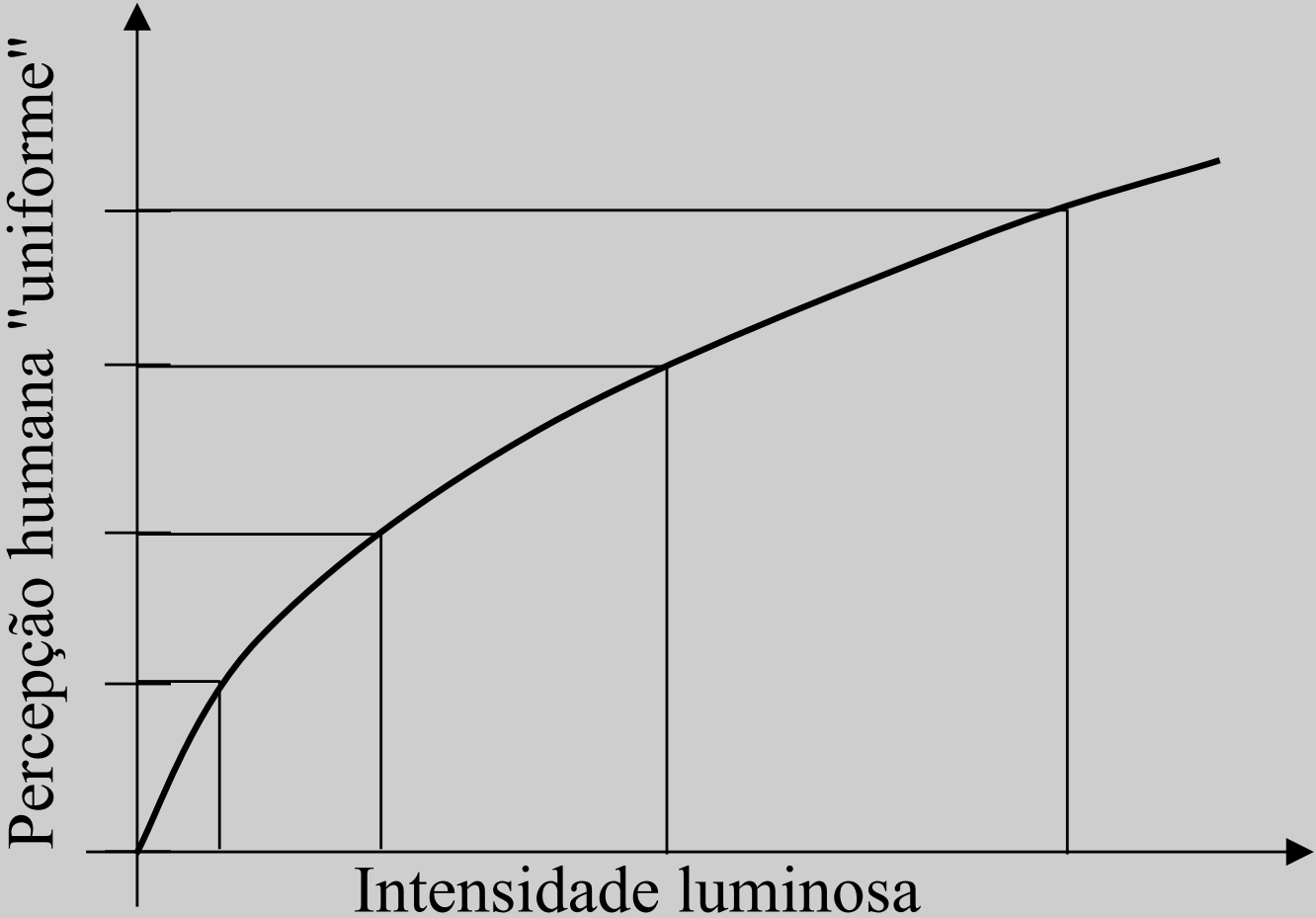
Cor

152

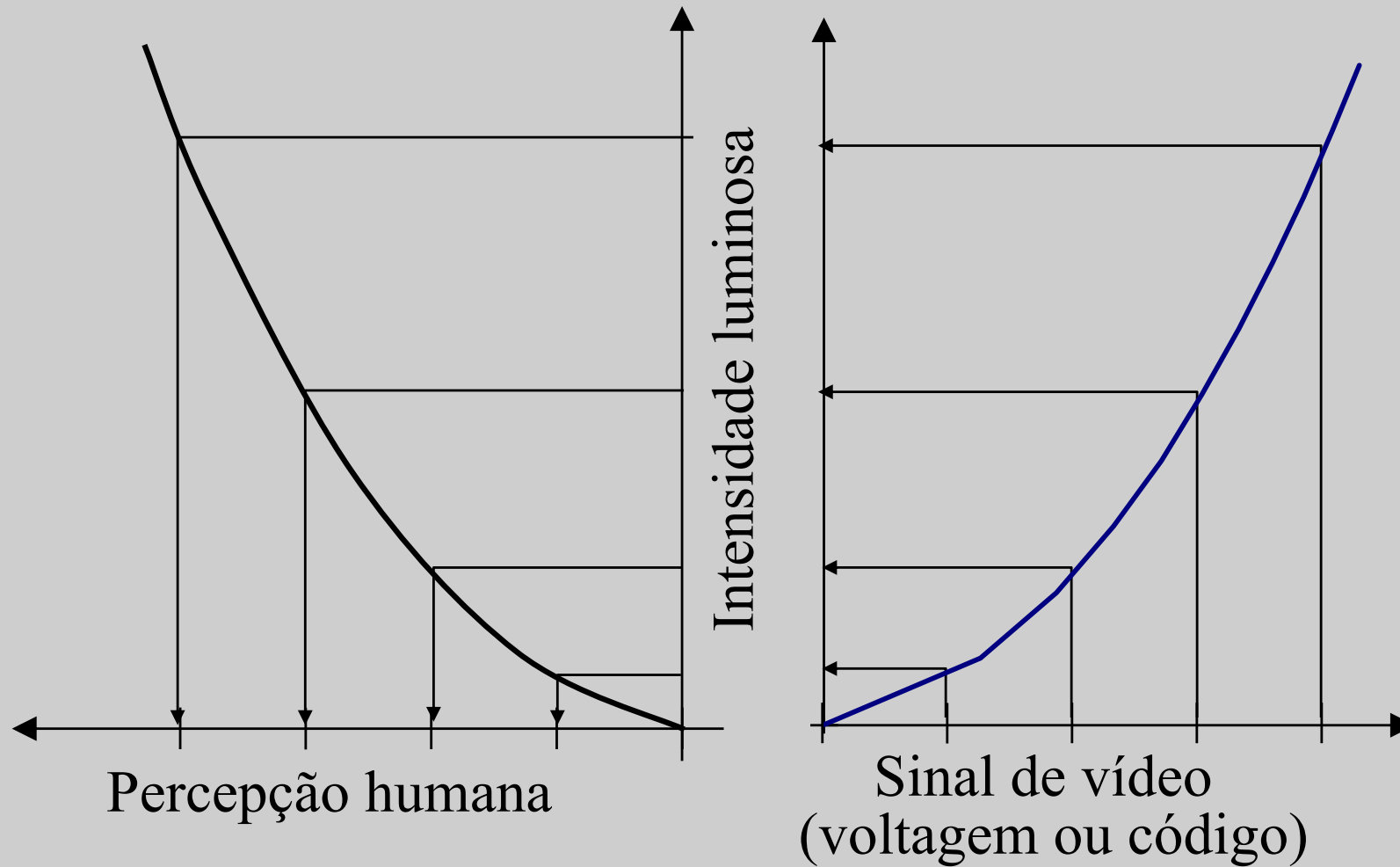
Curva do Monitor



Curva dos sentidos



Composição de sinais

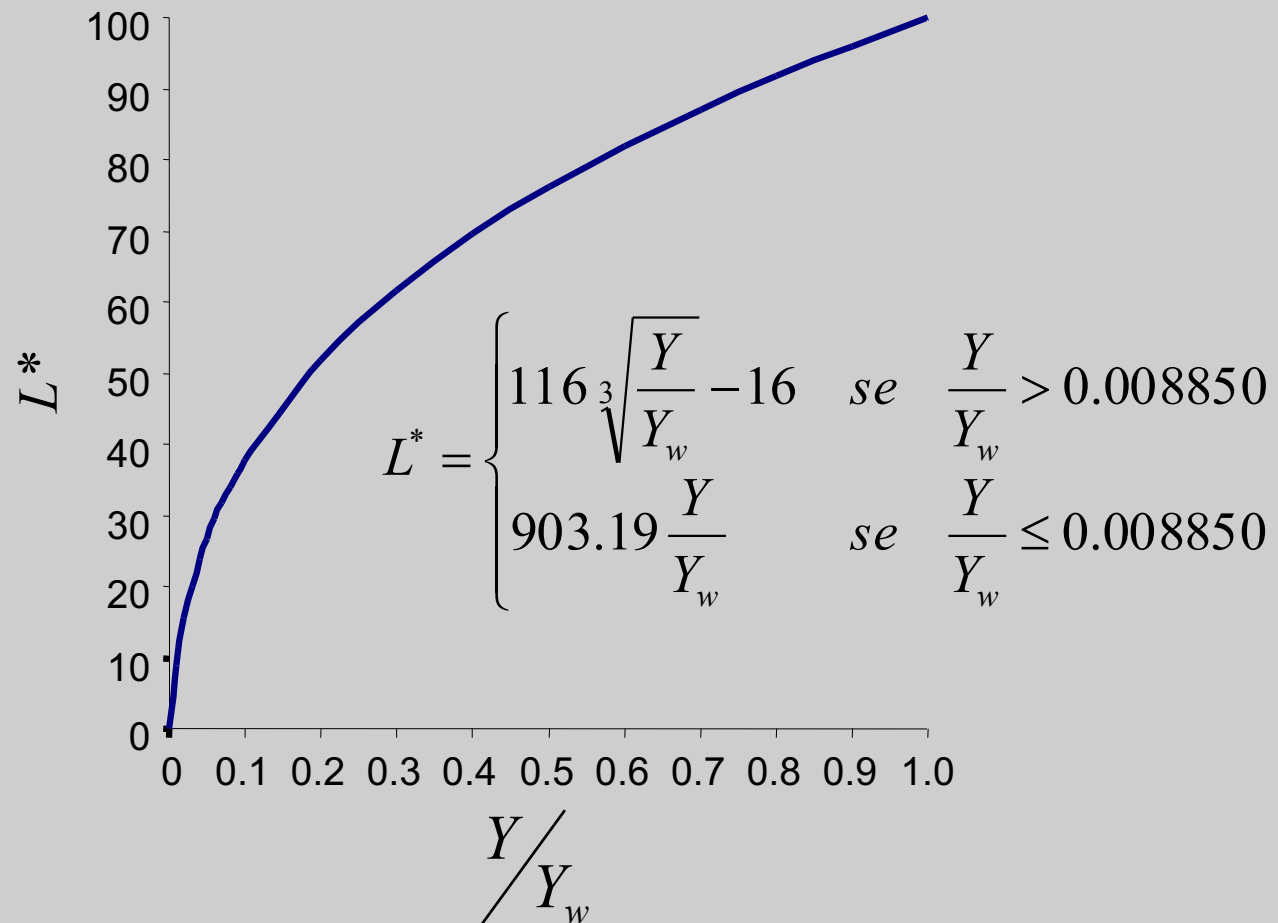


Gama de uma ponta a outra (end to end)

“Good end-to-end exponents are determined from experience. For example, for photographic prints it's about 1.0; for slides intended to be projected in a dark room it's about 1.5; for television it's about 1.14.”

<http://www.libpng.org/pub/png/spec/1.2/PNG-GammaAppendix.html>

CIE L* Correção perceptual



veja: <http://www.graphics.cornell.edu/~westin/gamma/gamma.html>

Sistemas de cor perceptualmente uniformes do CIE Luv e Hunter Lab

Dados:

(X, Y, Z) = componentes da cor no espaço CIE XYZ

(X_w, Y_w, Z_w) = componentes do branco de referência

Calcula-se:

$$u' = 4X / (X + 15Y + 3Z)$$

$$v' = 9Y / (X + 15Y + 3Z)$$

$$u_w = 4X_w / (X_w + 15Y_w + 3Z_w)$$

$$v_w = 9Y_w / (X_w + 15Y_w + 3Z_w)$$

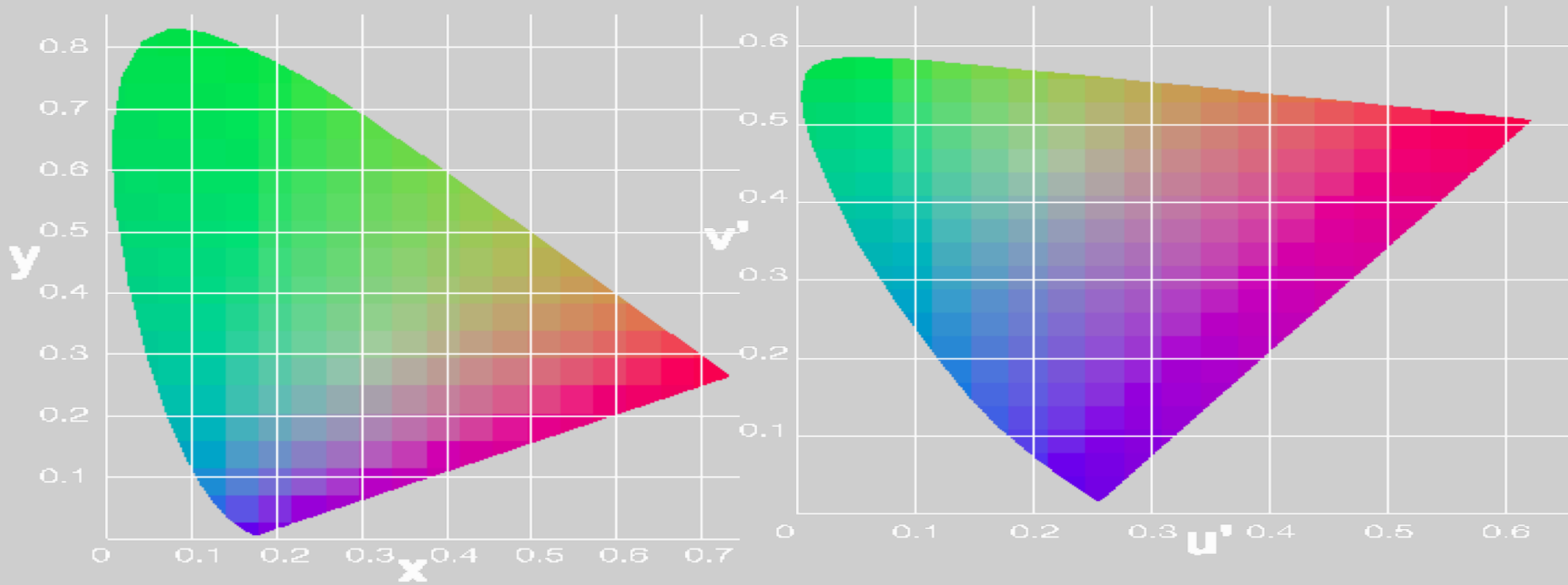
$L^* = 116 (Y/Y_w)^{1/3} - 16 \text{ se } Y/Y_w > 0.008850$ <p style="text-align: center;">ou</p> $L^* = 903.19(Y/Y_w) \text{ se } Y/Y_w \leq 0.008850$	
$u^* = 13L^*(u' - u_w)$ $v^* = 13L^*(v' - v_w)$	$a^* = 500[(X/X_w)^{1/3} - (Y/Y_w)^{1/3}]$ $b^* = 200[(Y/Y_w)^{1/3} - (Z/Z_w)^{1/3}]$

u^*, v^* (ou a^*, b^*) são as componentes de cromaticidade da cor

L^* é a luminosidade corrigida para uma escala perceptualmente linear

Cor

CIE $xyY \rightarrow$ CIE LUV

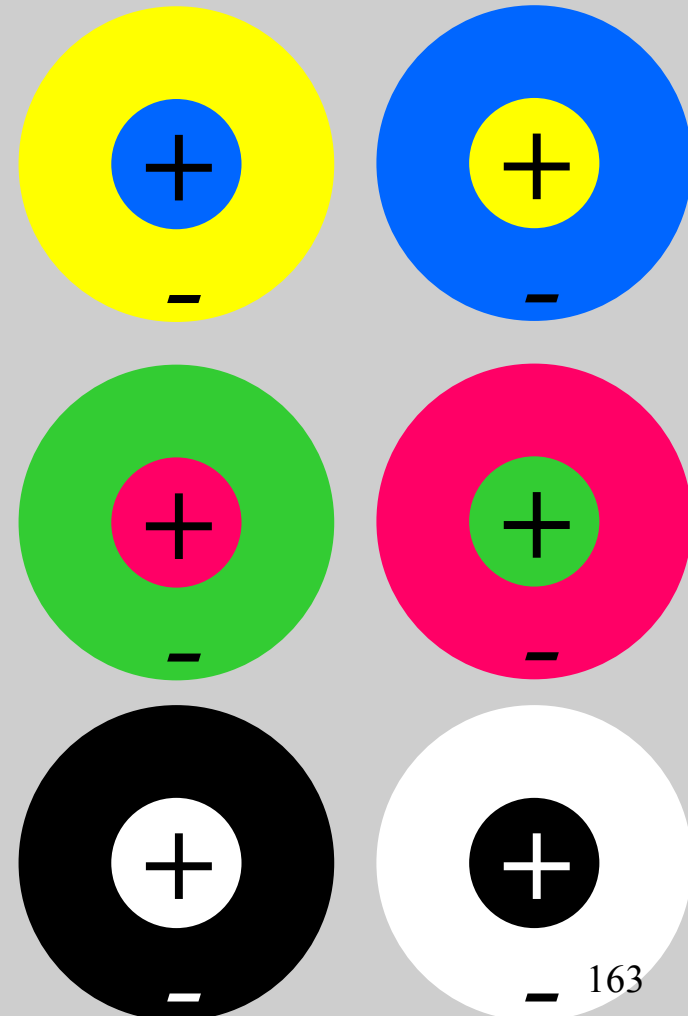
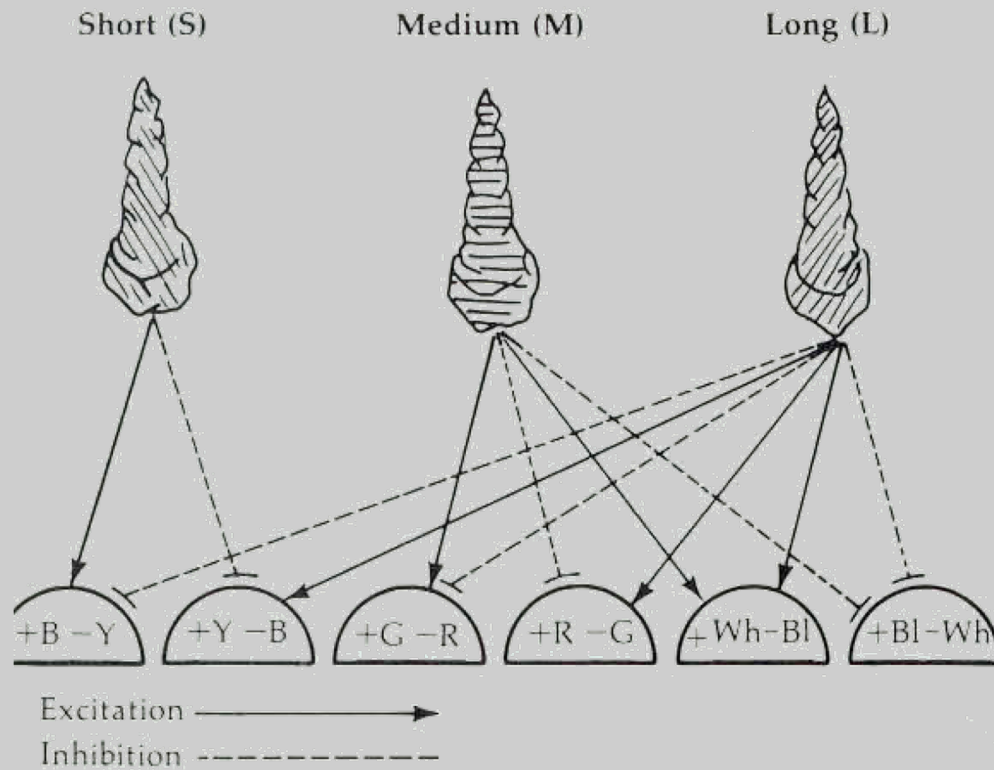




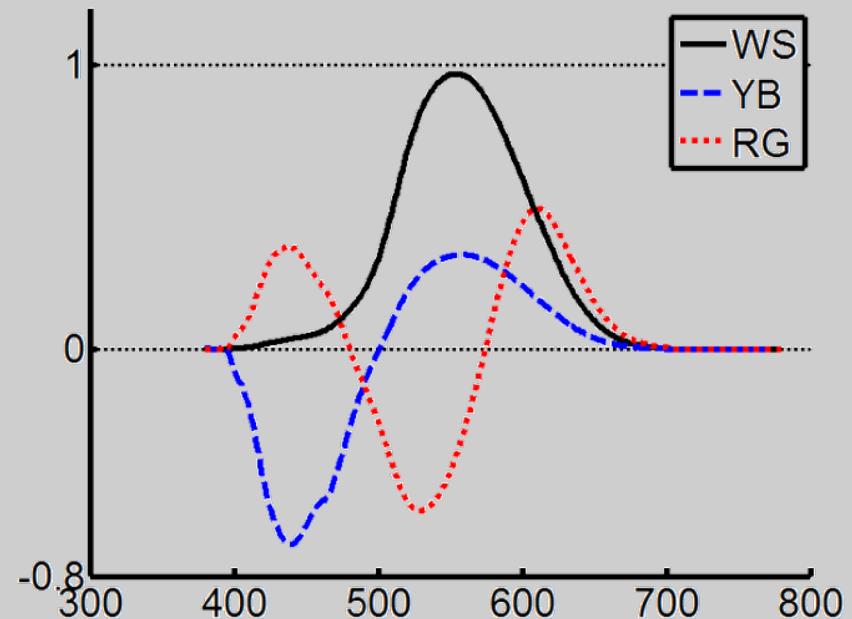
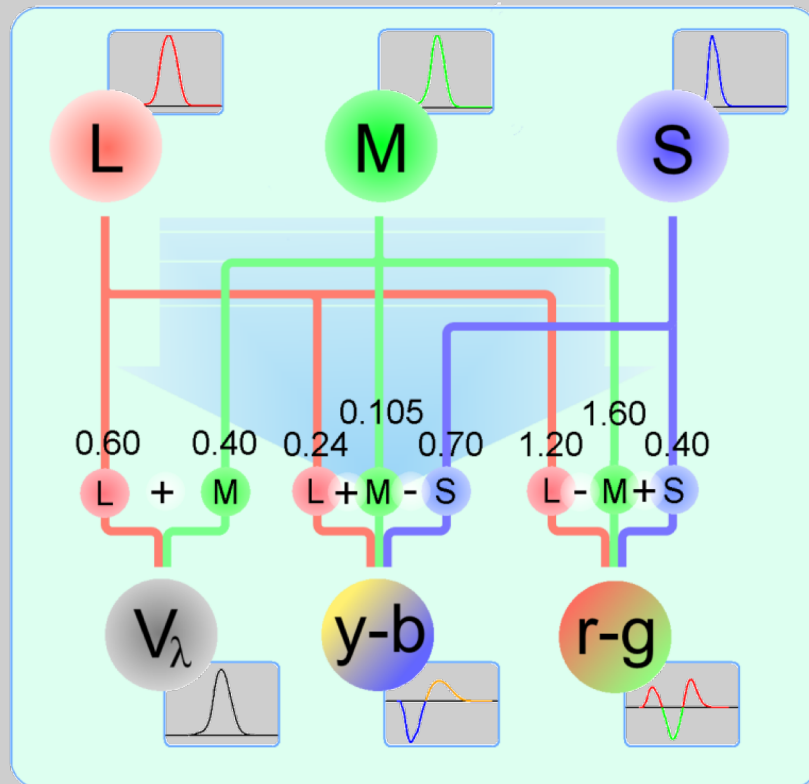


Teoria da cor oponente

Cores são processadas por diferenças. Existem células na retina que recebem impulsos de dois cones diferentes e processam.

