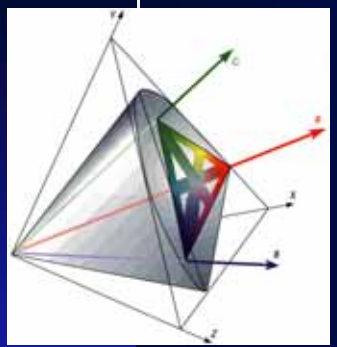
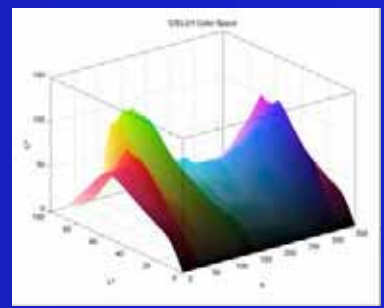
顯示器色彩工程
~ Part 1 色度學原理 ~

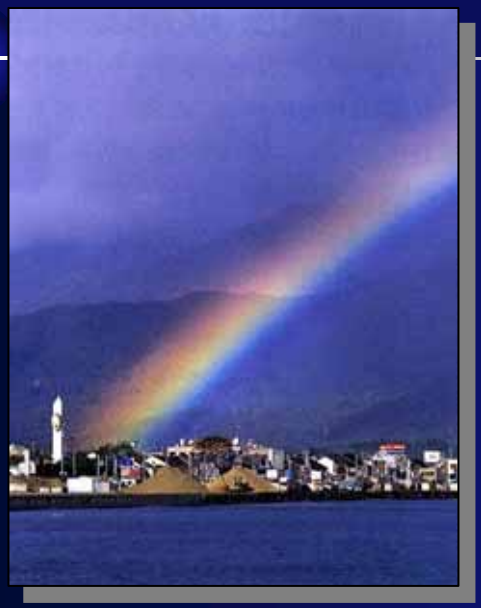


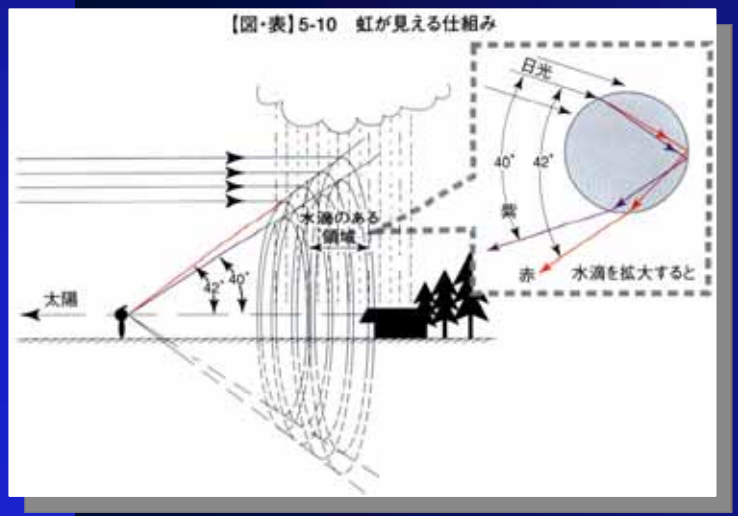
世新大學 資訊管理學系
助理教授 陳鴻興
2005/October/26



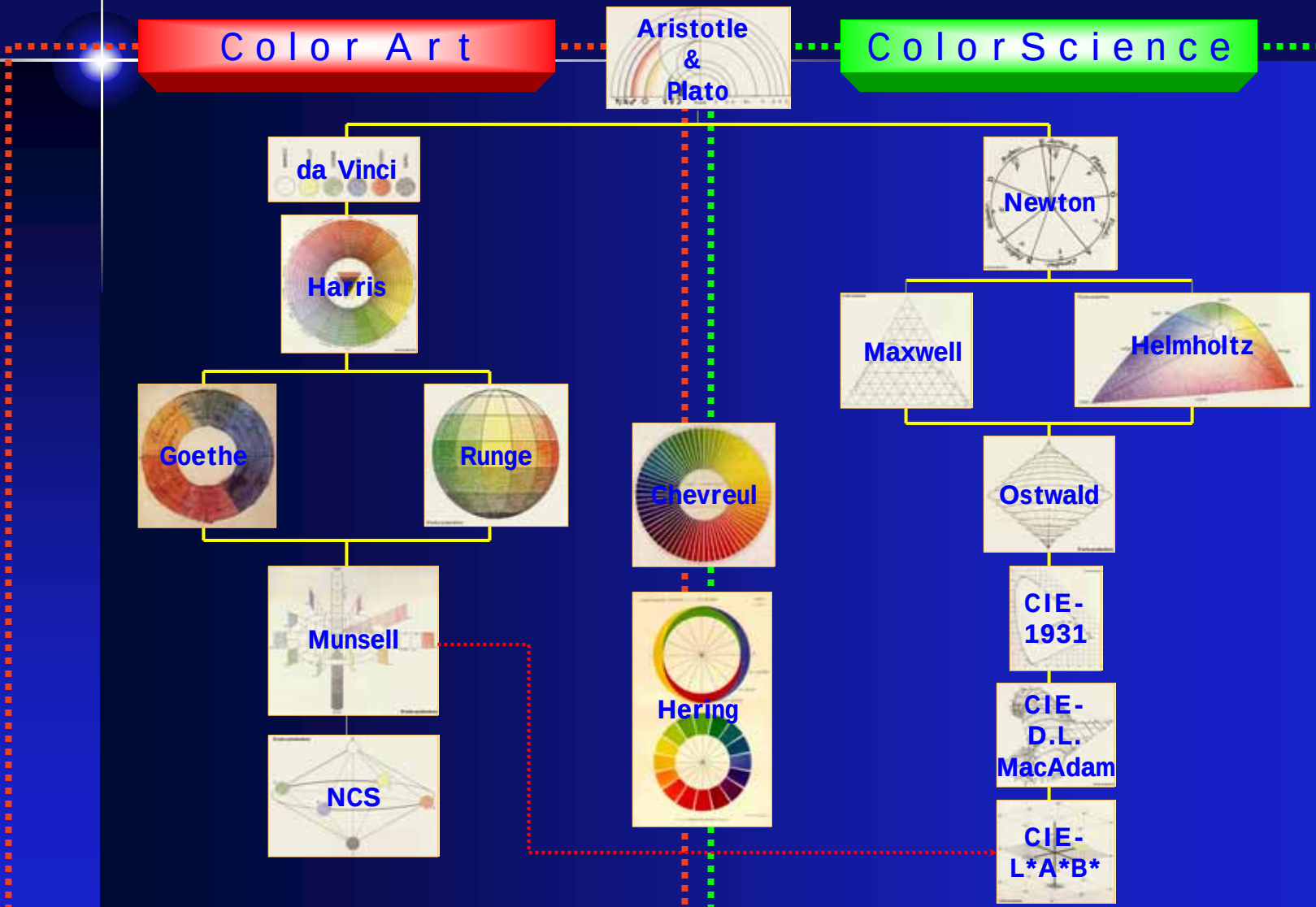