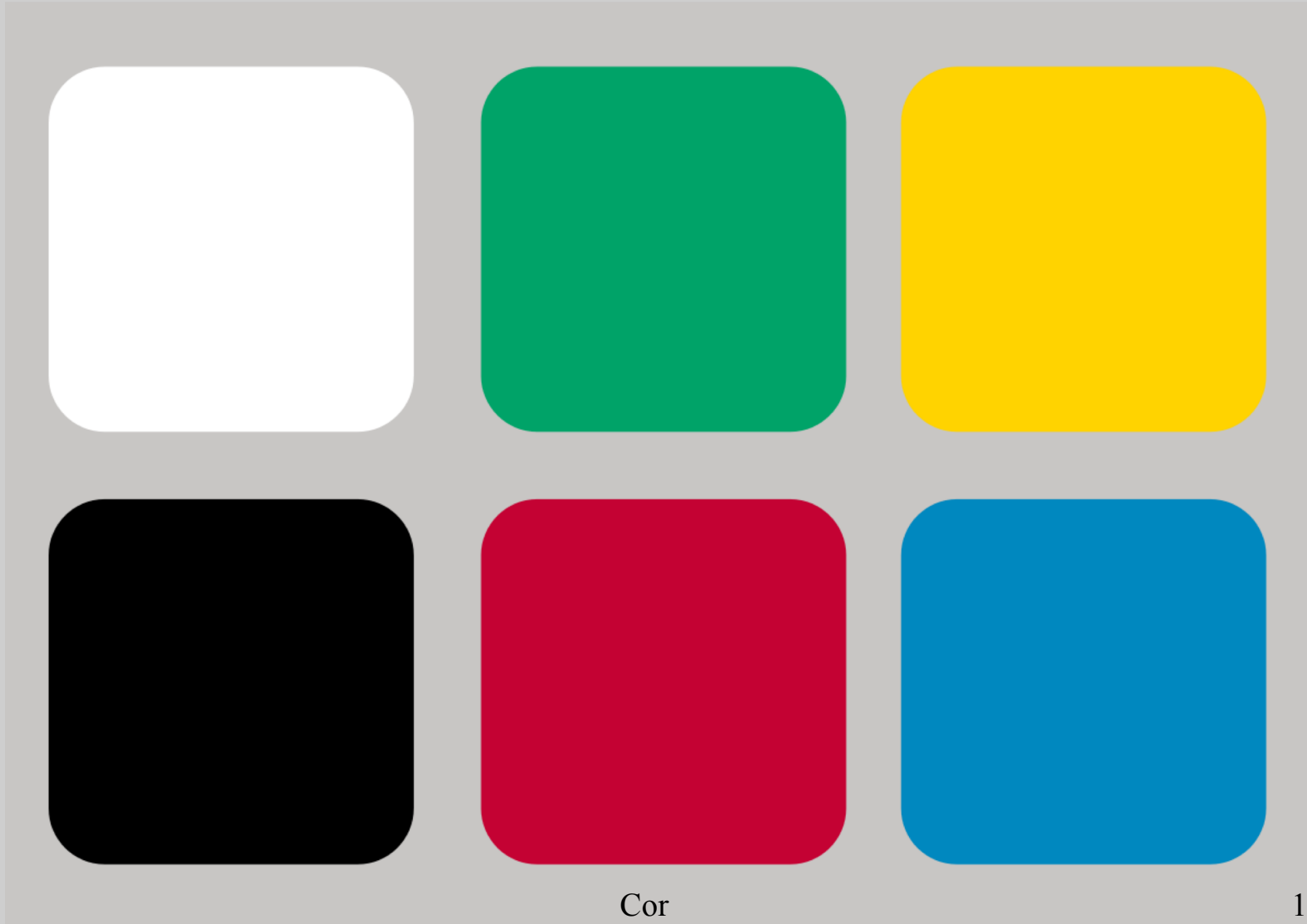


Opponent colors

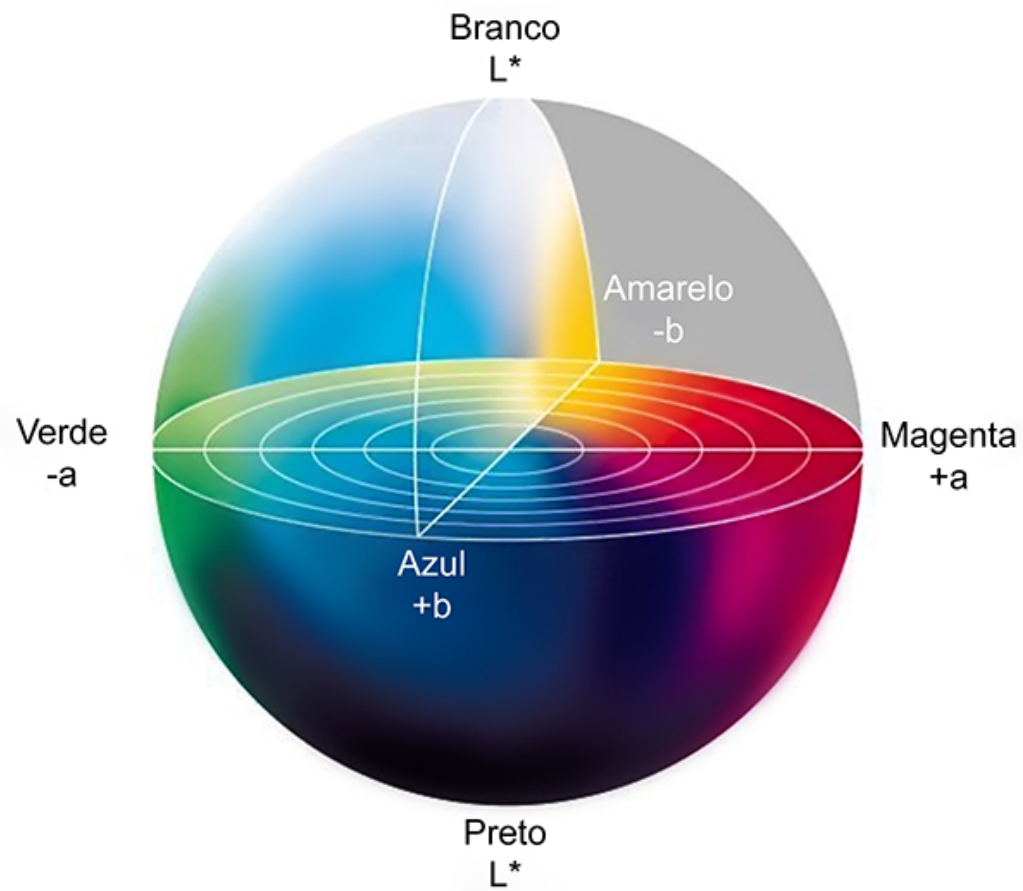
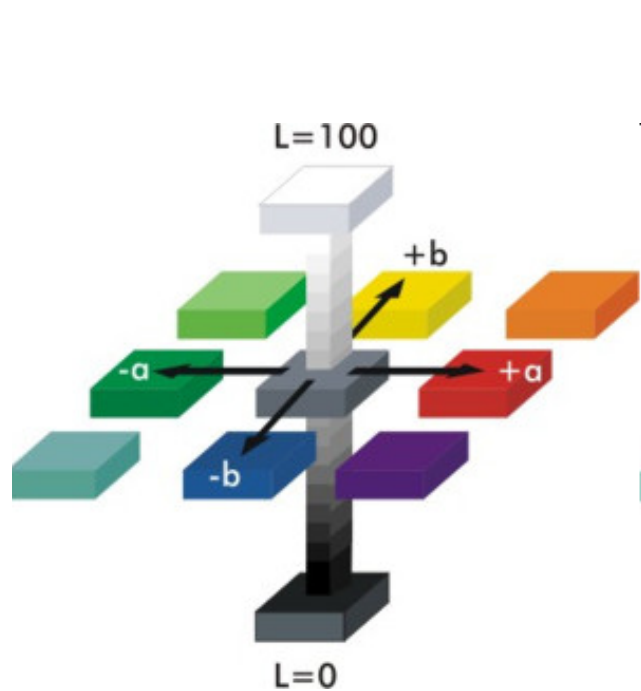


The output of the photoreceptor stage (L, M and S cones) is linearly combined in the opponent stage (V_λ , $y - b$, $r - g$)

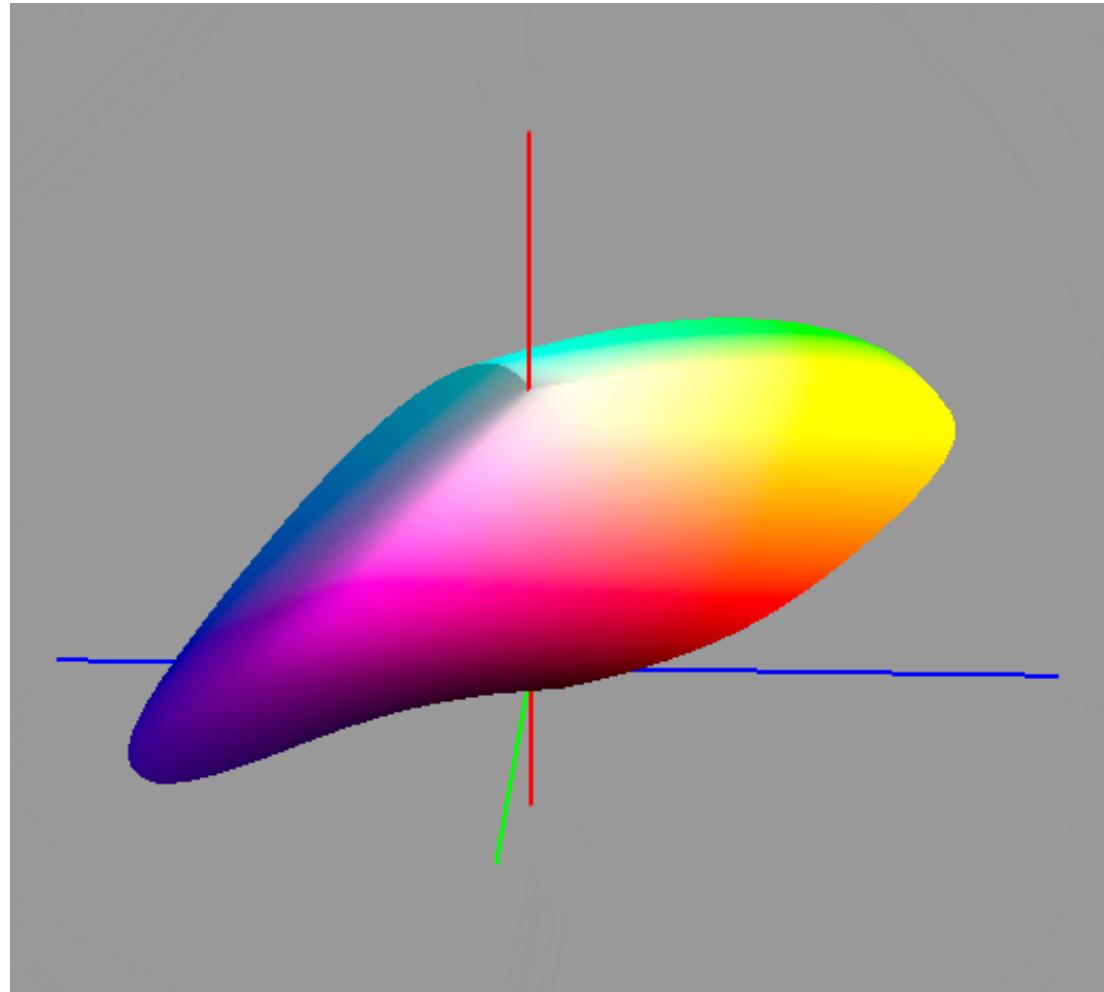
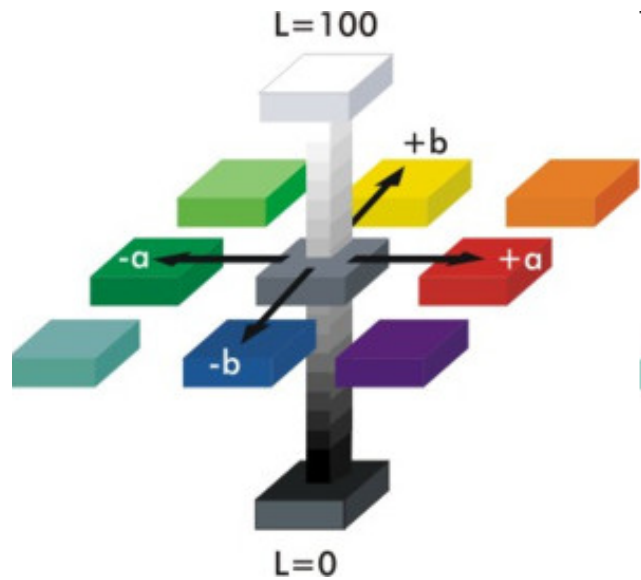
Opponent colors



CIE $L^*a^*b^*$



CIE $L^*a^*b^*$



Conversão CIE XYZ → L*a*b*

$$x_r = \frac{X}{X_r}$$

$$y_r = \frac{Y}{Y_r}$$

$$z_r = \frac{Z}{Z_r}$$

$$f_x = \begin{cases} \sqrt[3]{x_r} & x_r > \varepsilon \\ \frac{\kappa x_r + 16}{116} & x_r \leq \varepsilon \end{cases}$$

$$f_y = \begin{cases} \sqrt[3]{y_r} & y_r > \varepsilon \\ \frac{\kappa y_r + 16}{116} & y_r \leq \varepsilon \end{cases}$$

$$f_z = \begin{cases} \sqrt[3]{z_r} & z_r > \varepsilon \\ \frac{\kappa z_r + 16}{116} & z_r \leq \varepsilon \end{cases}$$

$$L = 116 f_y - 16$$

$$a = 500(f_x - f_y)$$

$$b = 200(f_y - f_z)$$

$$\varepsilon = \begin{cases} 0.008856 & \text{Actual CIE Standard} \\ 216/24389 & \text{Intent of the CIE Standard} \end{cases}$$

$$\kappa = \begin{cases} 903.3 & \text{Actual CIE Standard} \\ 24389/27 & \text{Intent of the CIE Standard} \end{cases}$$



Conversão inversa CIE L*a*b* → XYZ

$$f_x = \frac{a}{500} + f_y$$

$$f_z = f_y - \frac{b}{200}$$

$$f_y = (L + 16)/116$$

$$x_r = \begin{cases} f_x^3 & f_x^3 > \varepsilon \\ (116f_x - 16)/\kappa & f_x^3 \leq \varepsilon \end{cases}$$

$$y_r = \begin{cases} ((L + 16)/116)^3 & L > \kappa\varepsilon \\ L/\kappa & L \leq \kappa\varepsilon \end{cases}$$

$$z_r = \begin{cases} f_z^3 & f_z^3 > \varepsilon \\ (116f_z - 16)/\kappa & f_z^3 \leq \varepsilon \end{cases}$$

$$X = x_r X_r$$

$$Y = y_r Y_r$$

$$Z = z_r Z_r$$

$$\varepsilon = \begin{cases} 0.008856 & \text{Actual CIE Standard} \\ 216/24389 & \text{Intent of the CIE Standard} \end{cases}$$

$$\kappa = \begin{cases} 903.3 & \text{Actual CIE Standard} \\ 24389/27 & \text{Intent of the CIE Standard} \end{cases}$$



Branco de referência

Name	CIE 1931 2°			CIE 1931 10°			CCT (K)	Note
	X ₂	Y ₂	Z ₂	X ₂	Y ₂	Z ₂		
A	109.847	100	35.582	111.142	100	35.200	2856	Incandescent / Tungsten
B	99.093	100	85.313	99.178	100	84.349	4874	{obsolete} Direct sunlight at noon
C	98.071	100	118.225	97.286	100	116.145	6774	{obsolete} Average / North sky Daylight
D50	96.421	100	82.519	96.721	100	81.428	5003	Horizon Light. ICC profile PCS
D55	95.680	100	92.148	95.797	100	90.925	5503	Mid-morning / Mid-afternoon Daylight
D65	95.043	100	108.890	94.810	100	107.305	6504	Noon Daylight: Television, sRGB color space
D75	94.972	100	122.639	94.417	100	120.643	7504	North sky Daylight
E	100.000	100	100.000	100.000	100	100.000	5454	Equal energy
F1	92.834	100	103.665	94.791	100	103.191	6430	Daylight Fluorescent
F2	99.145	100	67.316	103.245	100	68.990	4230	Cool White Fluorescent
F3	103.753	100	49.861	108.968	100	51.965	3450	White Fluorescent
F4	109.147	100	38.813	114.961	100	40.963	2940	Warm White Fluorescent
F5	90.872	100	98.723	93.369	100	98.636	6350	Daylight Fluorescent
F6	97.309	100	60.191	102.148	100	62.074	4150	Lite White Fluorescent
F7	95.017	100	108.630	95.780	100	107.618	6500	D65 simulator, Daylight simulator
F8	96.413	100	82.333	97.115	100	81.135	5000	D50 simulator, Sylvania F40 Design 50
F9	100.365	100	67.868	102.116	100	67.826	4150	Cool White Deluxe Fluorescent
F10	96.174	100	81.712	99.001	100	83.134	5000	Philips TL85, Ultralume 50
F11	100.899	100	64.262	103.820	100	65.555	4000	Philips TL84, Ultralume 40
F12	108.046	100	39.228	111.428	100	40.353	3000	Philips TL83, Ultralume 30

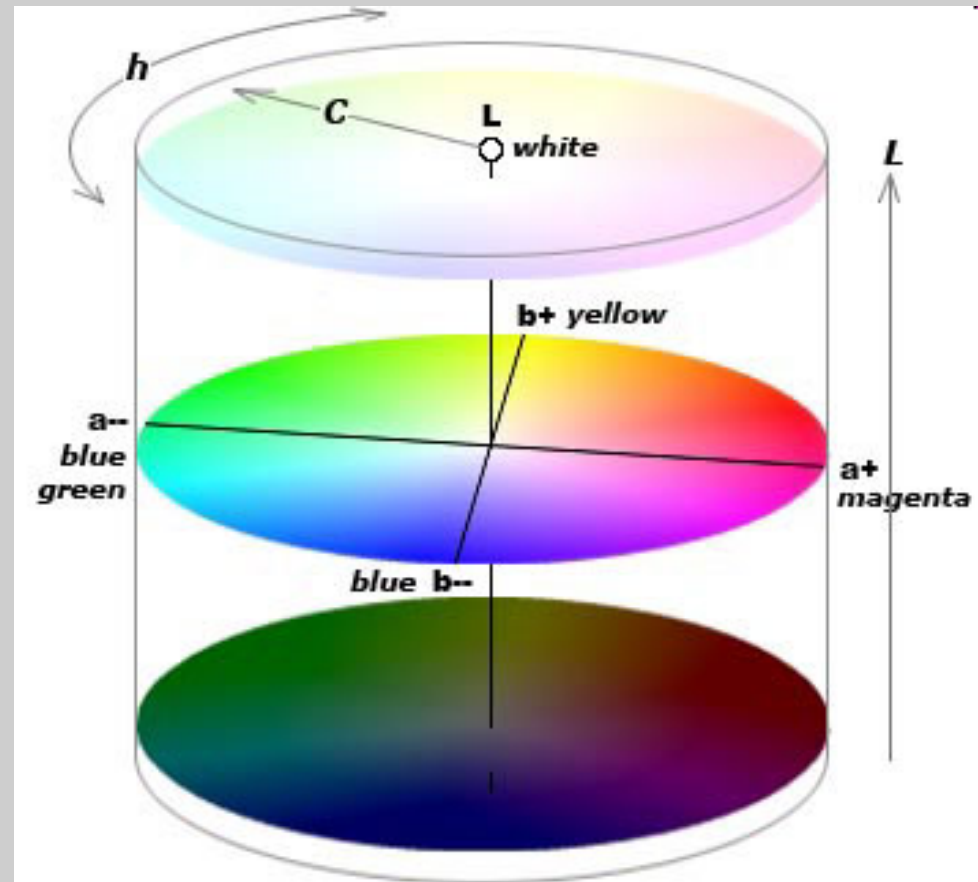
CIE 1976 (L*a*b*) colour space, Hue and Chroma

Hue (Matiz):

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

Chroma:

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



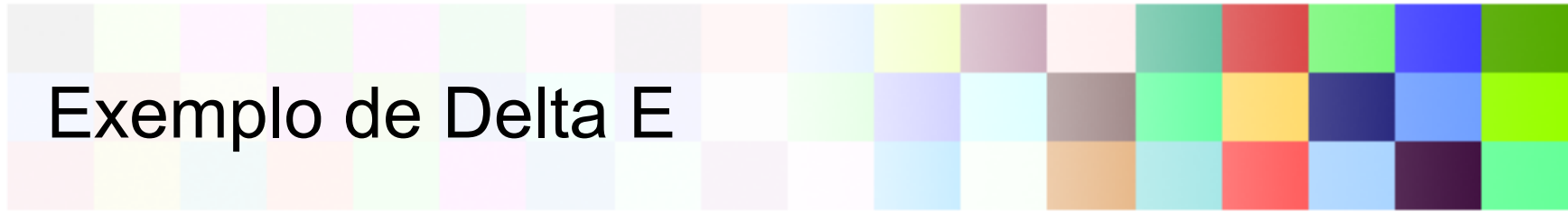
CIE 1976 a,b colour difference and CIELAB components

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad \left\{ \begin{array}{l} = 1 \text{ just noticeable difference} \\ < 5 \text{ small color differences} \end{array} \right.$$

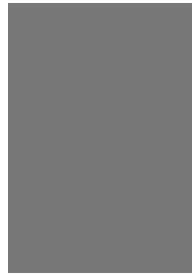
$$\Delta H_{ab}^* = \text{variação de ângulo} \quad \text{ou}$$

$$\Delta H_{ab}^* = \sqrt{(\Delta E_{ab}^*)^2 - (\Delta L^*)^2 + (\Delta C_{ab}^*)^2}$$

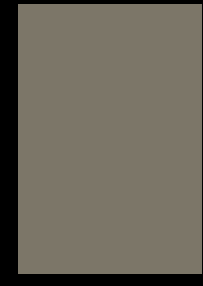
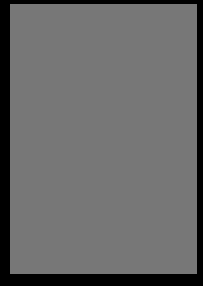
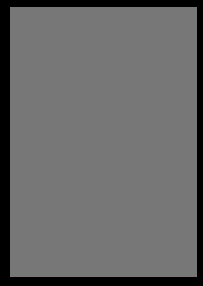
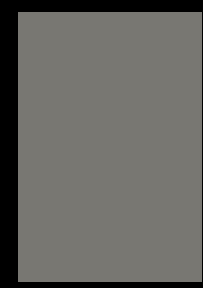
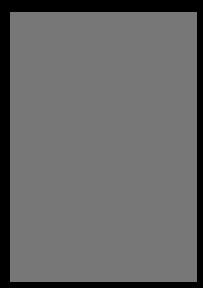
$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta C_{ab}^*)^2 + (\Delta H_{ab}^*)^2}$$

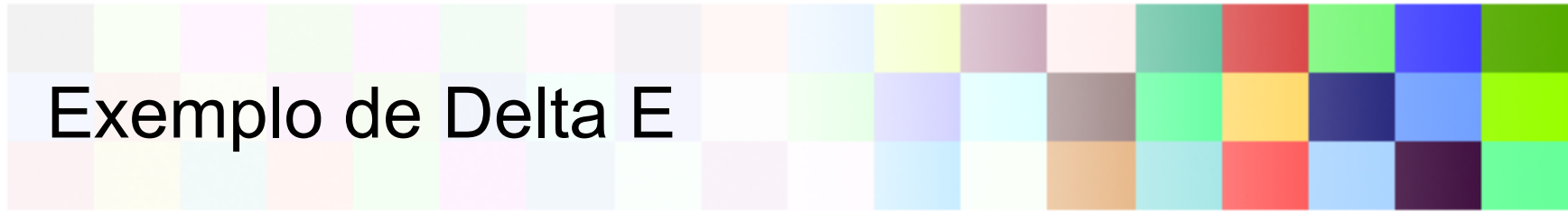


Exemplo de Delta E

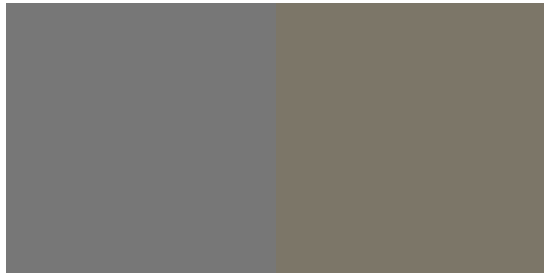


Exemplo de Delta E



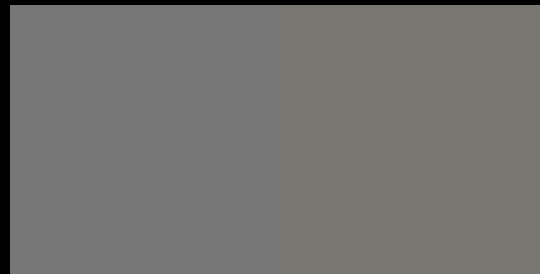


Exemplo de Delta E



Exemplo de Delta E

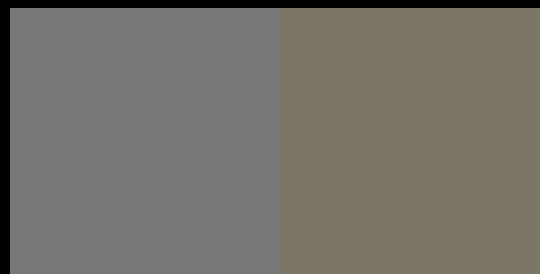
3 Delta-E

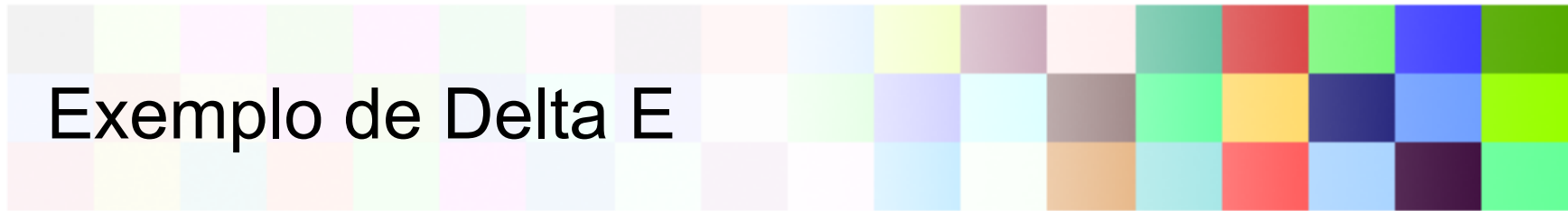


6 Delta-E



9 Delta-E





- Diferenças até 1 Delta-E entre duas cores não adjacentes mal é percebida por uma pessoa com visão normal
- Diferenças entre 3 e 4 Delta-E não adjacentes são aceitáveis para a maioria das pessoas com visão normal
- Diferenças entre 3 a 6 Delta-E são consideradas aceitáveis na reprodução de cores comercial

CIE 1994 colour difference

$$\Delta E_{94}^* = \left[\left(\frac{\Delta L^*}{k_L S_L} \right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C} \right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H} \right)^2 \right]^{1/2}$$

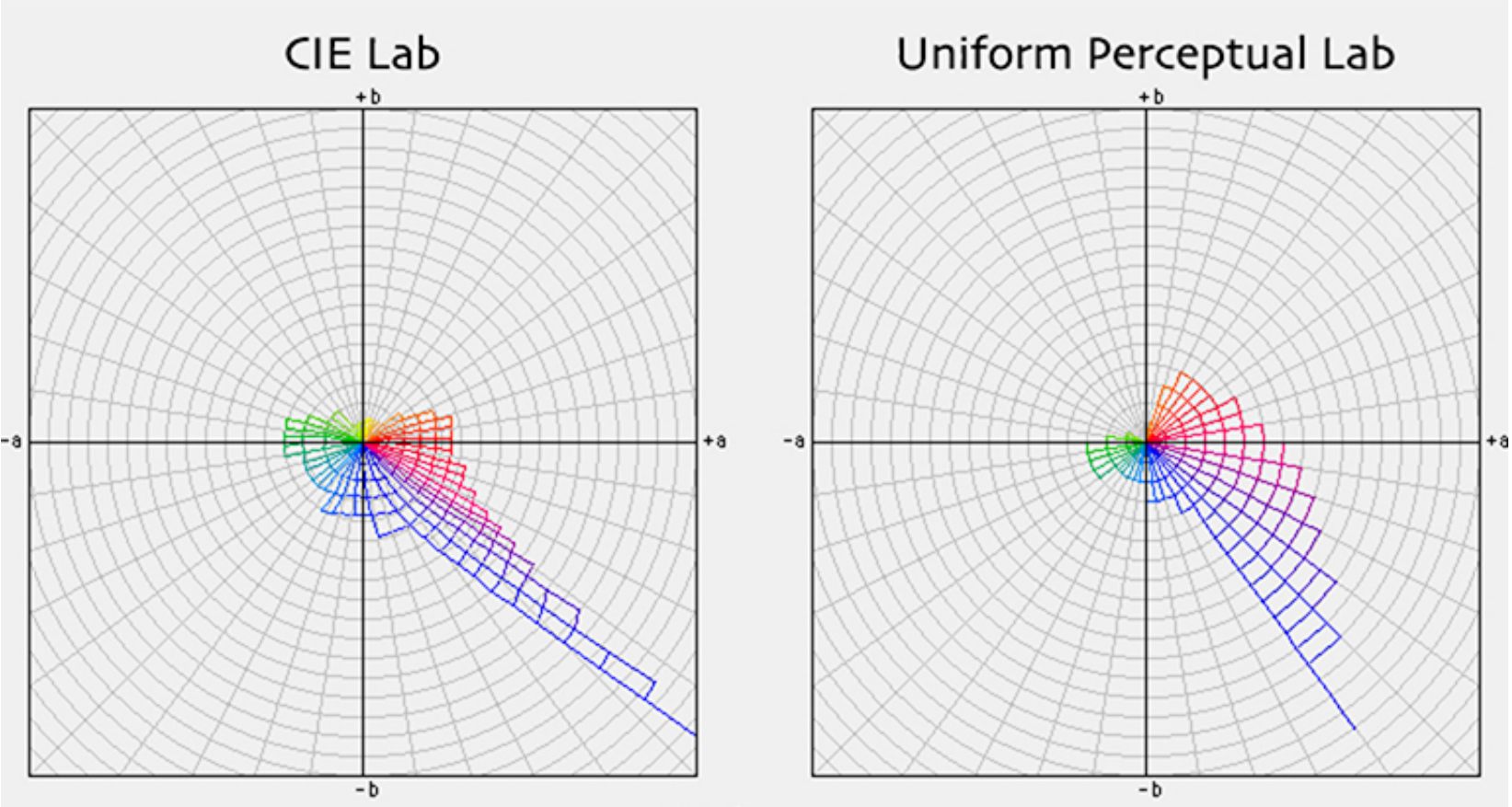
- k parametric factors, industry dependent
- S weighting functions, depend on location in colour space:

$$S_L = 1; \quad S_C = 1 + 0,045 C_{ab}^*; \quad S_H = 1 + 0,015 C_{ab}^*$$



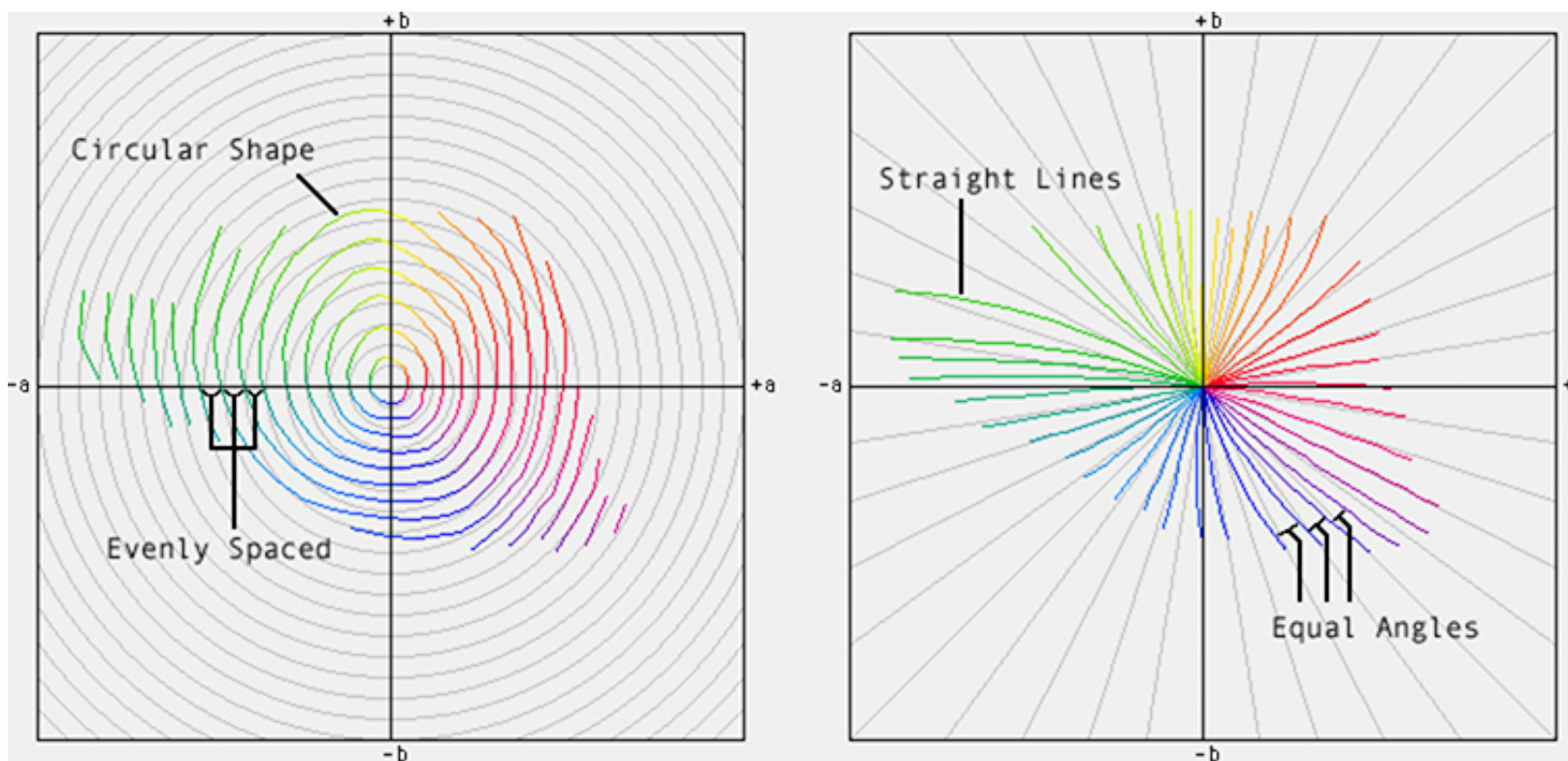
Problemas na uniformidade no Lab

- Falta de uniformidade na Matiz
 - Foco nos tons azuis que tendem a púrpura



Problemas na uniformidade no Lab

- Falta de uniformidade na Matiz
- Falta de uniformidade na Saturação



Fórmula CIEDE2000

Step 1. Calculate the CIELAB L^* , a^* , b^* , and C^* as usual:

$$L^* = 116f(Y/Y_n) - 16$$

$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$

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

where

$$f(I) = \begin{cases} I^{1/3} & \text{for } I > 0.008856 \\ f(I) = 7.7871 + 16/116 & \text{Otherwise.} \end{cases}$$

Fórmula CIEDE2000

Step 2. Calculate a' , C' and h' :

$$L' = L^*$$

$$a' = (1 + G)a^*$$

$$b' = b^*$$

$$C' = \sqrt{a'^2 + b'^2}$$

$$h' = \tan^{-1}(b'/a'),$$

where

$$G = 0.5 \left(1 - \sqrt{\frac{C_{ab}^{*7}}{C_{ab}^{*7} + 25^7}} \right),$$

where $\overline{C_{ab}^*}$ is the arithmetic mean of the C_{ab}^* values for a pair of samples.

where

$$S_L = 1 + \frac{0.015(\overline{L'} - 50)^2}{\sqrt{20 + (\overline{L'} - 50)^2}}$$

and

$$S_C = 1 + 0.045\overline{C'}$$

and

$$S_H = 1 + 0.015\overline{C'}T,$$

where

$$T = 1 - 0.17 \cos(\overline{h'} - 30^\circ) + 0.24 \cos(2\overline{h'})$$

$$+ 0.32 \cos(3\overline{h'} + 6^\circ) - 0.20 \cos(4\overline{h'} - 63^\circ)$$

and

$$R_T = -\sin(2\Delta\theta)R_C,$$

Fórmula CIEDE2000

Step 3. Calculate $\Delta L'$, $\Delta C'$ and $\Delta H'$:

$$\Delta L' = L'_b - L'_s$$

$$\Delta C' = C'_b - C'_s$$

$$\Delta H' = 2 \sqrt{C'_b C'_s} \sin\left(\frac{\Delta h'}{2}\right)$$

where

$$\Delta h' = h'_b - h'_s$$

where

$$\Delta\theta = 30 \exp\{-[(\bar{h}' - 275^\circ)/25]^2\}$$

and

$$R_C = 2 \sqrt{\frac{\bar{C}'^2}{\bar{C}'^2 + 25^2}}$$

Fórmula CIEDE2000

Step 4. Calculate CIEDE2000 ΔE_{00} :

$$\Delta E_{00} =$$

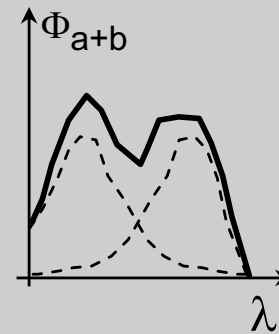
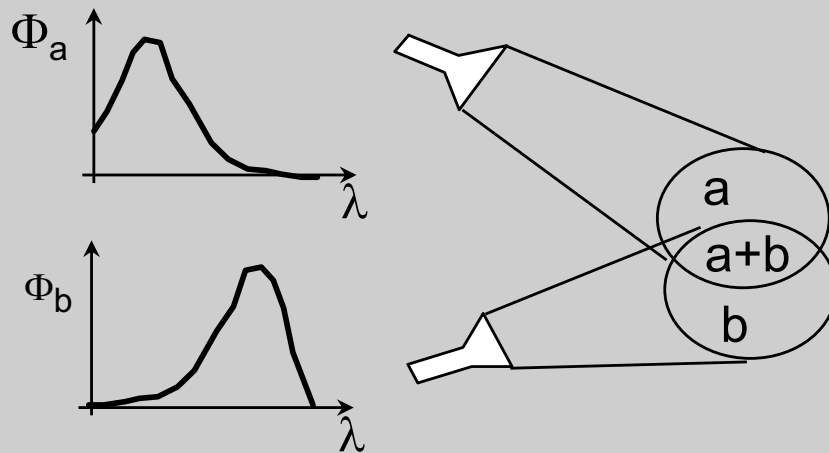
$$\sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C}\right) \left(\frac{\Delta H'}{k_H S_H}\right)},$$

Transformações de espectros

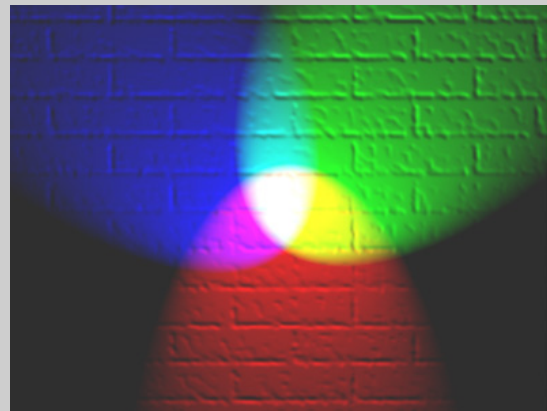
Adição e filtro

Processos aditivos de formação de cores

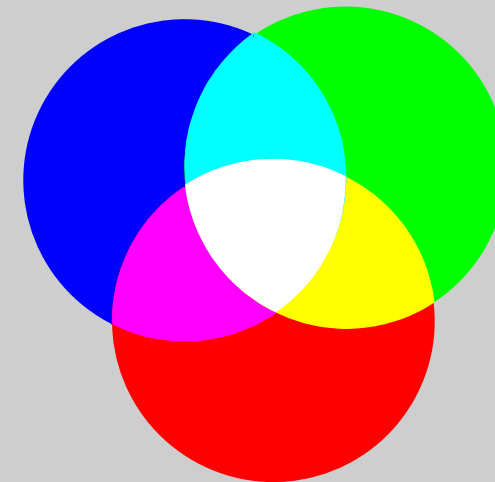
$$\Phi_{a+b}(\lambda) = \Phi_a(\lambda) + \Phi_b(\lambda)$$



O olho não vê componentes!



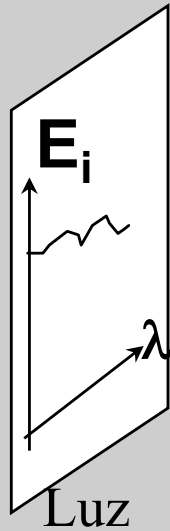
Cor



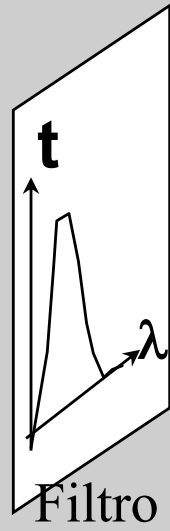


Processos subtrativos de formação de cores

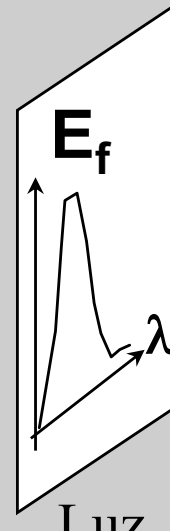
filtros



Luz
branca



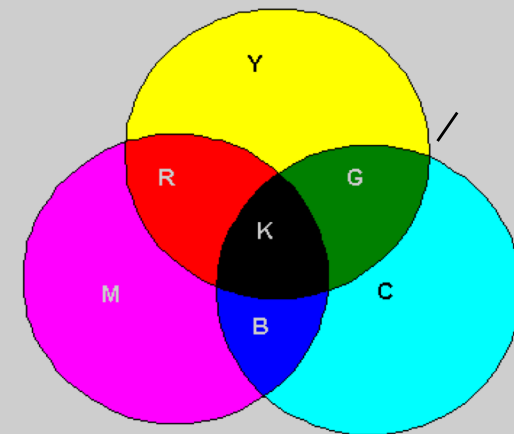
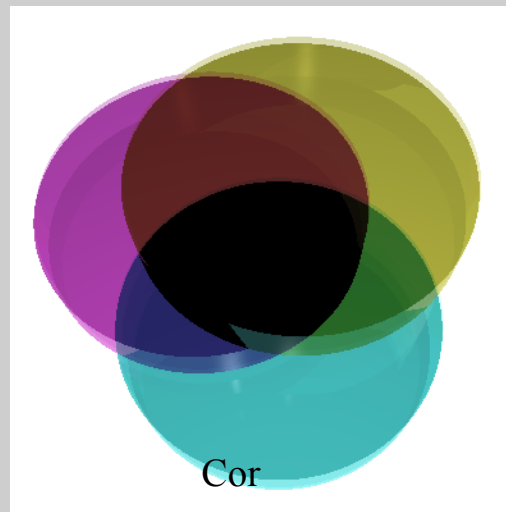
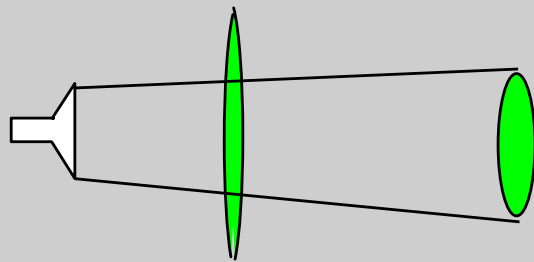
Filtro
verde

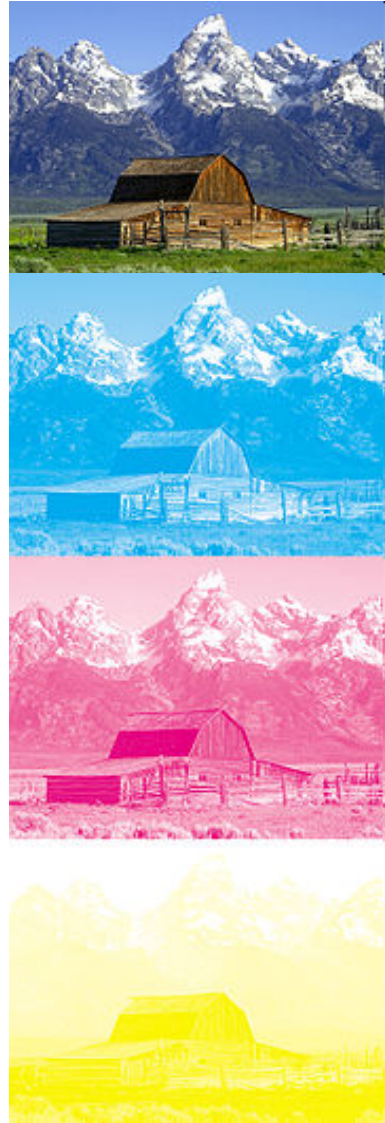


Luz
verde

$$E_f(\lambda) = t(\lambda)E_i(\lambda)$$

transparência





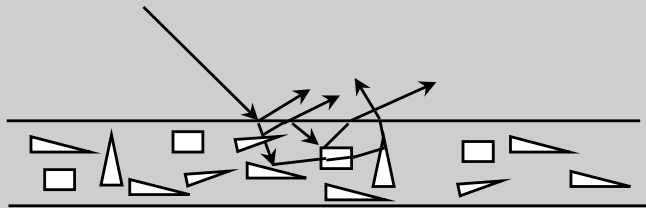
Cor



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Processos de formação de cores: por pigmentos

por pigmentação



△ □ índices de refração distinto do material base
▽

A sucessão de reflexão e refração determinam a natureza da luz refletida

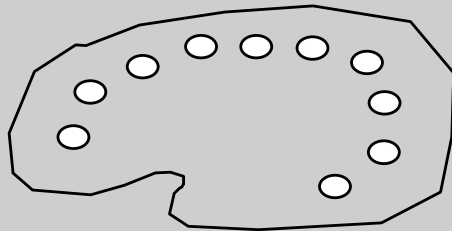


Cor

Processos de formação de cores: por pigmentos



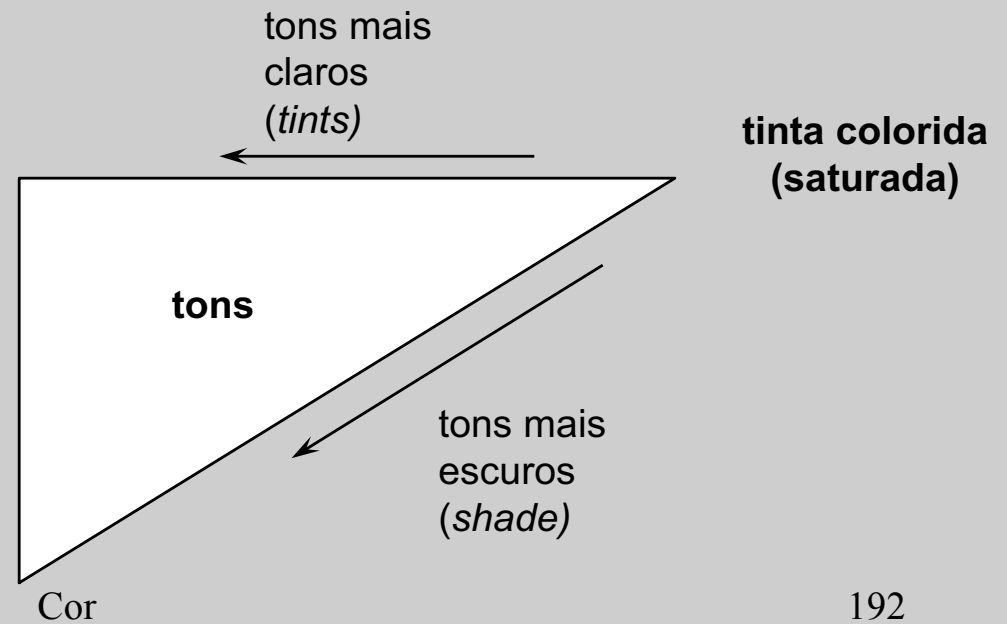
tinta branca



PALHETA
DO
PINTOR

Cinzas
(greys)