http://cc.shu.edu.tw/~bridge/color_speech
E-mail: bridge@cc.shu.edu.tw

色彩的認識：陌生？熟悉？



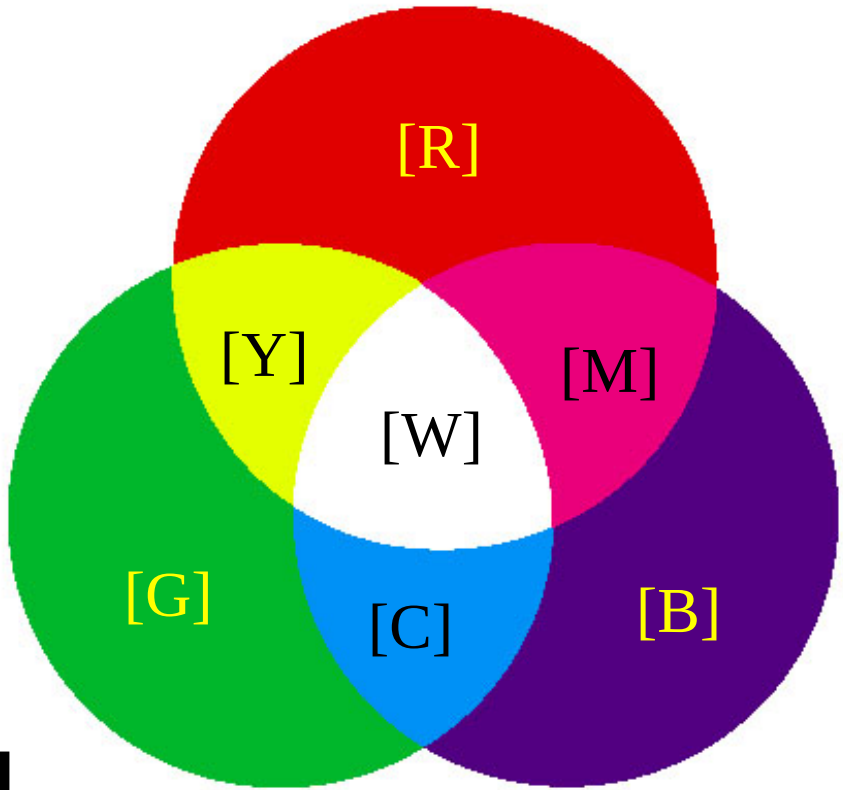


色彩體系發展


Color Art
Aristotle & Plato
ColorScience
da Vinci
Harris
Goethe
Runge
Munsell
NCS
Chevreul
Hering
Newton
Maxwell
Helmholtz
Ostwald
CIE-1931
CIE-D.L. MacAdam
CIE-L*A*B*