tinta preta



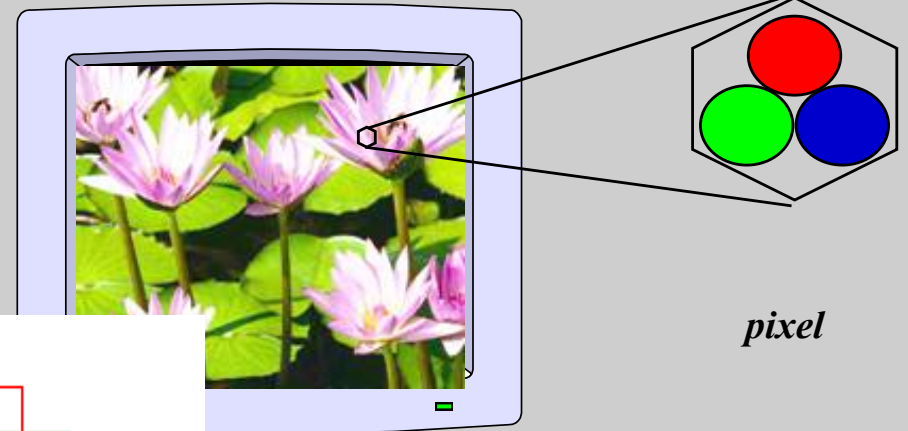
Monitores

I) Sistemas dos Monitores - *m*RGB



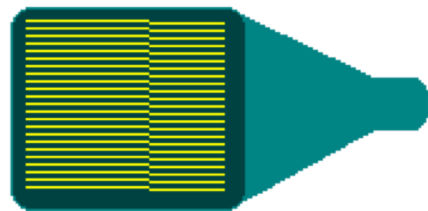
HiColor

Pixels are packed in a short
Each primary uses 5 bits

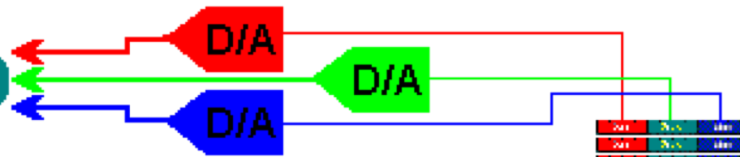


pixel

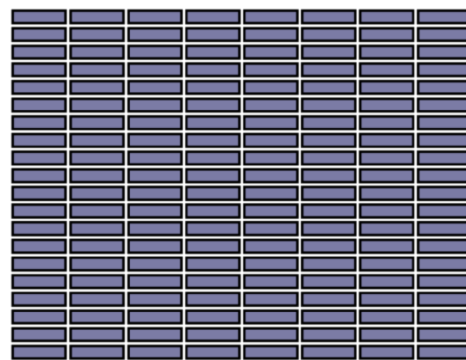
processo aditivo



Display

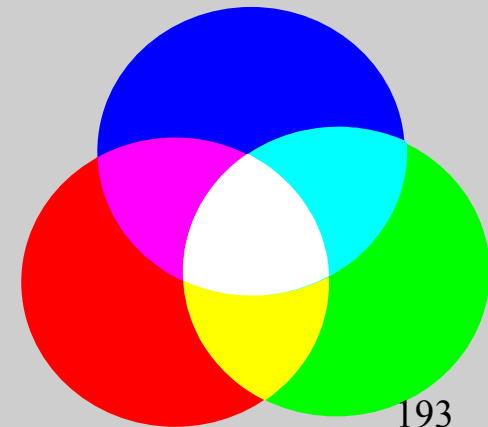


Framebuffer



Color Map
or Lookup Table

Cor

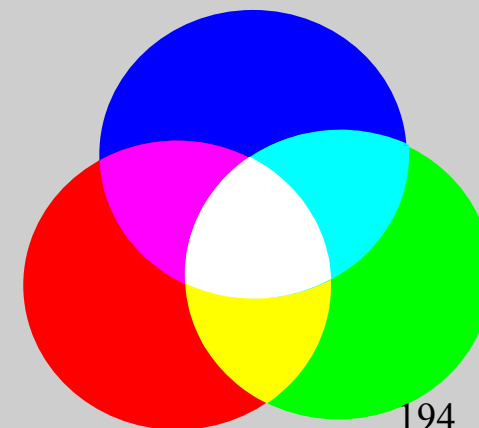
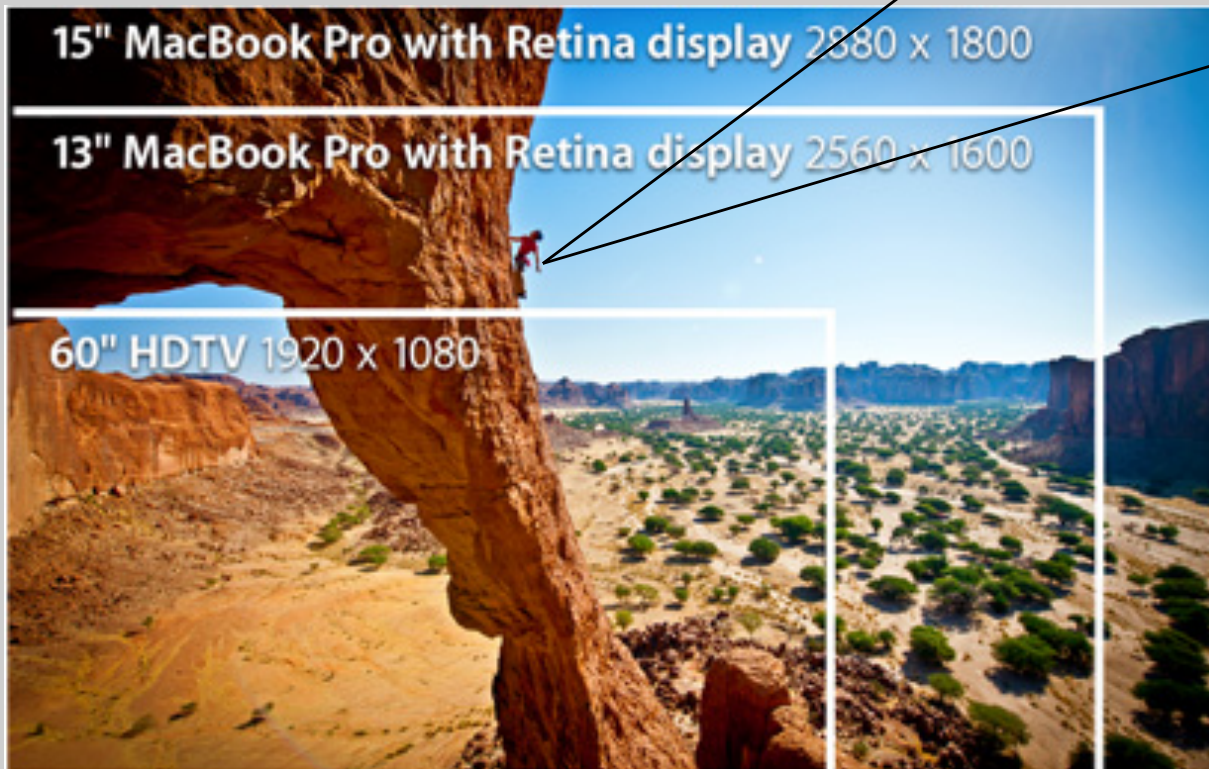
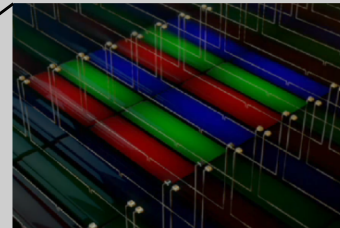


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Monitores

Sistemas atuais - mRGB

pixel



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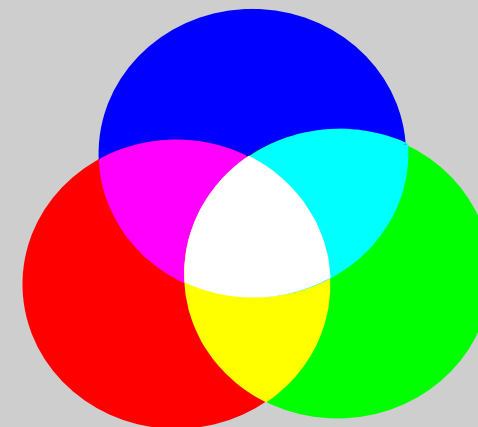
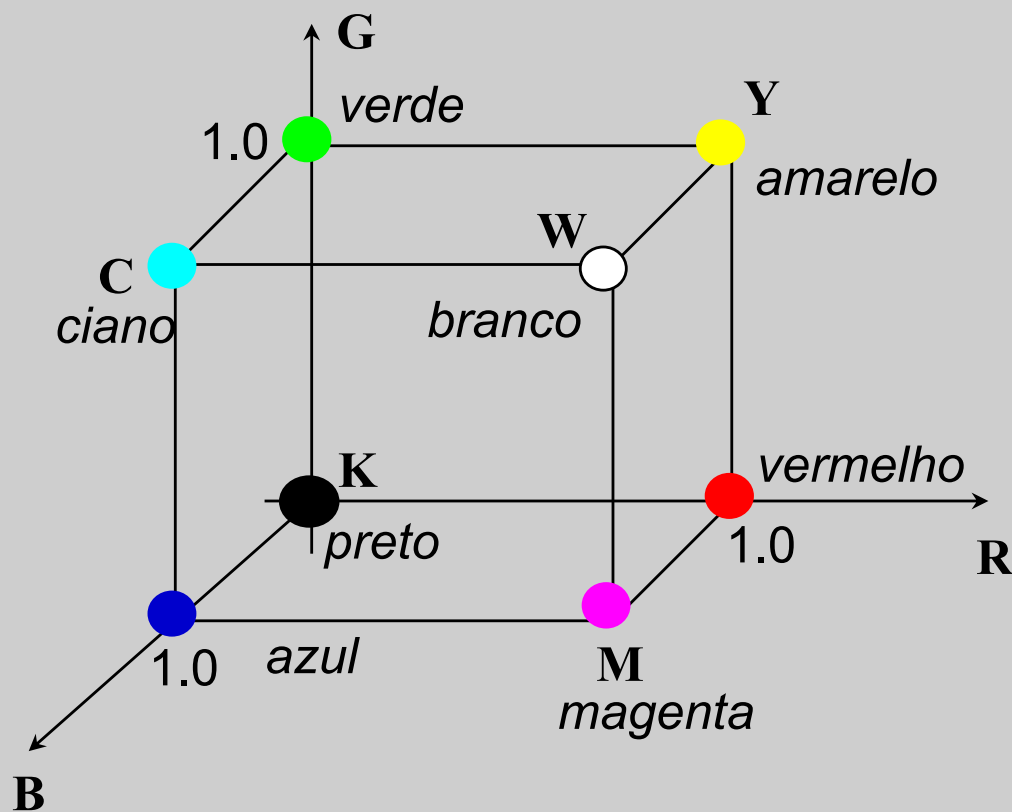
Cor

processo aditivo

Sistemas de cor dependentes de dispositivo - mRGB

I) Sistemas dos Monitores - *mRGB*

processo aditivo

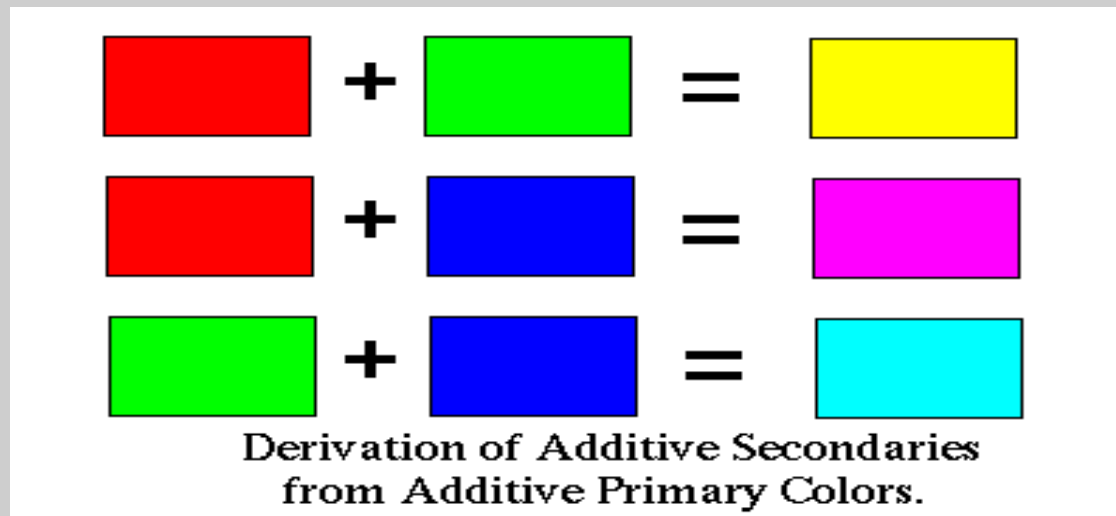


normalmente
temos 1 byte
para cada
componente
mapeando
[0, 255] em [0,1]

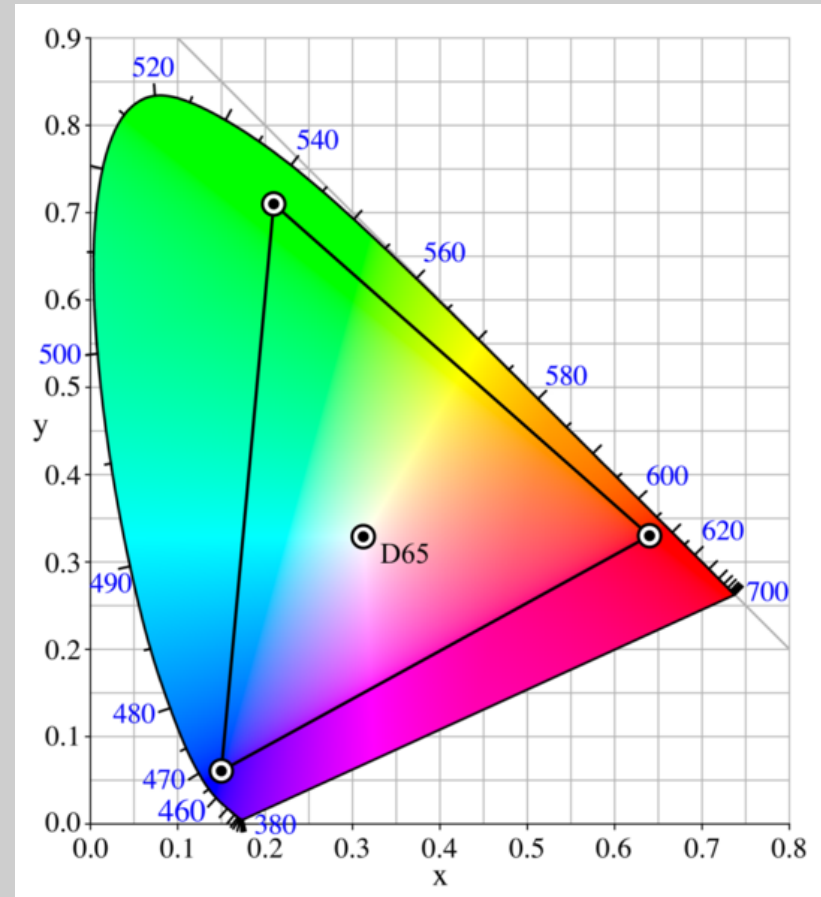
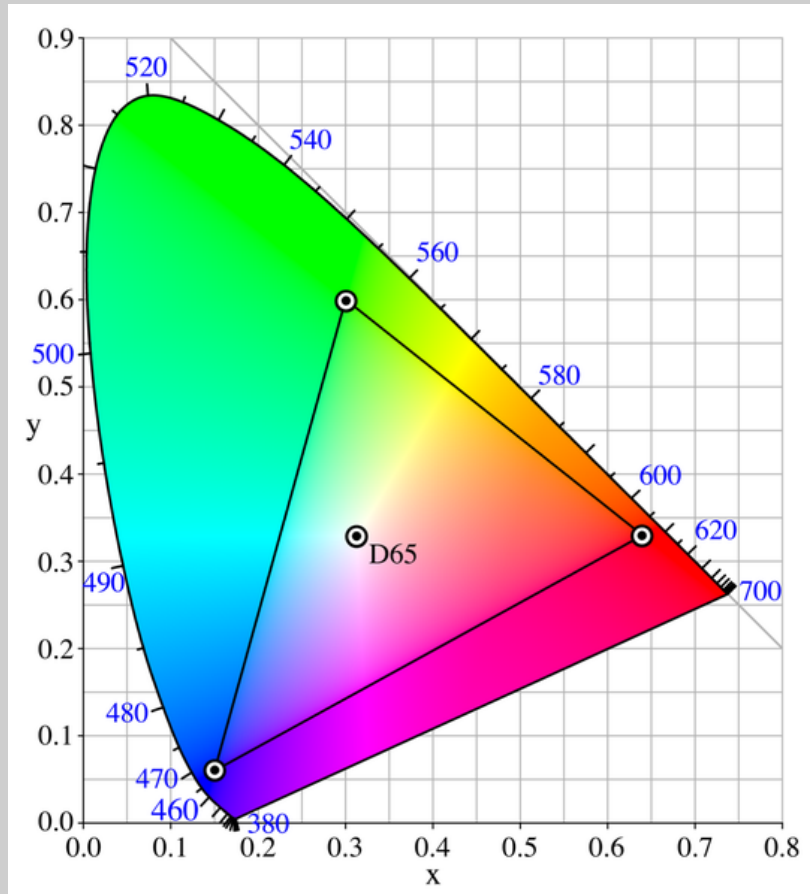
Componentes somam como vetores

Sistemas de cor dependentes de dispositivo - mRGB

I) Sistemas dos Monitores - mRGB



Espaços sRGB e Adobe RGB



Monitor padrão de TV HD

Dispositivo	Branco (D65)		Cores primárias					
	x_W	y_W	x_R	y_R	x_G	y_G	x_B	y_B
ITU-R BT.709	0.3127	0.3290	0.64	0.33	0.30	0.60	0.15	0.06

Cálculo da componente z

$$x + y + z = 1$$

$$z = 1 - (x + y)$$

CIE xyz				
	Red	Green	Blue	D65
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583

Cor correspondente a um *RGB*

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R \\ Y_R \\ Z_R \end{pmatrix} R + \begin{pmatrix} X_G \\ Y_G \\ Z_G \end{pmatrix} G + \begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix} B$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Relação entre XYZ e xyz

$$x_R = \frac{X_R}{X_R + Y_R + Z_R} = \frac{X_R}{\Sigma_R}$$

$$y_R = \frac{Y_R}{X_R + Y_R + Z_R} = \frac{Y_R}{\Sigma_R}$$

$$z_R = \frac{Z_R}{X_R + Y_R + Z_R} = \frac{Z_R}{\Sigma_R}$$

$$X_R = x_R \Sigma_R$$

$$Y_R = y_R \Sigma_R$$

$$Z_R = z_R \Sigma_R$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} x_R \Sigma_R & x_G \Sigma_G & x_G \Sigma_B \\ y_R \Sigma_R & y_G \Sigma_G & y_G \Sigma_B \\ z_R \Sigma_R & z_G \Sigma_G & z_G \Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.64 \Sigma_R & 0.30 \Sigma_G & 0.15 \Sigma_B \\ 0.33 \Sigma_R & 0.60 \Sigma_G & 0.06 \Sigma_B \\ 0.03 \Sigma_R & 0.10 \Sigma_G & 0.79 \Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Branco de referência D65

CIE	D65
x_w	0.3127
y_w	0.3290
z_w	0.3583

$$Y_W = 1.0 \quad \text{ou} \quad 100$$

$$X_W = x_R \Sigma_W = 0.3127 \Sigma_W$$

$$Y_W = y_R \Sigma_W = 0.3290 \Sigma_W$$

$$Z_W = z_R \Sigma_W = 0.3583 \Sigma_W$$

$$\Sigma_W = \frac{1}{0.3290} = 3.0395$$

$$X_W = \frac{0.3127}{0.3290} = 1.0891$$

$$Z_W = \frac{0.3583}{0.3290} = 0.9505$$

Reprodução do branco D65

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.64\Sigma_R & 0.30\Sigma_G & 0.15\Sigma_B \\ 0.33\Sigma_R & 0.60\Sigma_G & 0.06\Sigma_B \\ 0.03\Sigma_R & 0.10\Sigma_G & 0.79\Sigma_B \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} 1.0891 \\ 1.0 \\ 0.9505 \end{pmatrix} = \begin{bmatrix} 0.64\Sigma_R & 0.30\Sigma_G & 0.15\Sigma_B \\ 0.33\Sigma_R & 0.60\Sigma_G & 0.06\Sigma_B \\ 0.03\Sigma_R & 0.10\Sigma_G & 0.79\Sigma_B \end{bmatrix} \begin{pmatrix} 1.0 \\ 1.0 \\ 1.0 \end{pmatrix}$$

Resolvendo os Σ 's

$$\begin{pmatrix} 1.0891 \\ 1.0 \\ 0.9505 \end{pmatrix} = \begin{bmatrix} 0.64\Sigma_R & 0.30\Sigma_G & 0.15\Sigma_B \\ 0.33\Sigma_R & 0.60\Sigma_G & 0.06\Sigma_B \\ 0.03\Sigma_R & 0.10\Sigma_G & 0.79\Sigma_B \end{bmatrix} \begin{pmatrix} 1.0 \\ 1.0 \\ 1.0 \end{pmatrix}$$

$$\begin{pmatrix} 1.0891 \\ 1.0 \\ 0.9505 \end{pmatrix} = \begin{bmatrix} 0.64 & 0.30 & 0.15 \\ 0.33 & 0.60 & 0.06 \\ 0.03 & 0.10 & 0.79 \end{bmatrix} \begin{pmatrix} \Sigma_R \\ \Sigma_G \\ \Sigma_B \end{pmatrix}$$

$$\begin{pmatrix} \Sigma_R \\ \Sigma_G \\ \Sigma_B \end{pmatrix} = \begin{pmatrix} 0.644 \\ 1.192 \\ 1.203 \end{pmatrix}$$

Relação entre CIE XYZ e RGB em HDTV

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} 0.412 & 0.358 & 0.180 \\ 0.213 & 0.715 & 0.072 \\ 0.019 & 0.119 & 0.950 \end{bmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

ou

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{bmatrix} 3.240 & -1.537 & -0.499 \\ -0.969 & 1.876 & 0.042 \\ 0.056 & -0.204 & 1.057 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

- sRGB –

“A Standard Default Color Space for the Internet”

- **Hewlett-Packard and Microsoft propose the addition of support for a standard color space, sRGB, within the Microsoft operating systems, HP products, the Internet, and all other interested vendors.**
- **The aim of this color space is to complement the current color management strategies by enabling a third method of handling color in the operating systems, device drivers and the Internet that utilizes a simple and robust device independent color definition.**

ITU-R BT.709

CIE chromaticities for ITU-R BT.709 reference primaries and CIE standard illuminant

	Red	Green	Blue	D65
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583

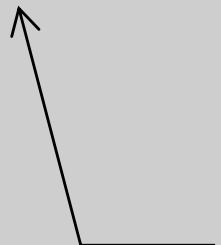
sRGB viewing environment Parameters

Condition	sRGB
Luminance level (typical CRT)	80 cd/m ²
Illuminant White	$x = 0.3127, y = 0.3291$ (D65)
Image surround	20% reflectance
Encoding Ambient Illuminance Level	64 lux
Encoding Ambient White Point	$x = 0.3457, y = 0.3585$ (D50)
Encoding Viewing Flare	1.0%
Typical Ambient Illuminance Level	200 lux
Typical Ambient White Point	$x = 0.3457, y = 0.3585$ (D50)
Typical Viewing Flare	5.0%

XYZ → sRGB: Passo 1

Converte utilizando ITU-R BT.709:

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$


$$[0 \dots 1]$$

Cor

$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = [M]^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

210

XYZ → sRGB: Passo 2

The sRGB tristimulus values are next transformed to nonlinear sR'G'B' values as follows:

If $R_{sRGB}, G_{sRGB}, B_{sRGB} \leq 0.00304$

$$R'_{sRGB} = 12.92 \times R_{sRGB}$$

$$G'_{sRGB} = 12.92 \times G_{sRGB}$$

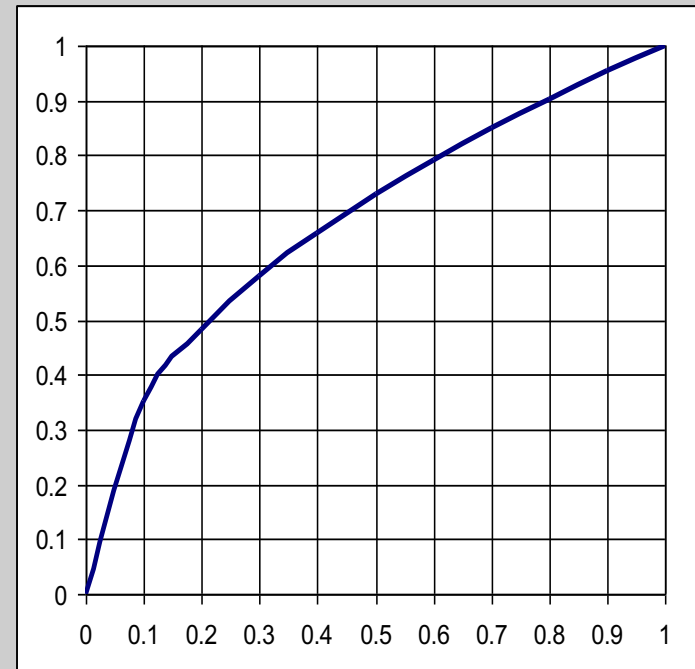
$$B'_{sRGB} = 12.92 \times B_{sRGB}$$

else if $R_{sRGB}, G_{sRGB}, B_{sRGB} > 0.00304$

$$R'_{sRGB} = 1.055 \times R_{sRGB}^{(1.0/2.4)} - 0.055$$

$$G'_{sRGB} = 1.055 \times G_{sRGB}^{(1.0/2.4)} - 0.055$$

$$B'_{sRGB} = 1.055 \times B_{sRGB}^{(1.0/2.4)} - 0.055$$



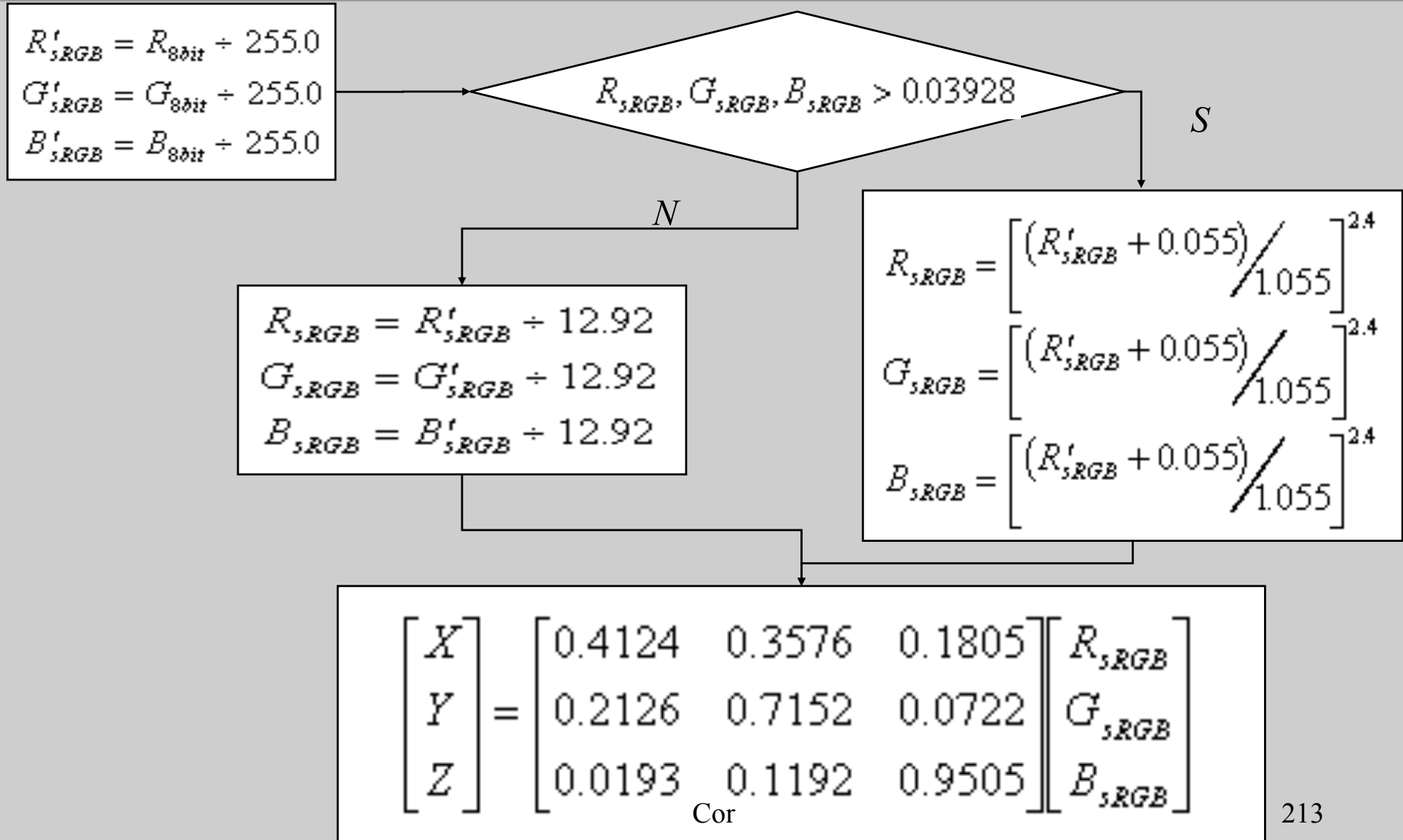
XYZ → sRGB: Passo 3 – Digital Color

$$\begin{aligned}R_{8bit} &= \left((WDC - KDC) \times R'_{sRGB} \right) + KDC \\G_{8bit} &= \left((WDC - KDC) \times G'_{sRGB} \right) + KDC \\B_{8bit} &= \left((WDC - KDC) \times B'_{sRGB} \right) + KDC\end{aligned}$$

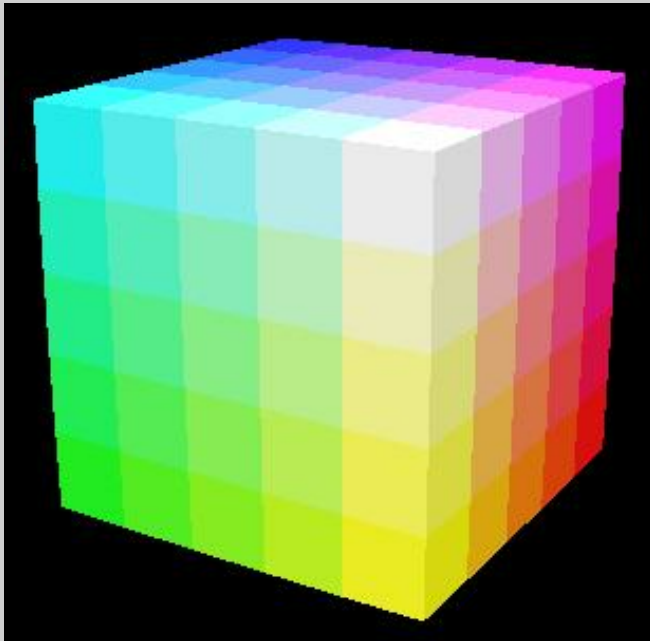
$$\begin{aligned}R_{8bit} &= \left((255.0 - 0.0) \times R'_{sRGB} \right) + 0.0 \\G_{8bit} &= \left((255.0 - 0.0) \times G'_{sRGB} \right) + 0.0 \\B_{8bit} &= \left((255.0 - 0.0) \times B'_{sRGB} \right) + 0.0\end{aligned}$$

$$\begin{aligned}R_{8bit} &= 255.0 \times R'_{sRGB} \\G_{8bit} &= 255.0 \times G'_{sRGB} \\B_{8bit} &= 255.0 \times B'_{sRGB}\end{aligned}$$

sRGB → XYZ



RGB “normalizado”



Cubo RGB

$$r = \frac{R}{\sqrt{R^2 + G^2 + B^2}}$$

$$g = \frac{G}{\sqrt{R^2 + G^2 + B^2}}$$

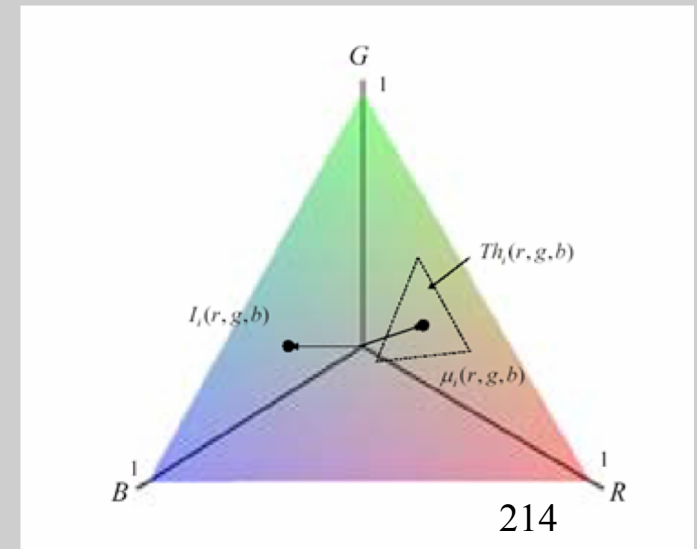
$$b = \frac{B}{\sqrt{R^2 + G^2 + B^2}}$$

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

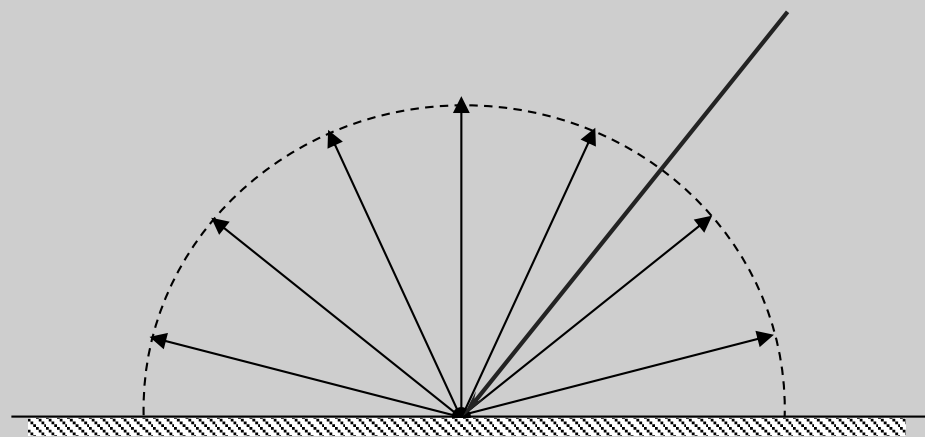
$$g = \frac{G}{R + G + B}$$

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

Cor



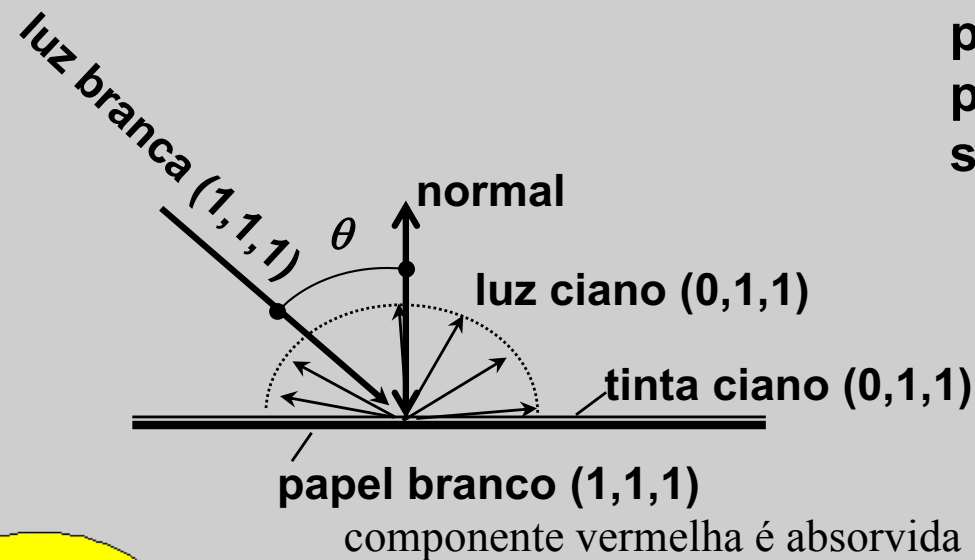
Reflexão da luz num papel



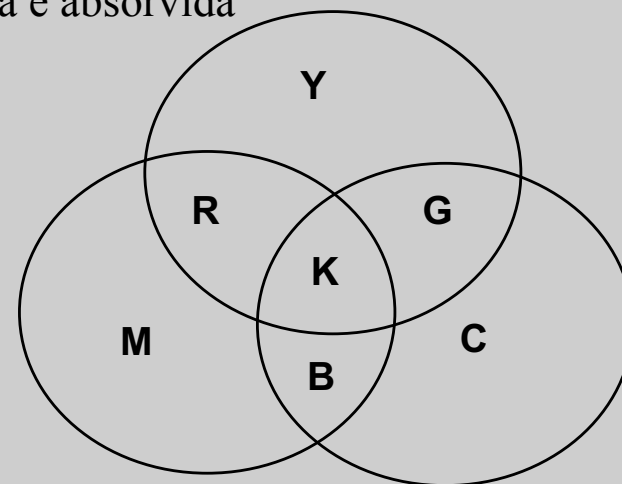
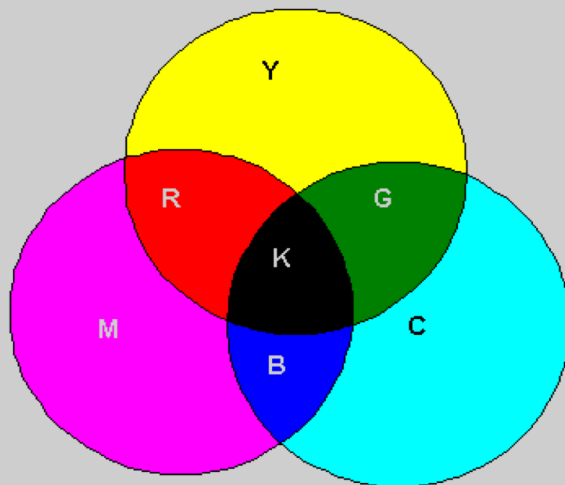
Reflexão difusa ou lambertiana

Sistemas de cor dependentes de dispositivo - CMY

II) Sistemas das Impressoras -*CMY* ou *CMYK*



processo
predominantemente
subtrativo

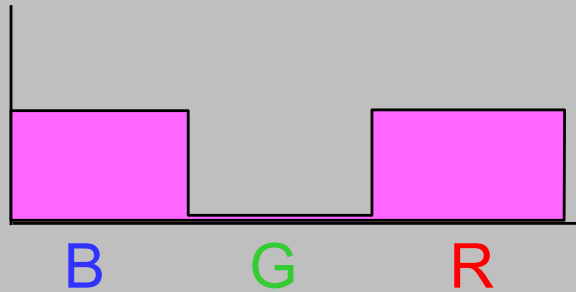


Cor

216

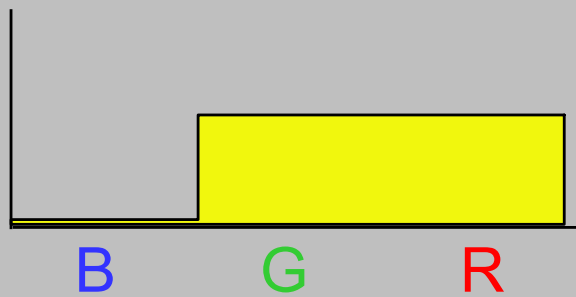
$$R=M+Y$$

magenta



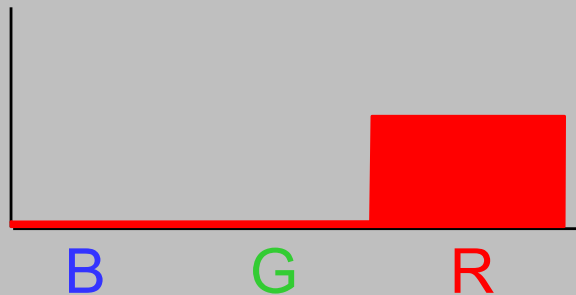
+

yellow

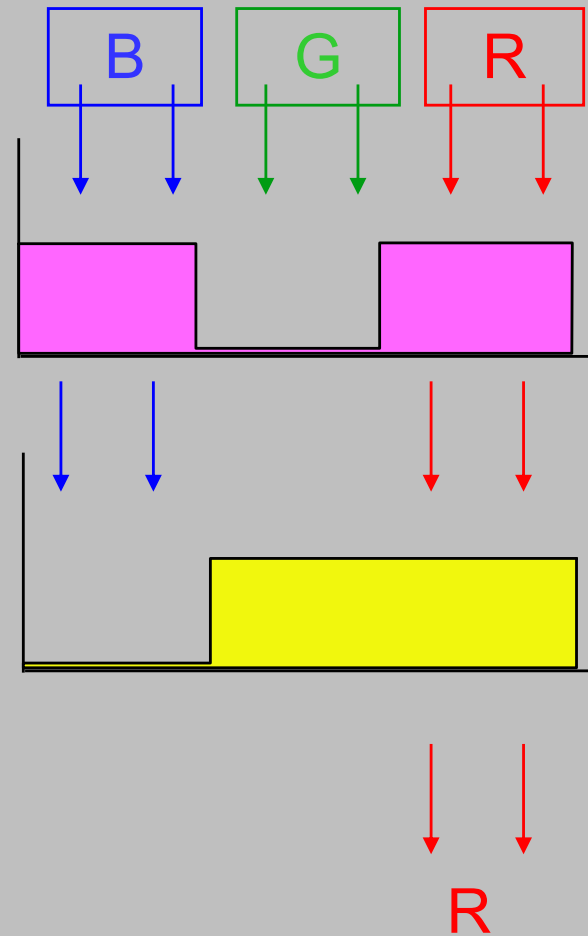


=

red



Cor

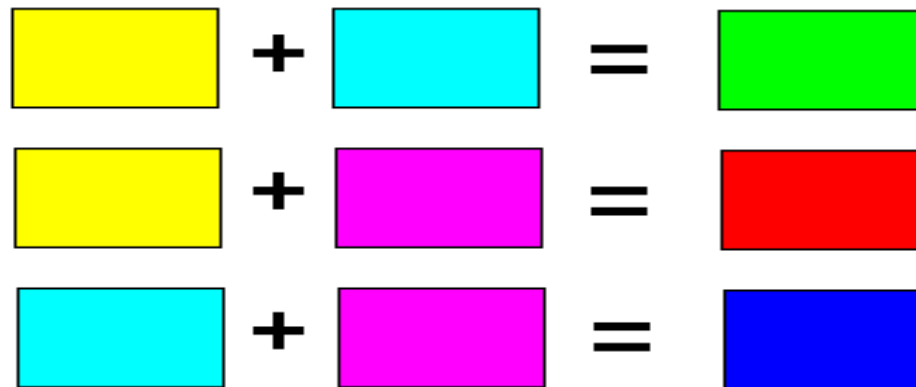


Idit Haran

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Sistemas de cor dependentes de dispositivo - CMY

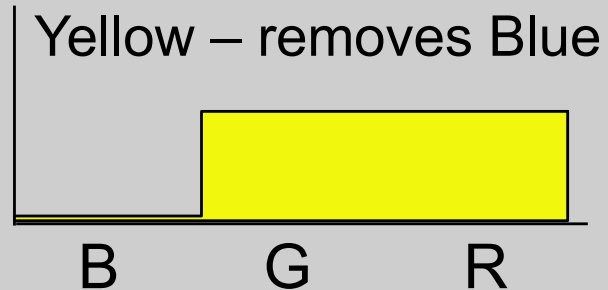
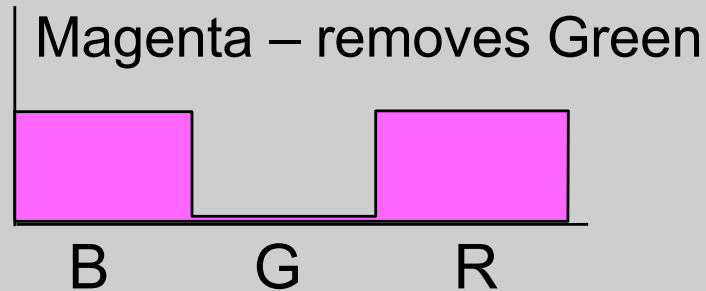
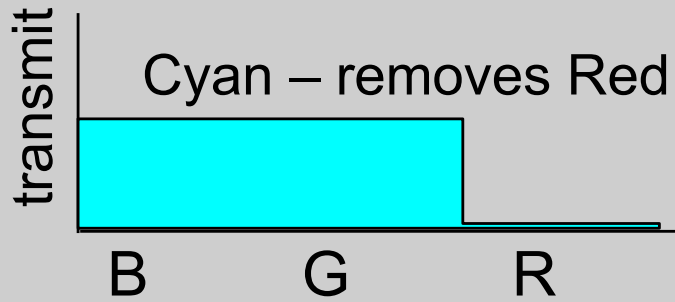
II) Sistemas das Impressoras -CMY ou CMYK



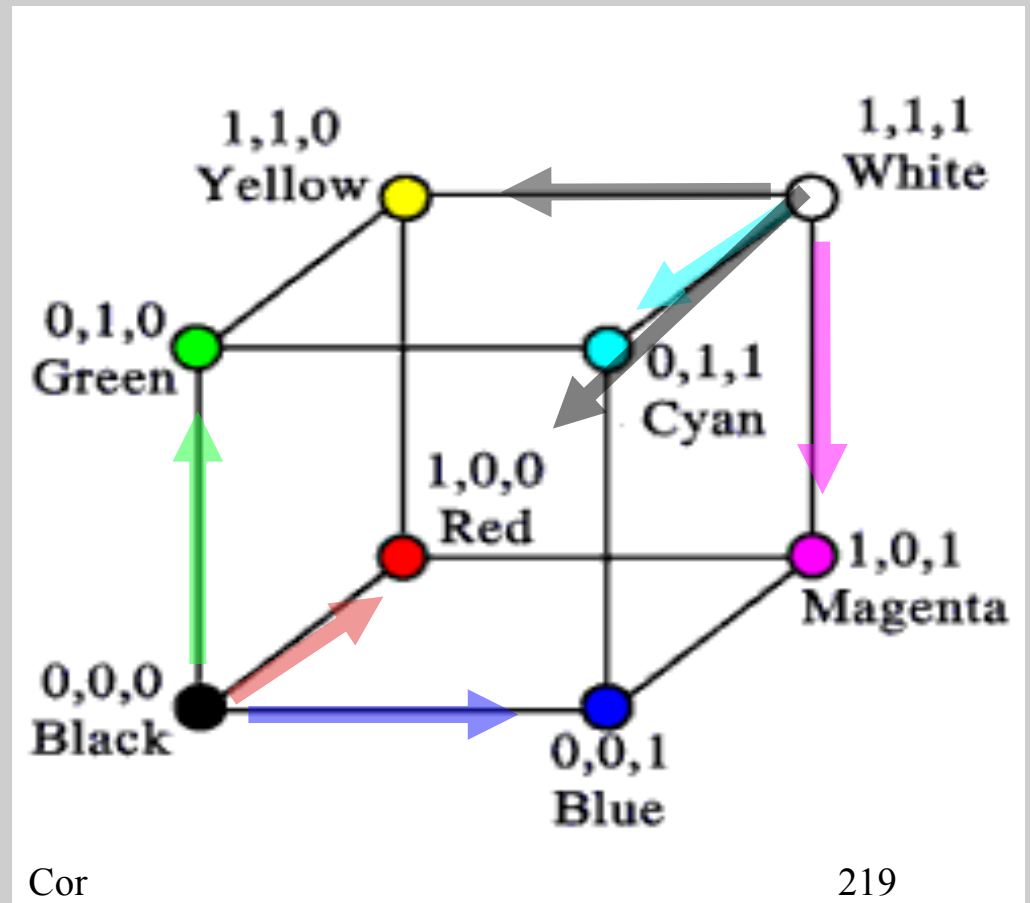
Subtractive Primaries Mixing Chart

CMYK Color Model

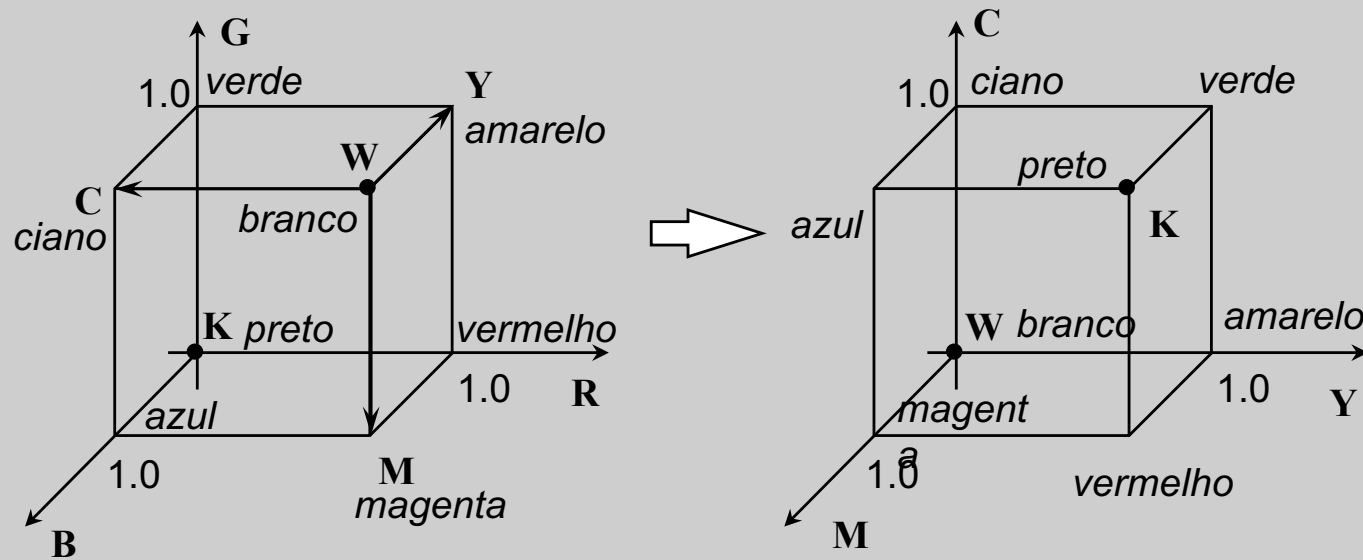
CMYK = Cyan, Magenta, Yellow, black



Black – removes all



Conversão RGB para CMY e vice-versa

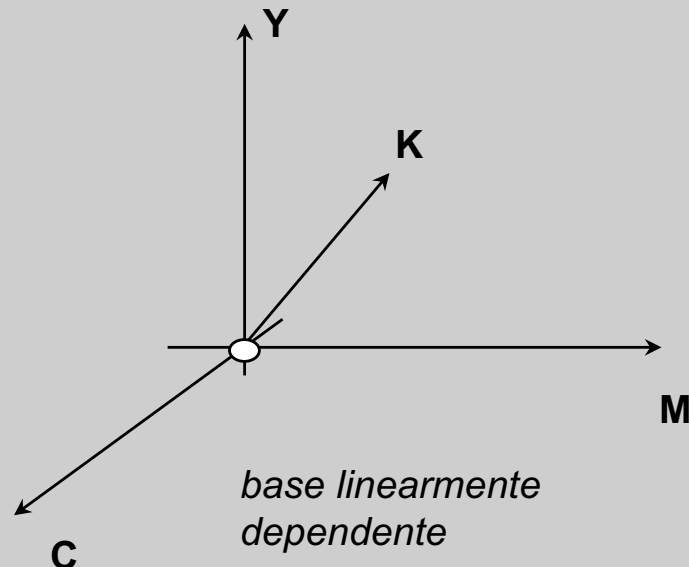


$$(r,g,b) \quad \begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad (c,m,y)$$

Cor

Sistemas de cor dependentes de dispositivo - CMYK

- O sistema CMYK usa o preto (black) porque o pigmento (carbono) é mais barato;
- A superposição de ciano, magenta e amarelo para produzir preto gera um tom meio puxado para o marron.



$$K := \alpha \min (C, M, Y)$$

$$\alpha \in [0,1]$$

$$C := C - K$$

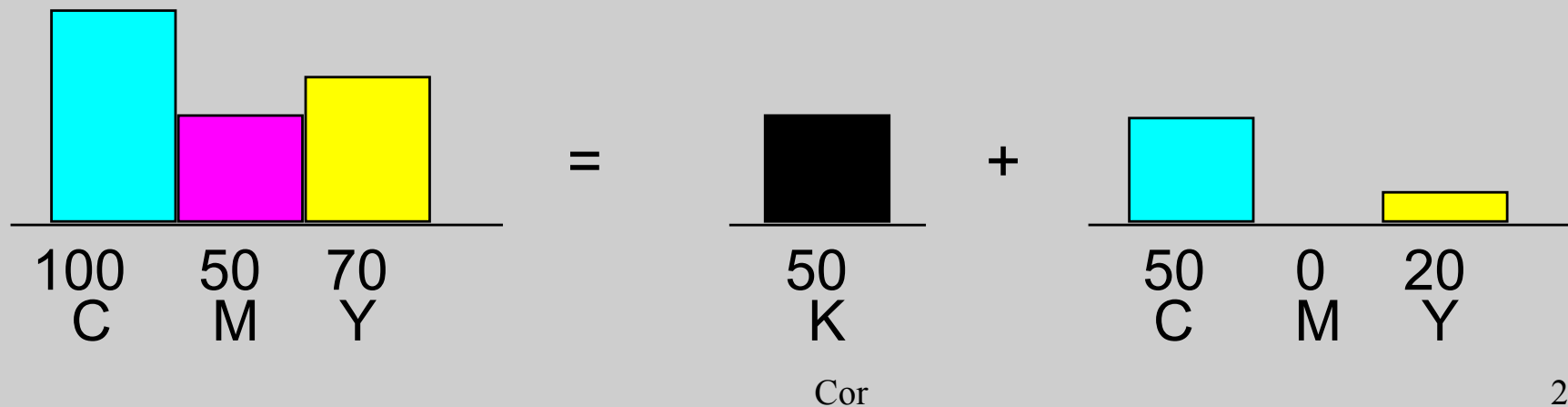
$$M := M - K$$

$$Y := Y - K$$

CMY + Black

$$C + M + Y = K \text{ (black)}$$

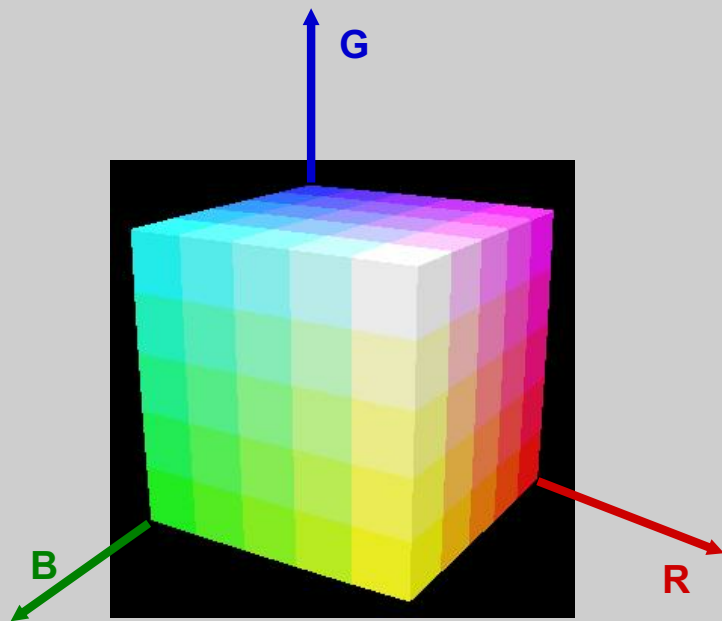
- **Using three inks for black is expensive**
- **C+M+Y = dark brown not black**
- **Black instead of C+M+Y is crisper with more contrast**



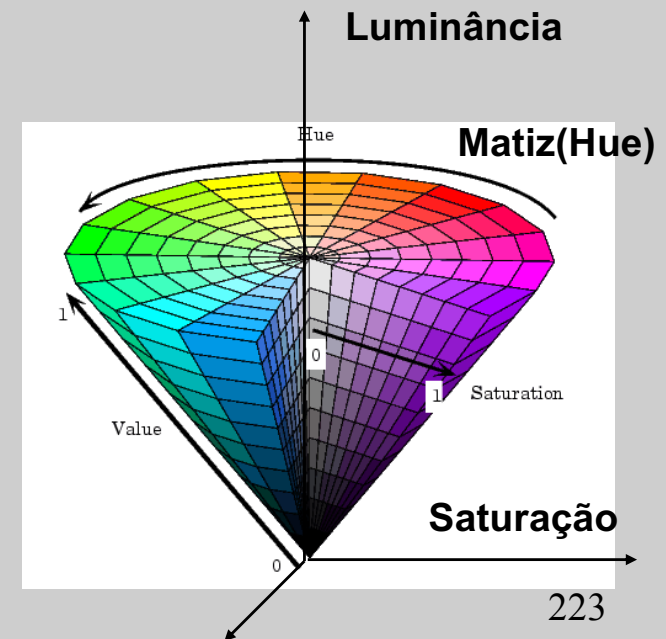
3D Color Spaces

- Tri-cromático sugere espaço 3D

Cartesiano

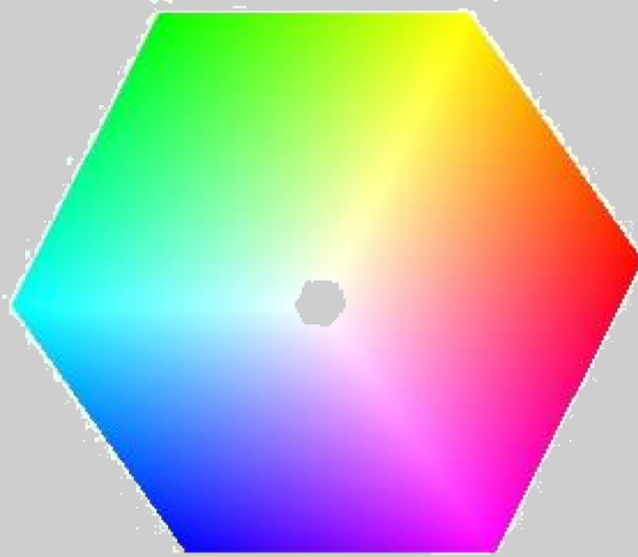


Polar

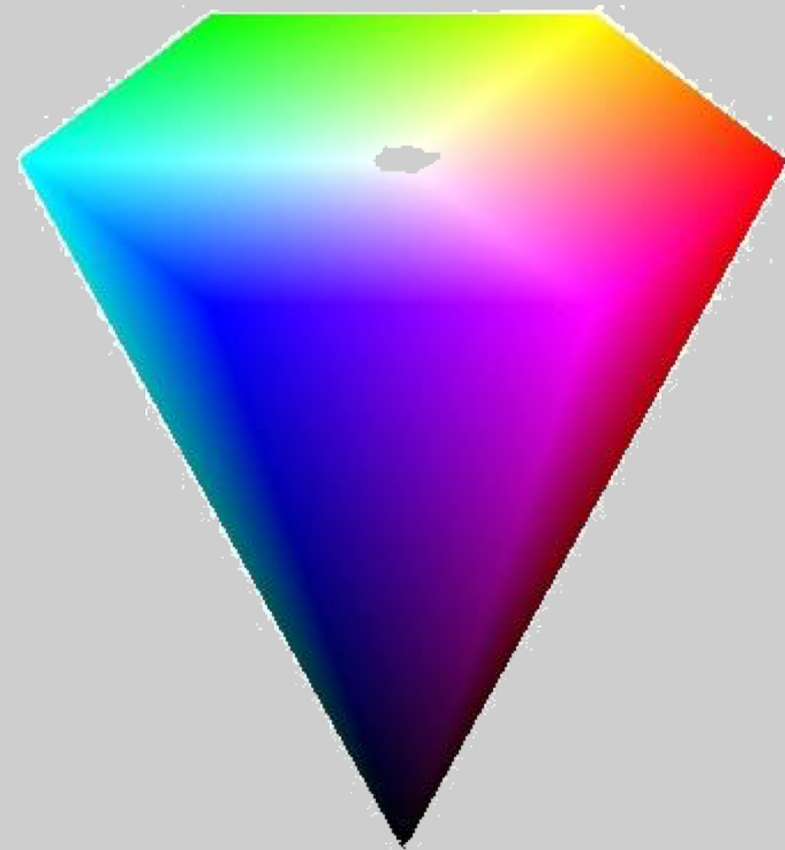


Cor

HSV



Le cube chromatique RVB vu de la couleur blanche

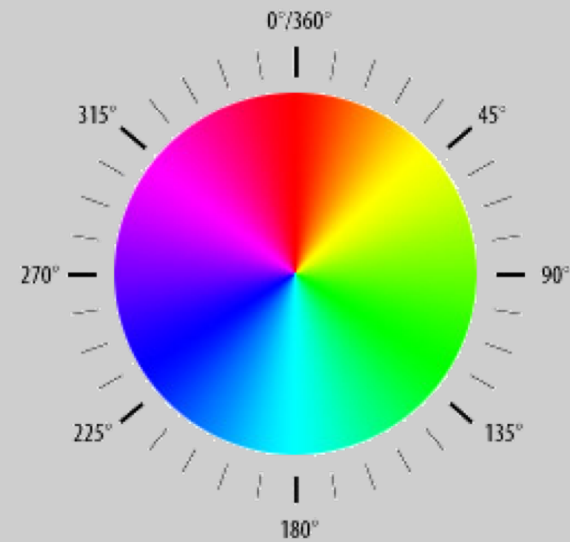
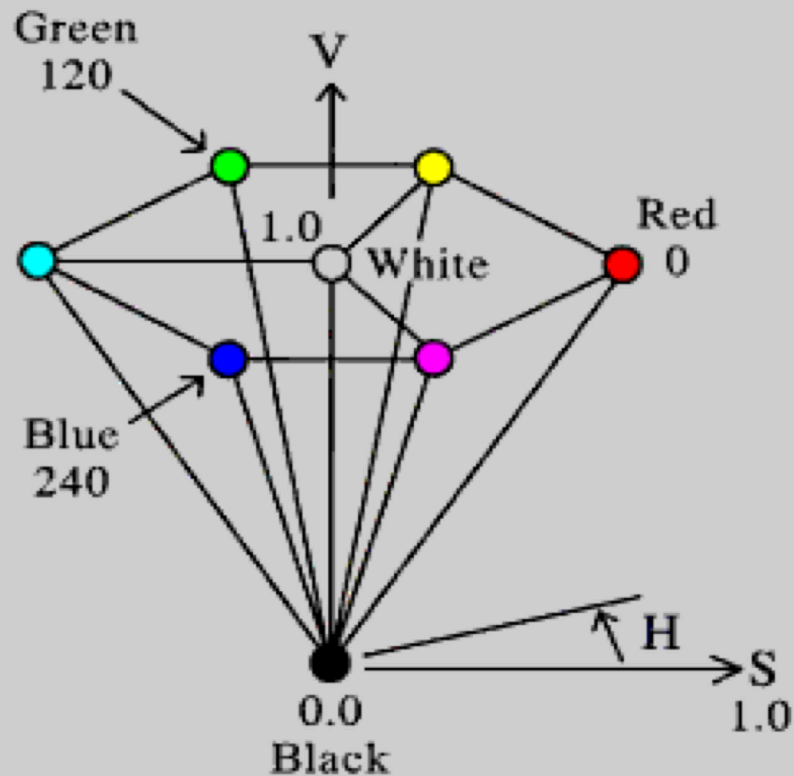


Vue latérale de l'hexacone HSV

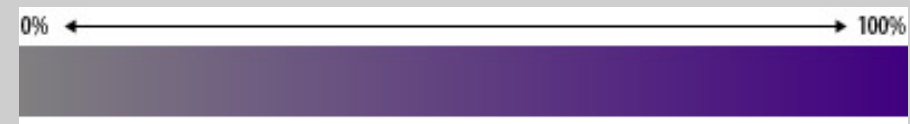
HSV/HSB Color Space

HSV = Hue Saturation Value

HSB = Hue Saturation Brightness



Saturation Scale



Brightness Scale



Cor

225

HSV

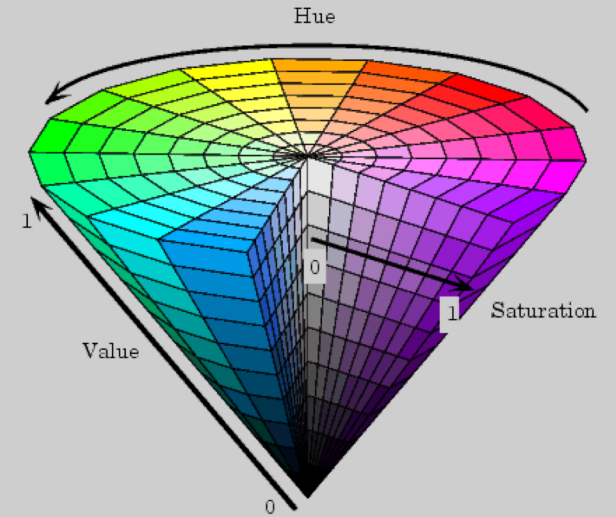


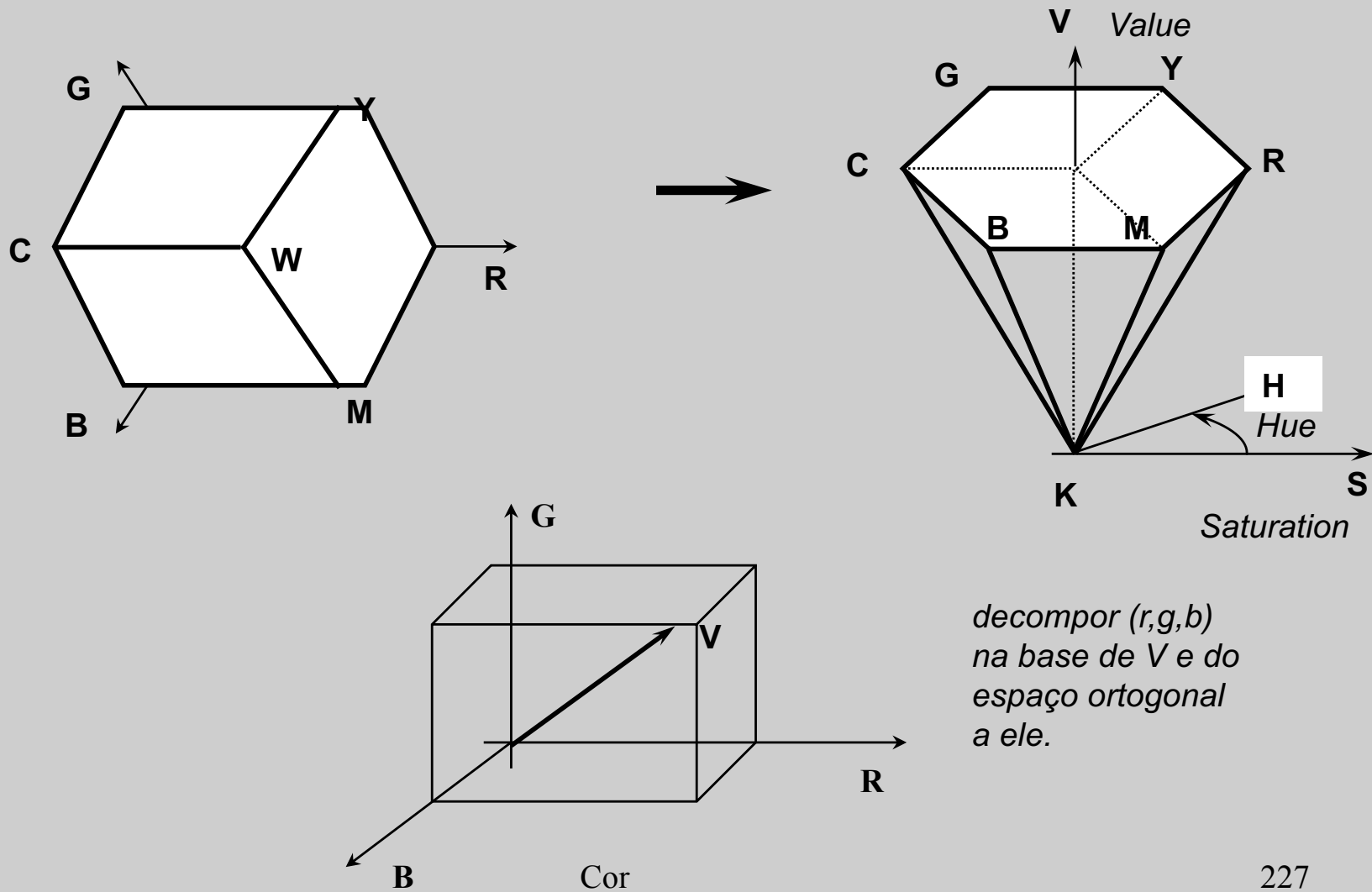
Diagram illustrating the HSV color model components and their corresponding controls in a software interface:

- Hue:** The horizontal axis of the color wheel, representing the color's position in the spectrum.
- Saturation:** The radial distance from the center of the color wheel, representing the intensity of the color.
- Value:** The vertical axis of the color wheel, representing the brightness or lightness of the color.

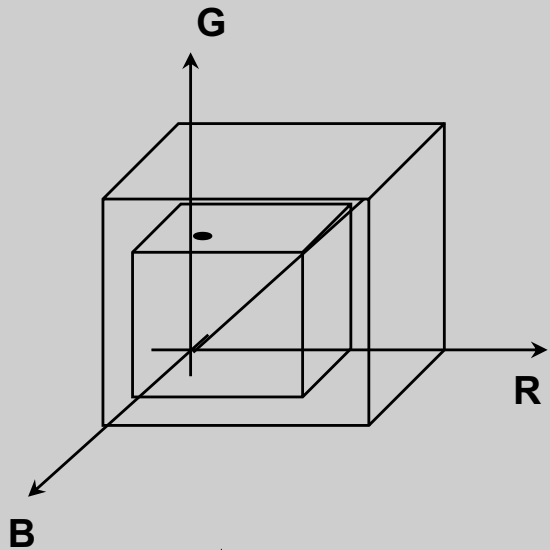
The software interface (Colors dialog) shows the following controls and values:

- Standard / Custom:** Selection tabs.
- Colors:** A color selection area with a hue wheel and a value slider.
- OK / Cancel / Preview:** Action buttons.
- Color Values:**
 - Hue: 47
 - Sat: 162
 - Lum: 154
 - Red: 206
 - Green: 218
 - Blue: 90
- New / Current:** Color swatches for the selected and current colors.

Sistemas de cor mais indicados para interface com usuário - HSV



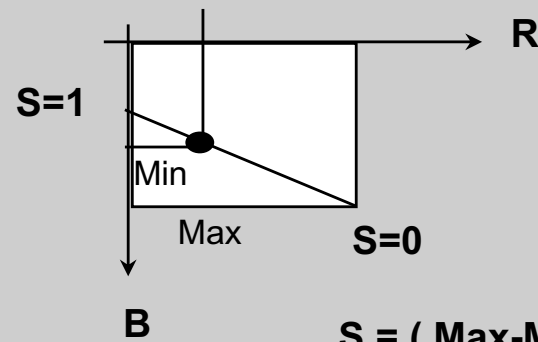
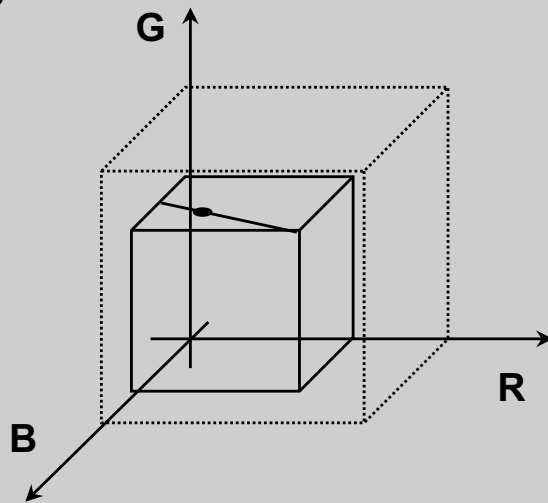
Transformação RGB para HSV e vice-versa



$$\text{Max} = \max(R, G, B)$$
$$\text{Min} = \min(R, G, B)$$

no caso **G** e **B**,
respectivamente

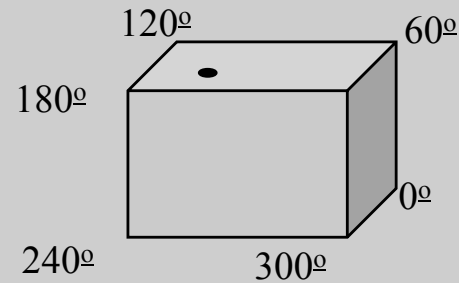
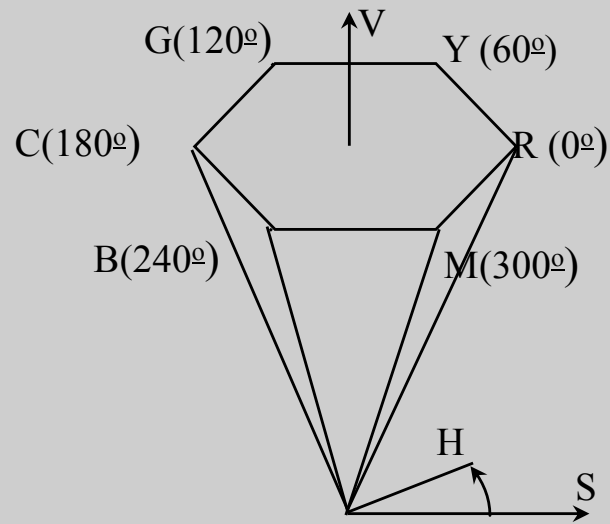
$$V = \text{Max}$$



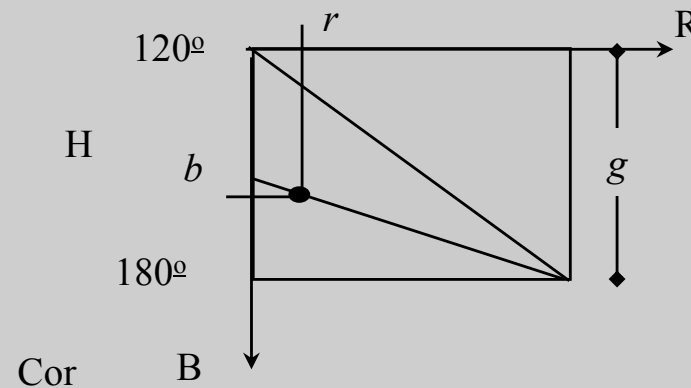
$$S = (\text{Max} - \text{Min}) / \text{Max}$$

Conversão RGB para HSV

cálculo de H

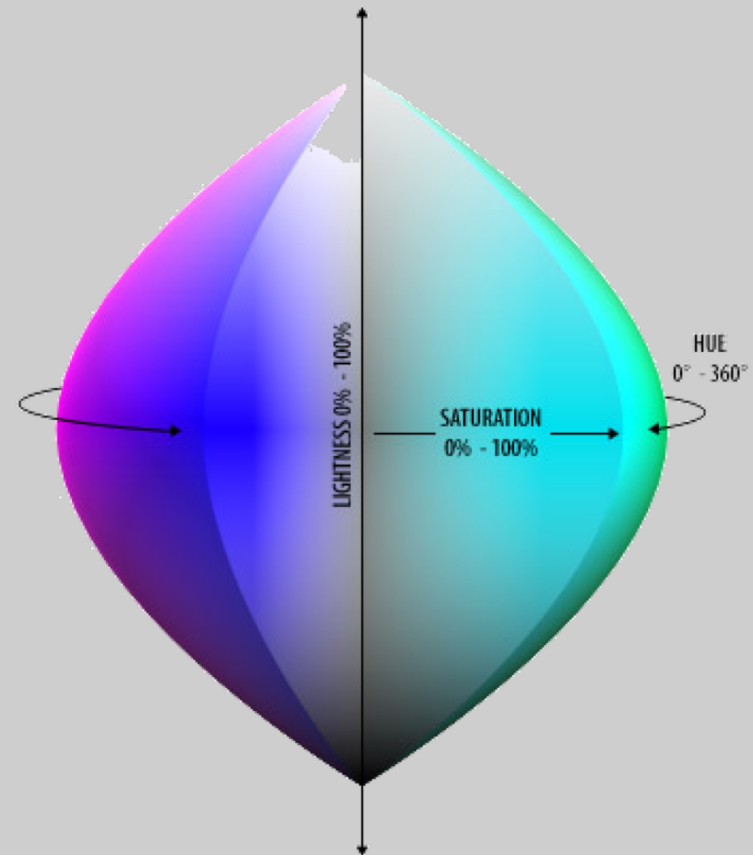
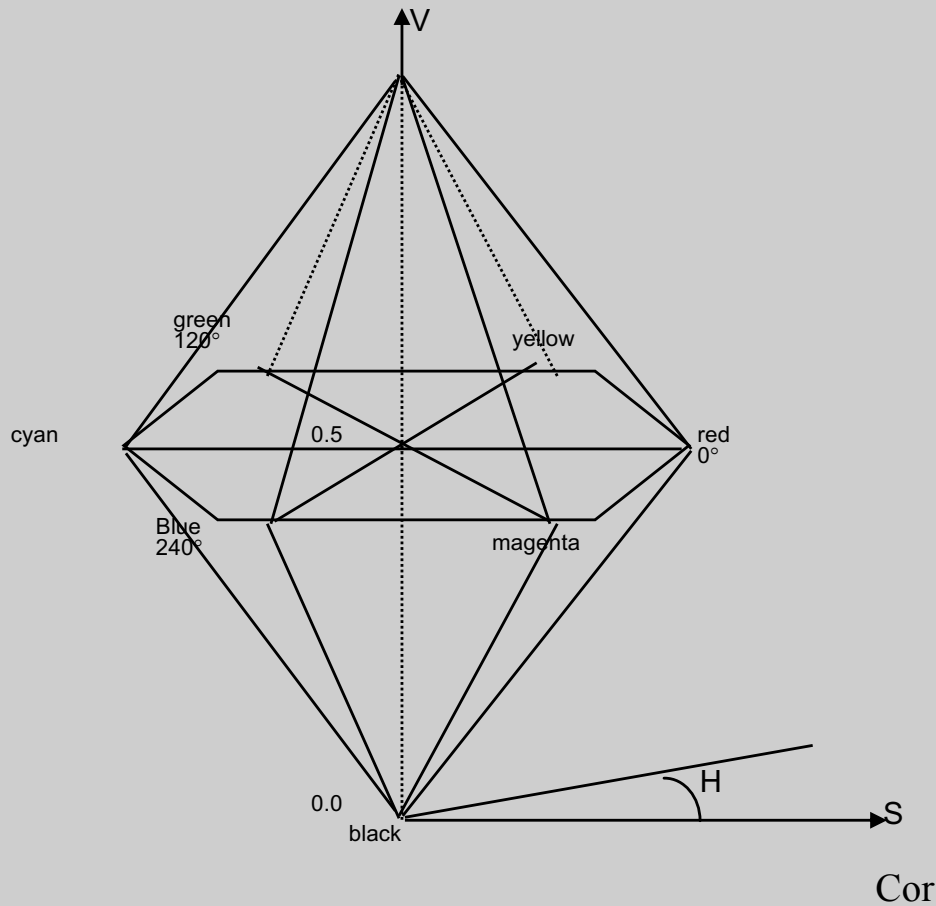


$$H = 120 + 60 \frac{b}{g}$$

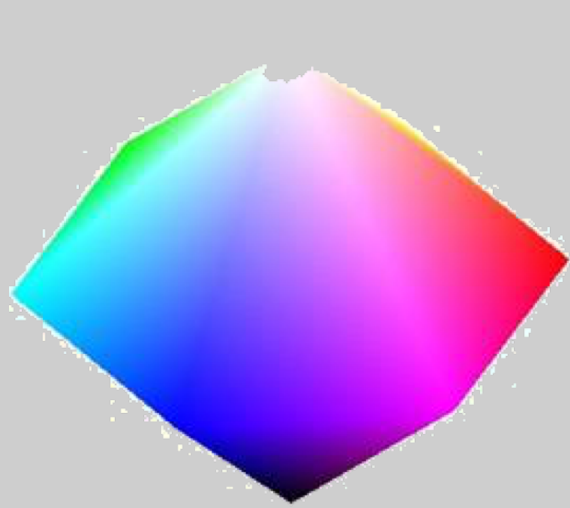


HLS Color Space

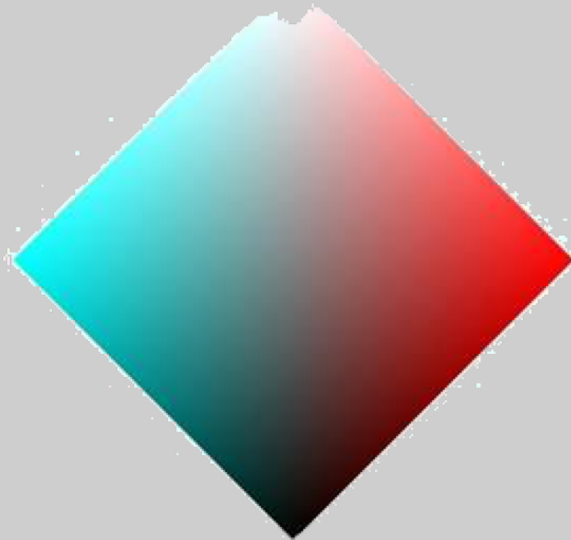
HLS = Hue Lightness Saturation



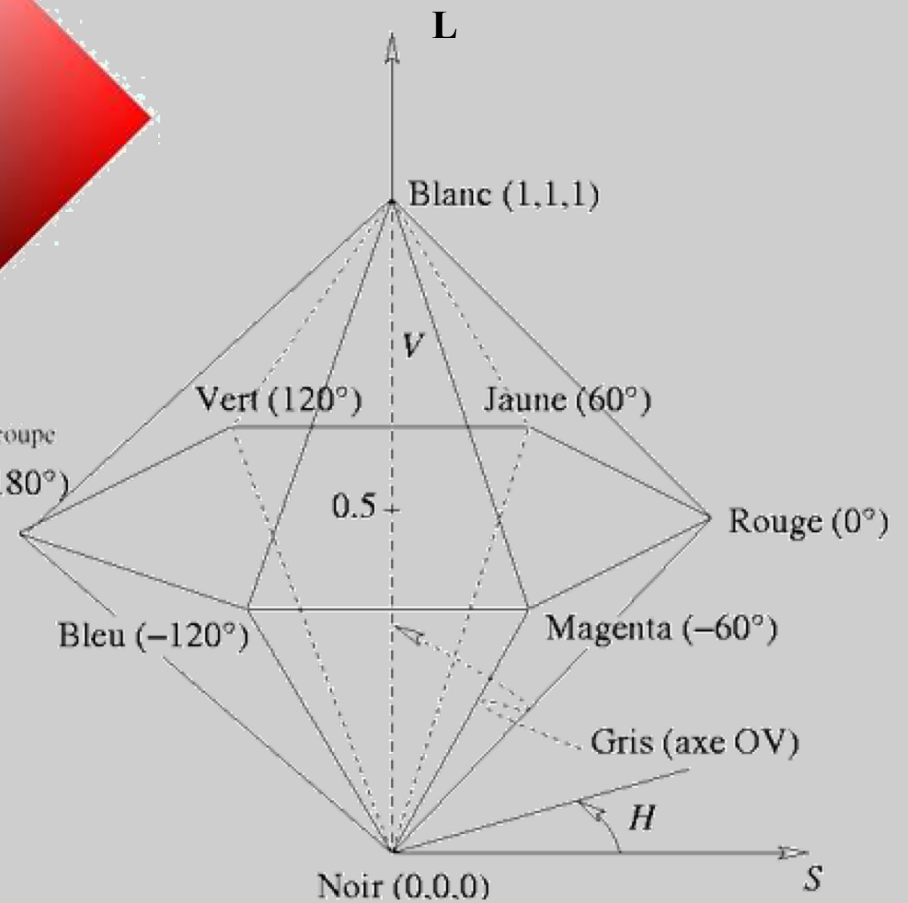
HLS



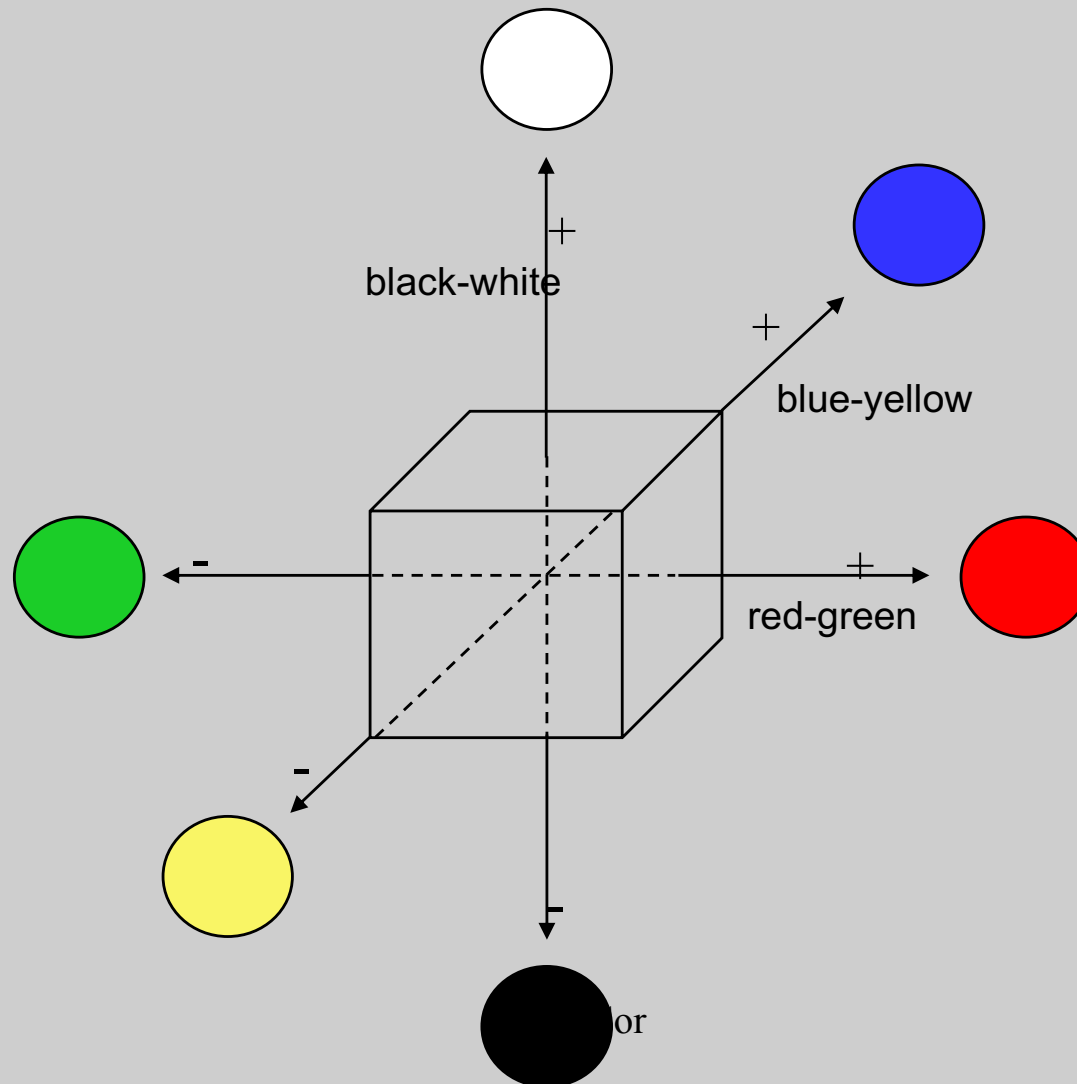
Double hexacone HLS : vue en perspective



Double hexacone HLS : coupe



Opponent Color Spaces



YIQ Color Model

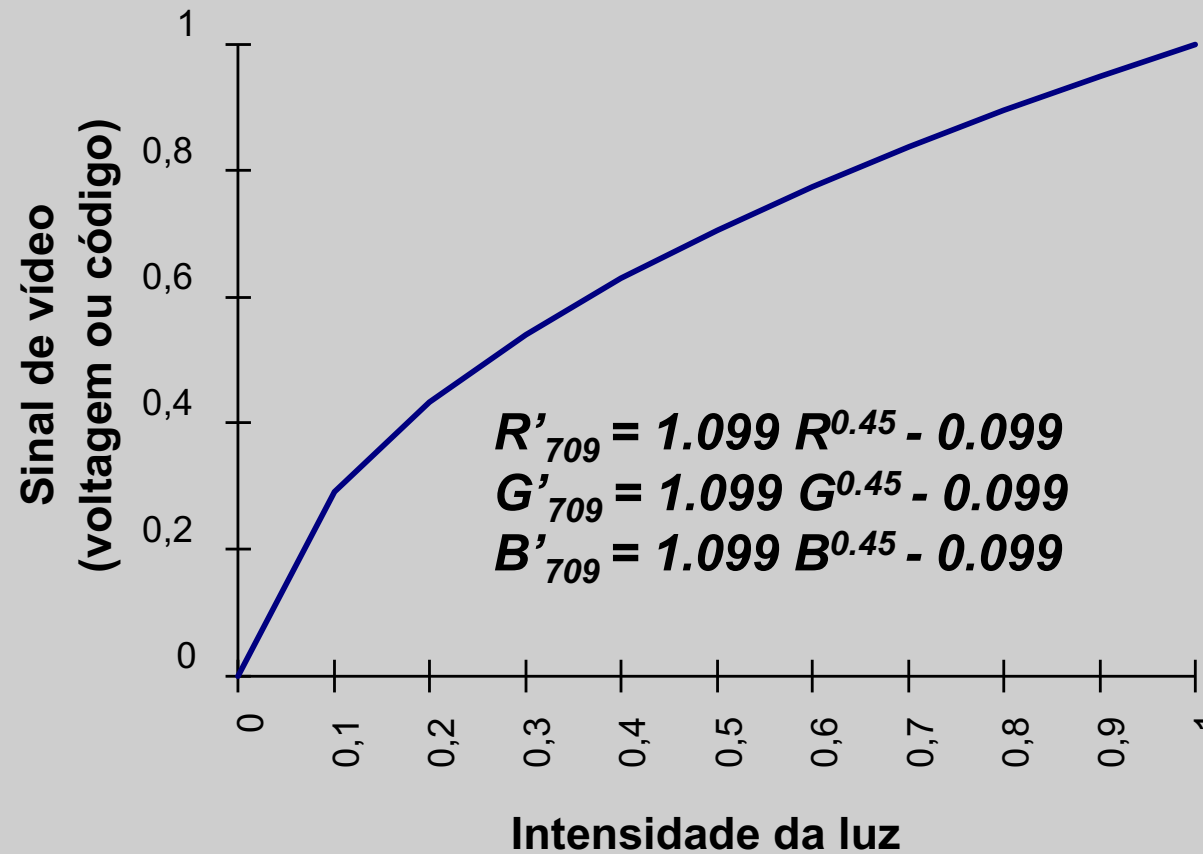
- **YIQ is the color model used for color TV in America (NTSC= National Television Systems Committee)**
- **Y is luminance, I & Q are color (I=red/green,Q=blue/yellow)**
 - » **Note: Y is the same as CIE's Y**
 - » **Result: backwards compatibility with B/W TV!**
- **Convert from RGB to YIQ:**

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- **The YIQ model exploits properties of our visual system, which allows to assign different bandwidth for each of the primaries (4 MHz to Y, 1.5 to I and 0.6 to Q)**

Codificação de Vídeo

Função de Transferência
CCIR Rec.709



Sistema $(Y', B'-Y', R'-Y')$

$$Y'_{601} = 0.2999 R' + 0.587 G' + 0.114 B'$$

Componente
luma de vídeo

$$B'-Y'_{601} = B' - (0.2999 R' + 0.587 G' + 0.114 B')$$

$$R'-Y'_{601} = R' - (0.2999 R' + 0.587 G' + 0.114 B')$$

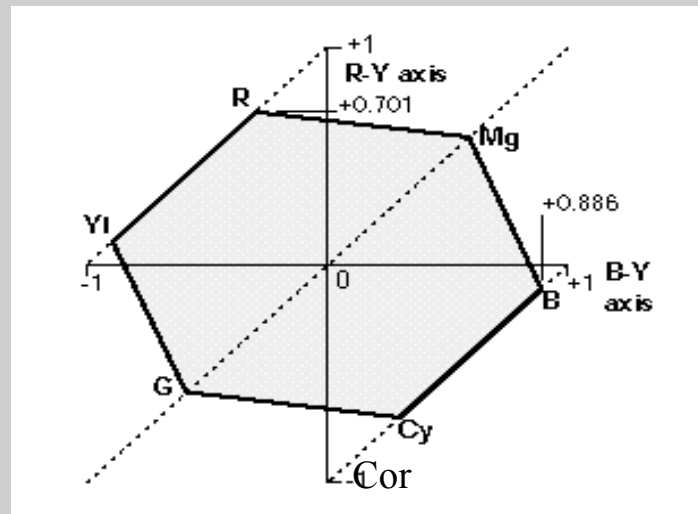
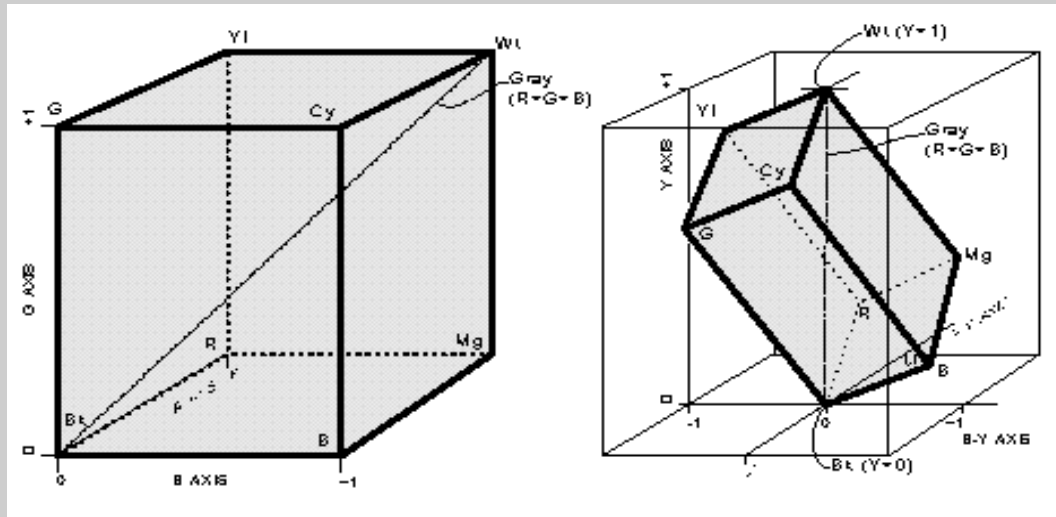
Componente
de diferença
de cor

$$\begin{bmatrix} Y' \\ B'-Y' \\ R'-Y' \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.299 & -0.587 & 0.886 \\ 0.701 & -0.587 & 0.114 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

Motivação:

As componentes de diferença de cor podem ser sub-amostradas!

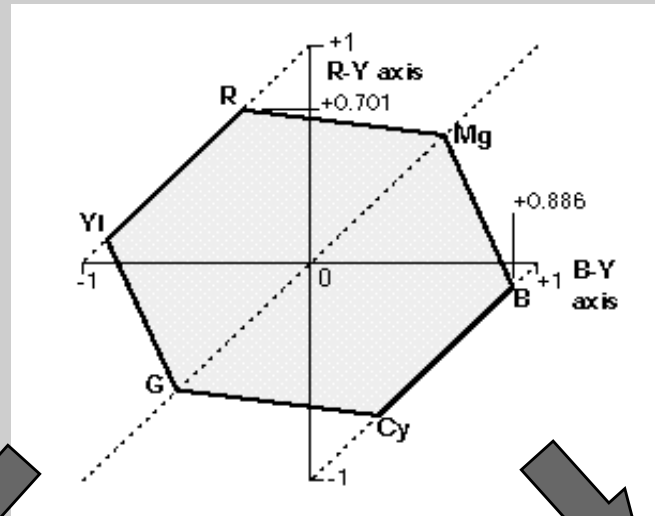
Cubo RGB no espaço (Y', B'-Y', R'-Y')



Conversão para vídeo

$$P_b = \frac{0.5}{1-0.114}(B'-Y')$$

$$P_r = \frac{0.5}{1-0.299}(R'-Y')$$



$$Y'_{8b} = 16 + 235Y'$$

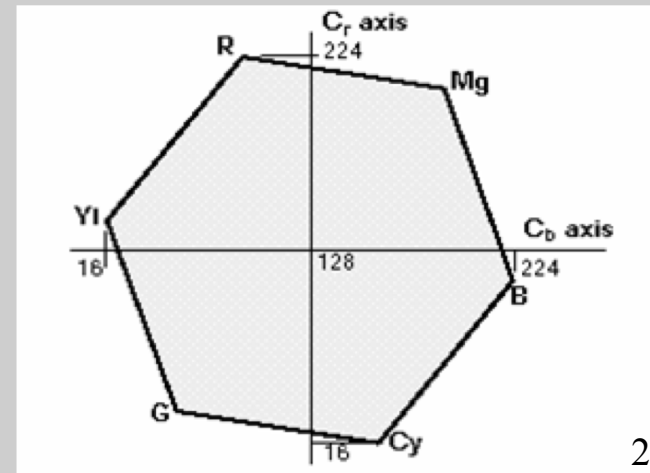
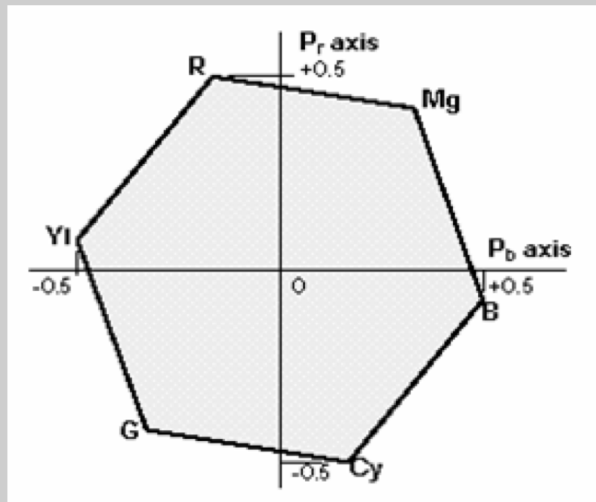
$$C_{b,8b} = 128 + 112 \left(\frac{0.5}{1-0.114}(B'-Y') \right)$$

$$C_{r,8b} = 128 + 112 \left(\frac{0.5}{1-0.299}(R'-Y') \right)$$

vídeos analógicos (BetaCam e M-II)



vídeos digitais com 8 bits/componente (JPEG, MPEG)



Cor

237

Uma fórmula para conversão para video

RGB to YCrCb

$$\begin{bmatrix} Y \\ Cr \\ Cb \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 & 0.00 \\ 0.50 & -0.42 & -0.08 & 128.00 \\ -0.17 & -0.33 & 0.50 & 128.00 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}$$

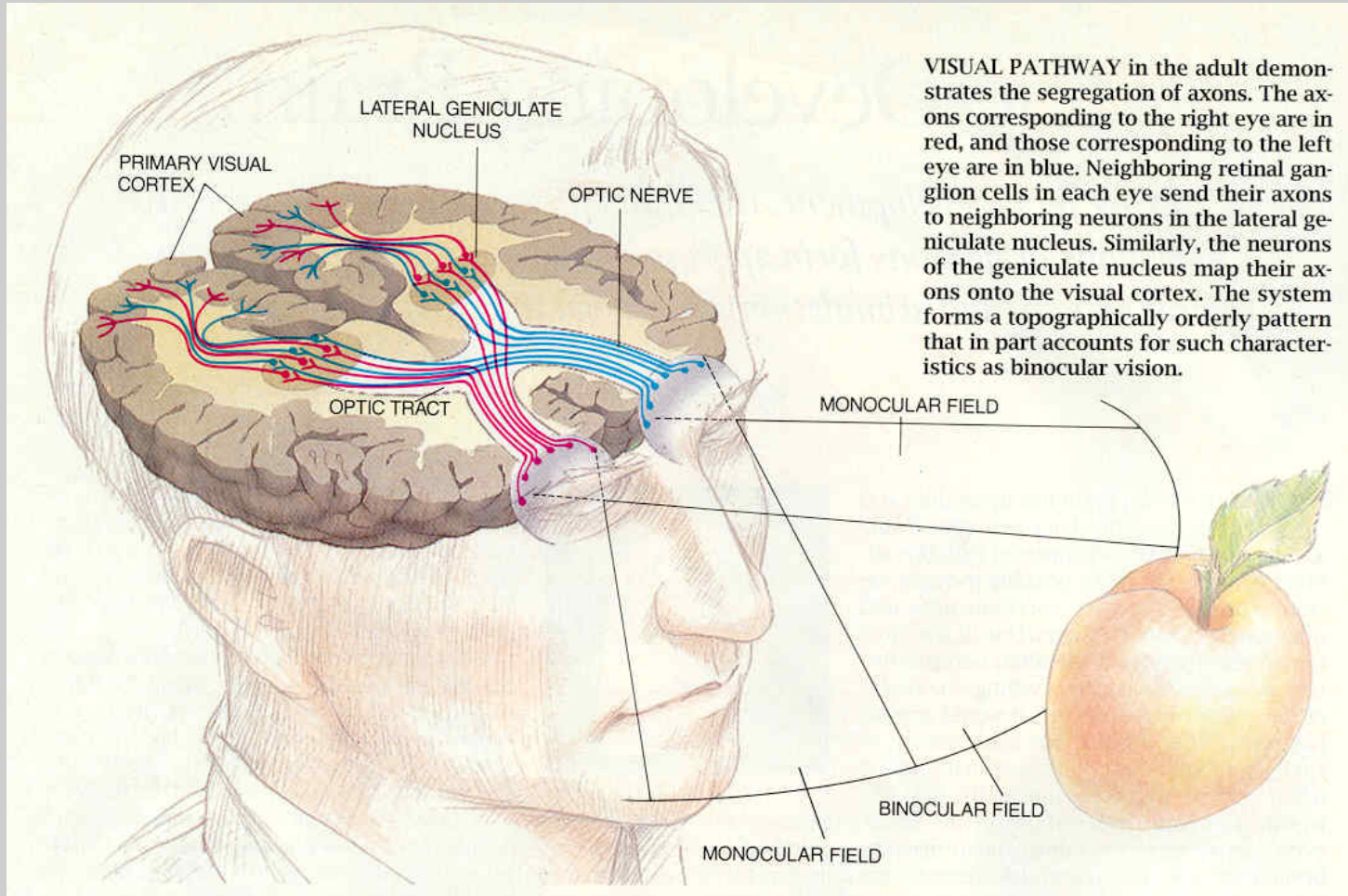
YCrCb to RGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.00 & 1.40 & 0.00 & -179.20 \\ 1.00 & -0.71 & -0.34 & 135.42 \\ 1.00 & 0.00 & 1.77 & -227.07 \end{bmatrix} \begin{bmatrix} Y \\ Cr \\ Cb \\ 1 \end{bmatrix}$$

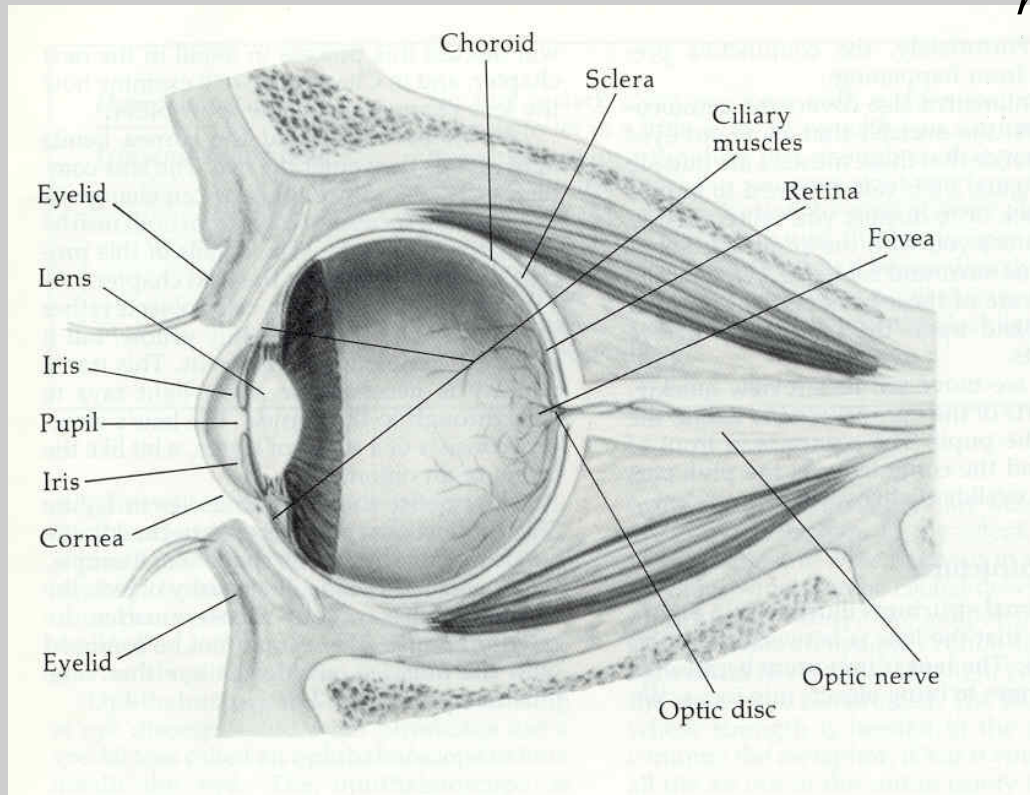
<http://www.efg2.com/Lab/Library/Color/Science.htm>

O que não abordamos?

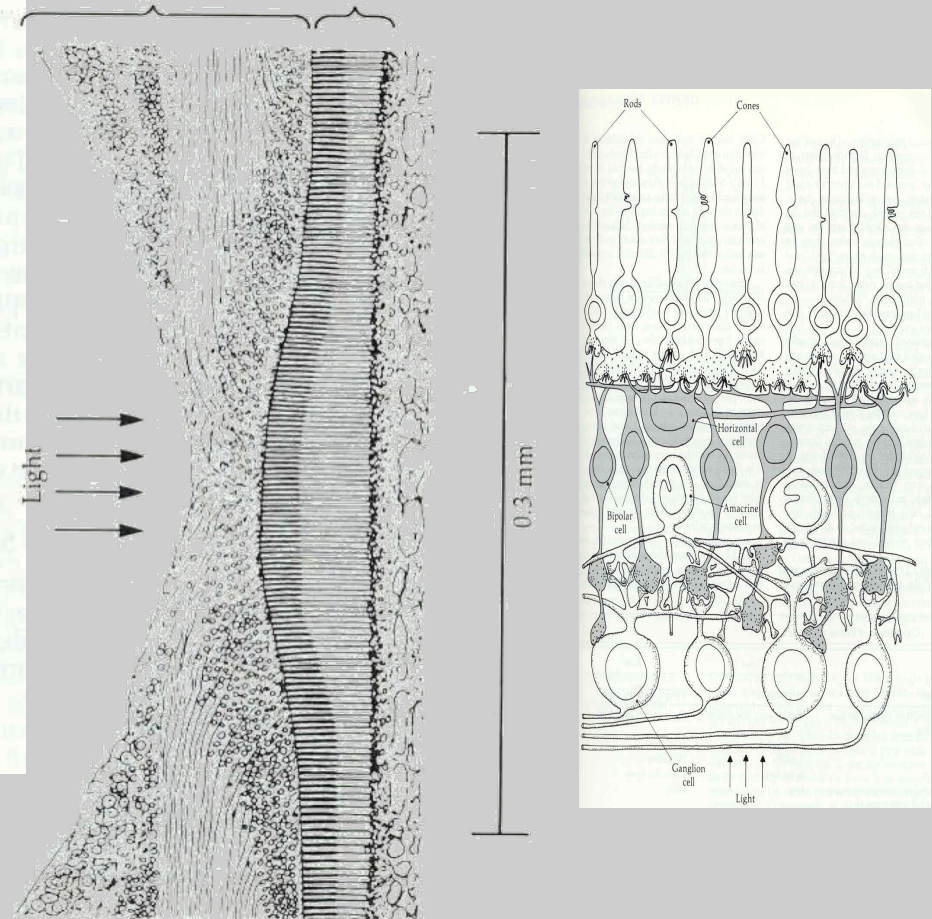
Sistema visual



Anatomia do olho



neuronios fotoreceptores



$\sim 140 \times 10^6$ receptores em cada olho

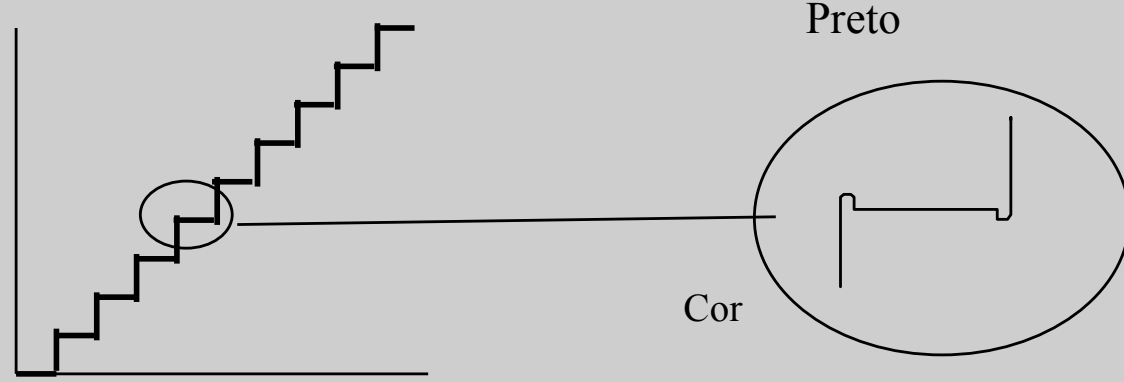
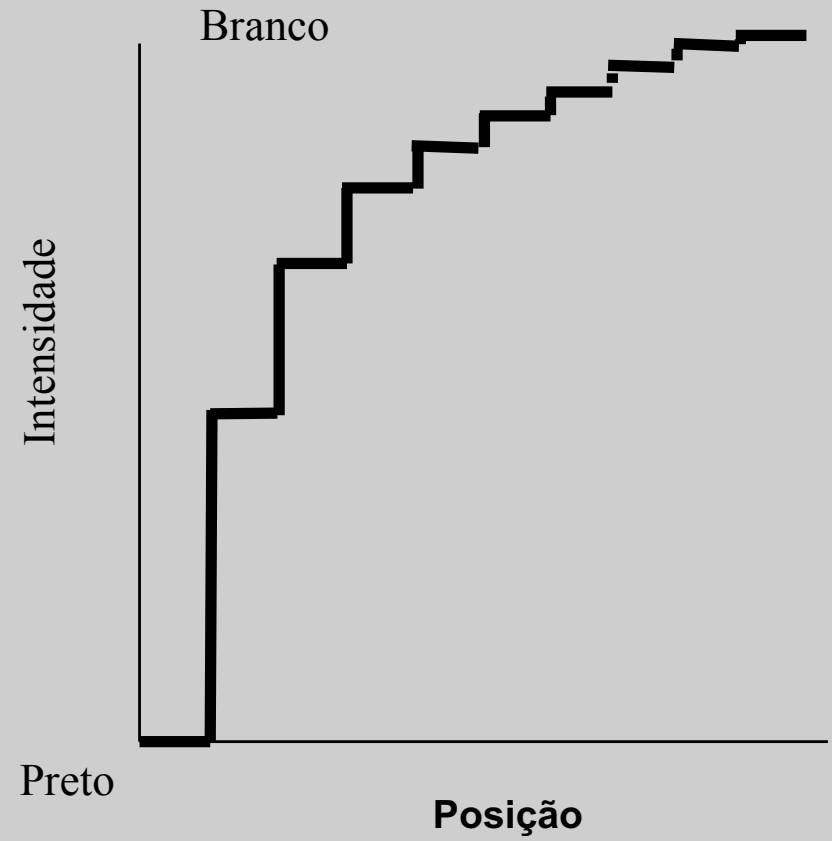
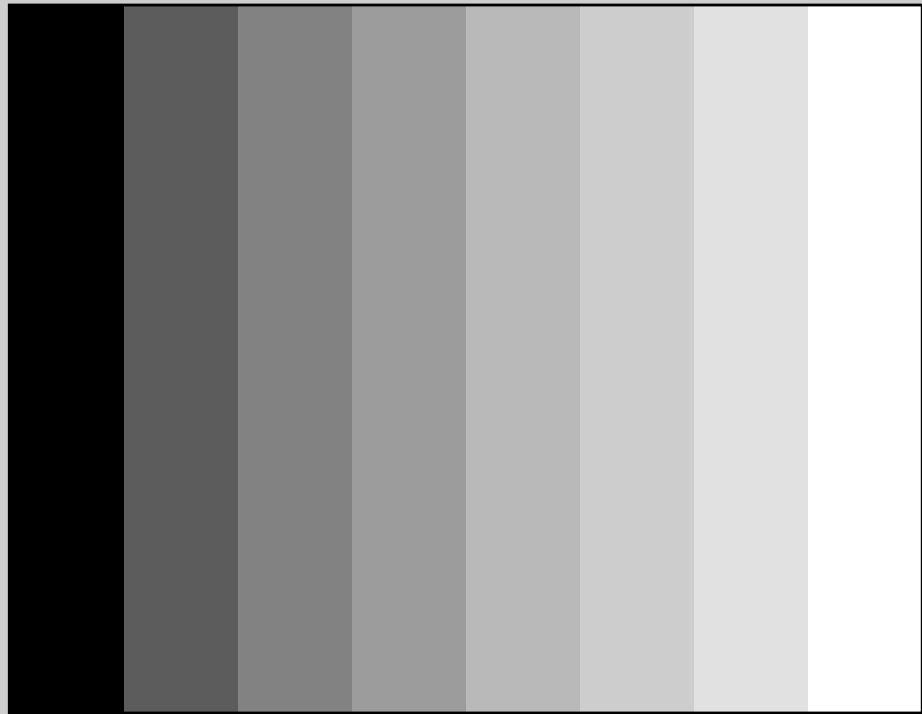
$\sim 1 \times 10^6$ fibras nos nervos ópticos

$\sim 650 \times 10^6$ neuronios

Cor

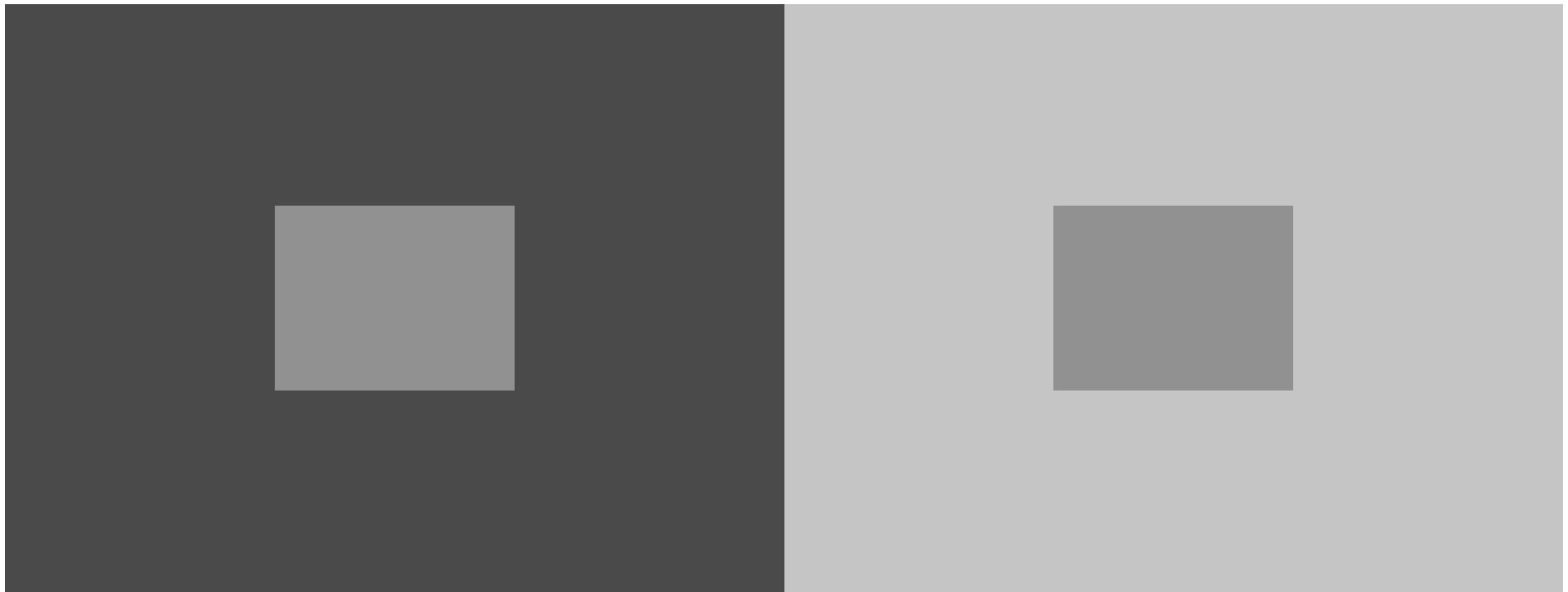
Sistema muito complexo!

Banda de Mach



Efeito da Banda de Mach

Contraste Simultâneo

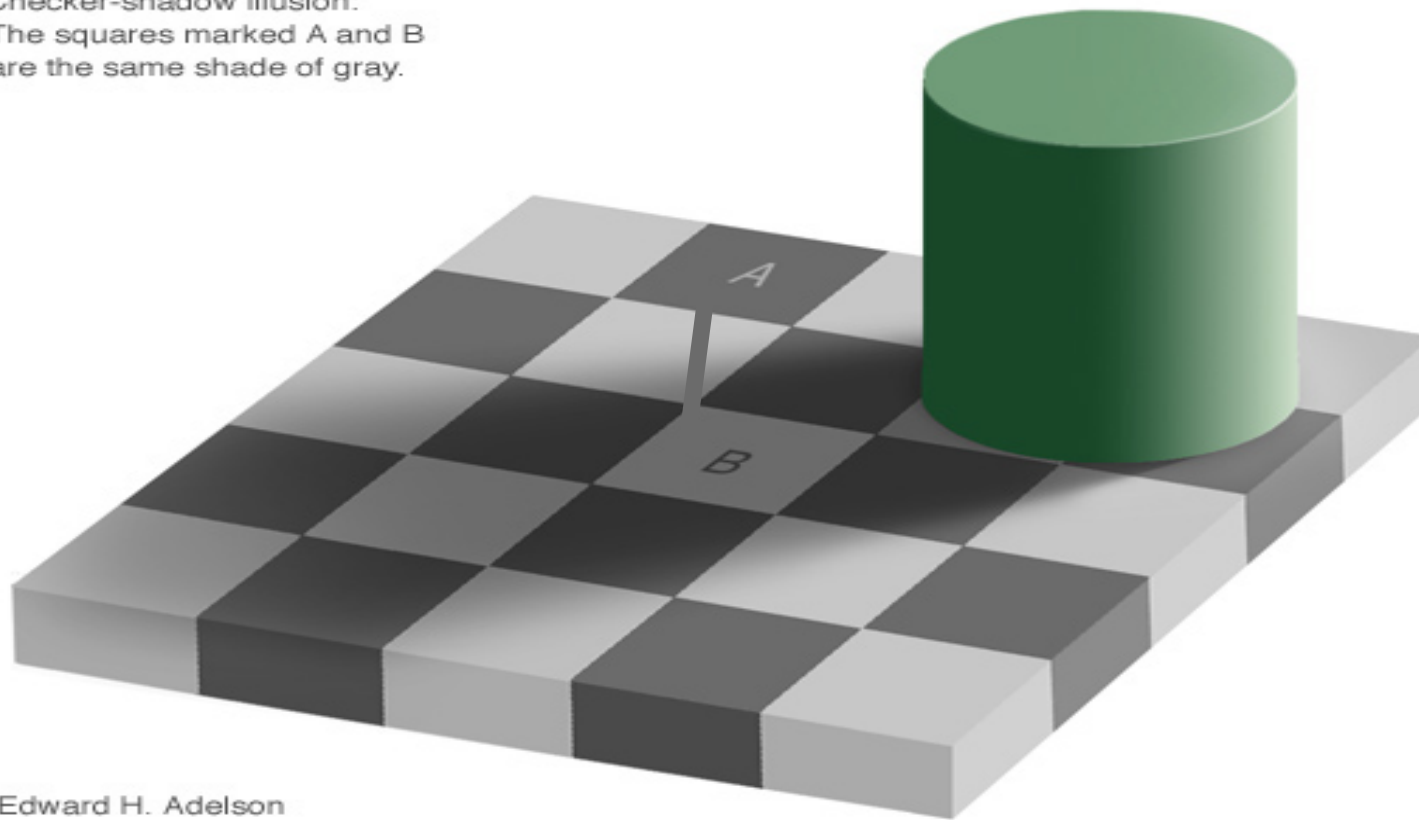


Cor

243

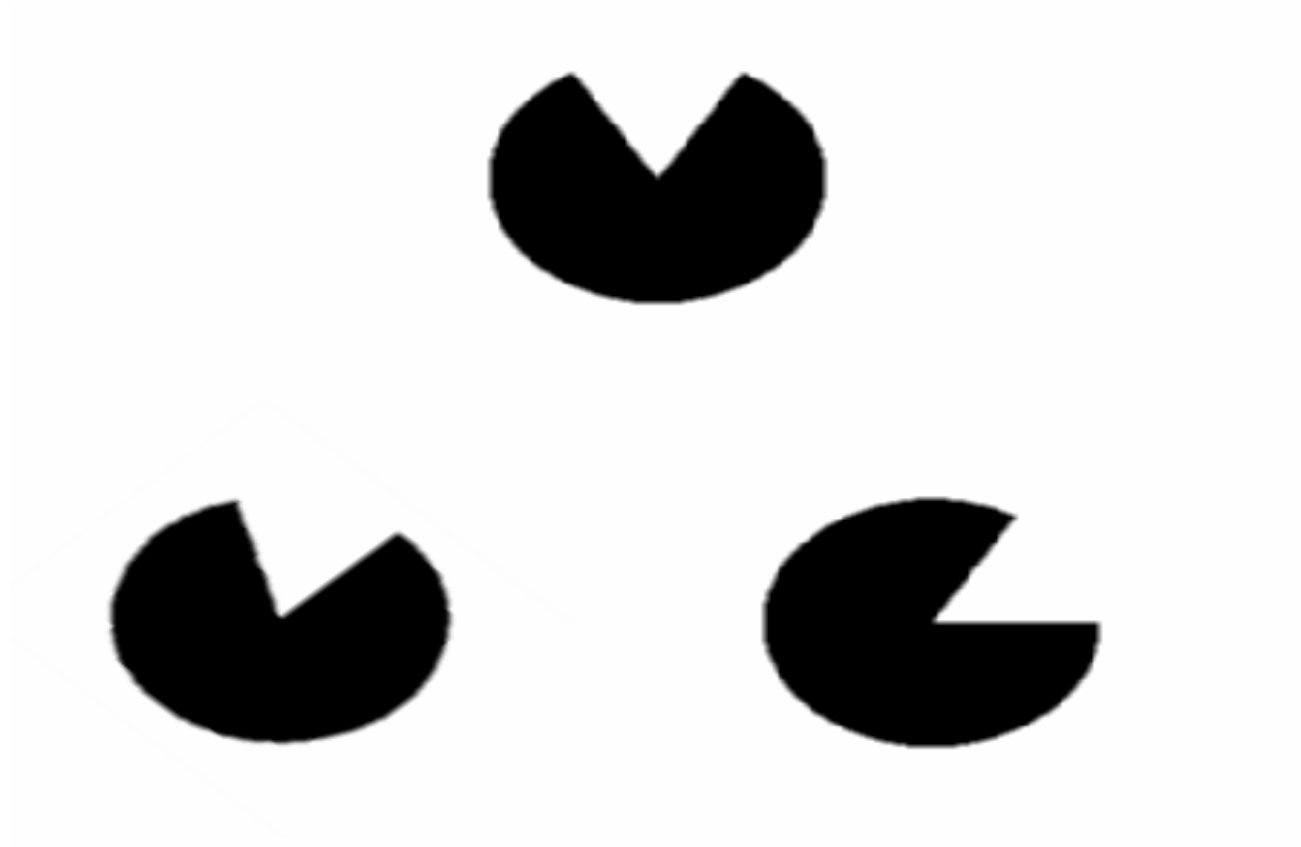
Contraste

Checker-shadow illusion:
The squares marked A and B
are the same shade of gray.

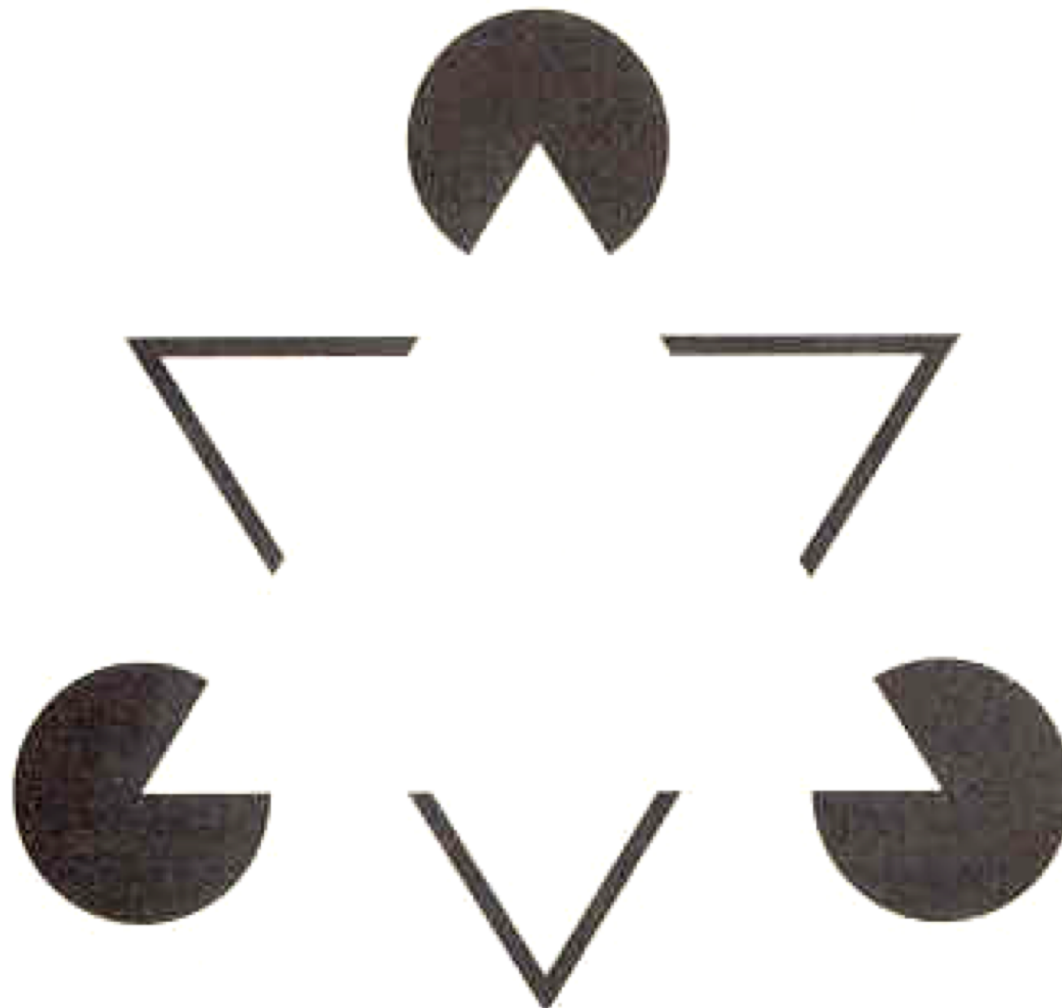


Edward H. Adelson

Conclusões do cérebro



Tiângulo de Kanizsa



Cor

Referências

- <http://www.cvrl.org>
- <http://www.poynton.com/Poynton-color.html>
- <http://www.efg2.com/Lab/>
- <http://www.easyrgb.com/>
- <http://cvrl.ioo.ucl.ac.uk/cmfs.htm>
- <http://www.brucelindbloom.com/>

FIM