色光加法混色

[C] ⟷ [R]
[M] ⟷ [G]
[Y] ⟷ [B]



Red
Green
Blue
Cyan
Magenta
Yellow
White

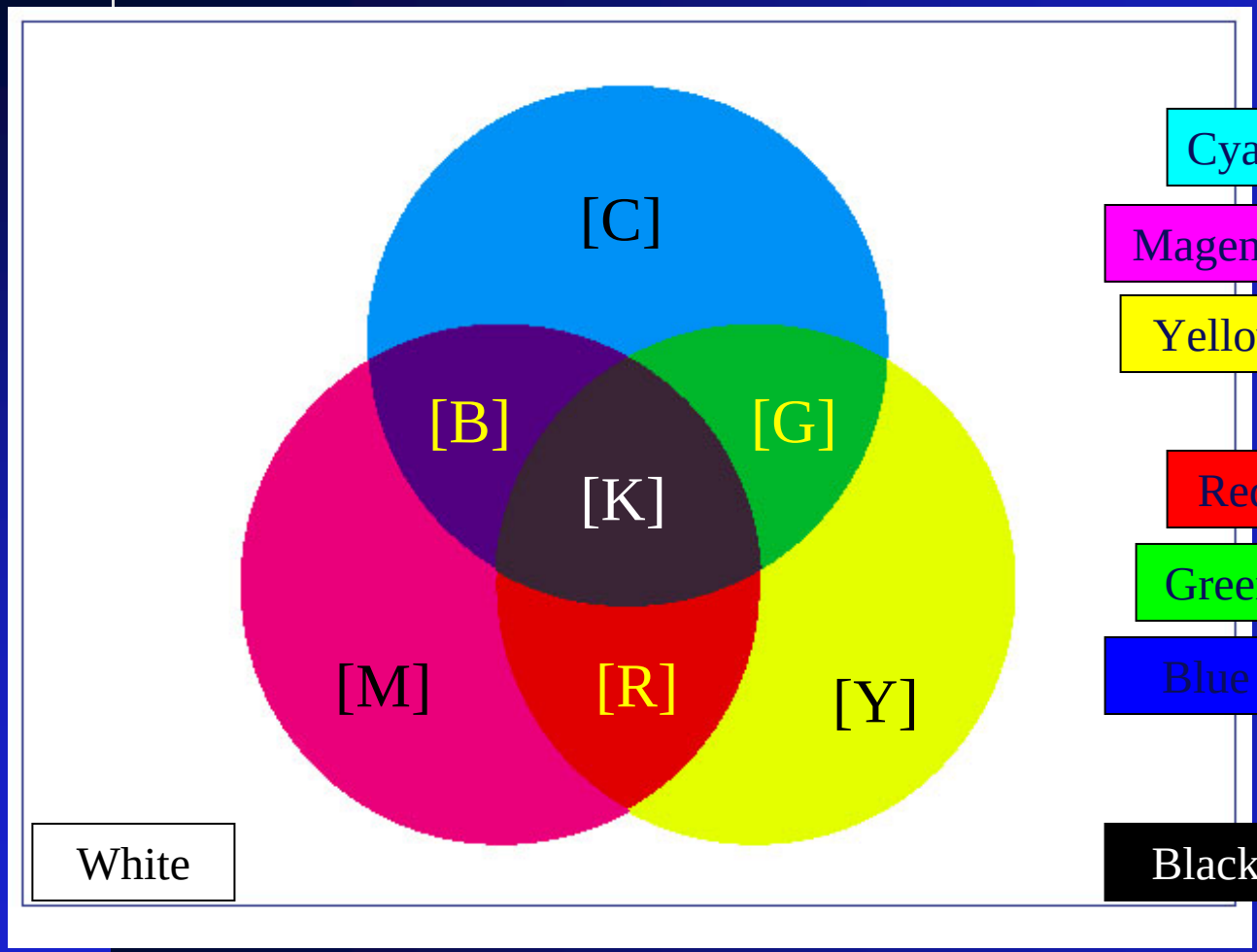
一次色:
[R]
[G]
[B]

二次色:
[C]
[M]
[Y]

三次色:
[w]

色料減法混色

[C] ⟷ [R]
[M] ⟷ [G]
[Y] ⟷ [B]



Cyan
Magenta
Yellow

Red
Green
Blue

Black

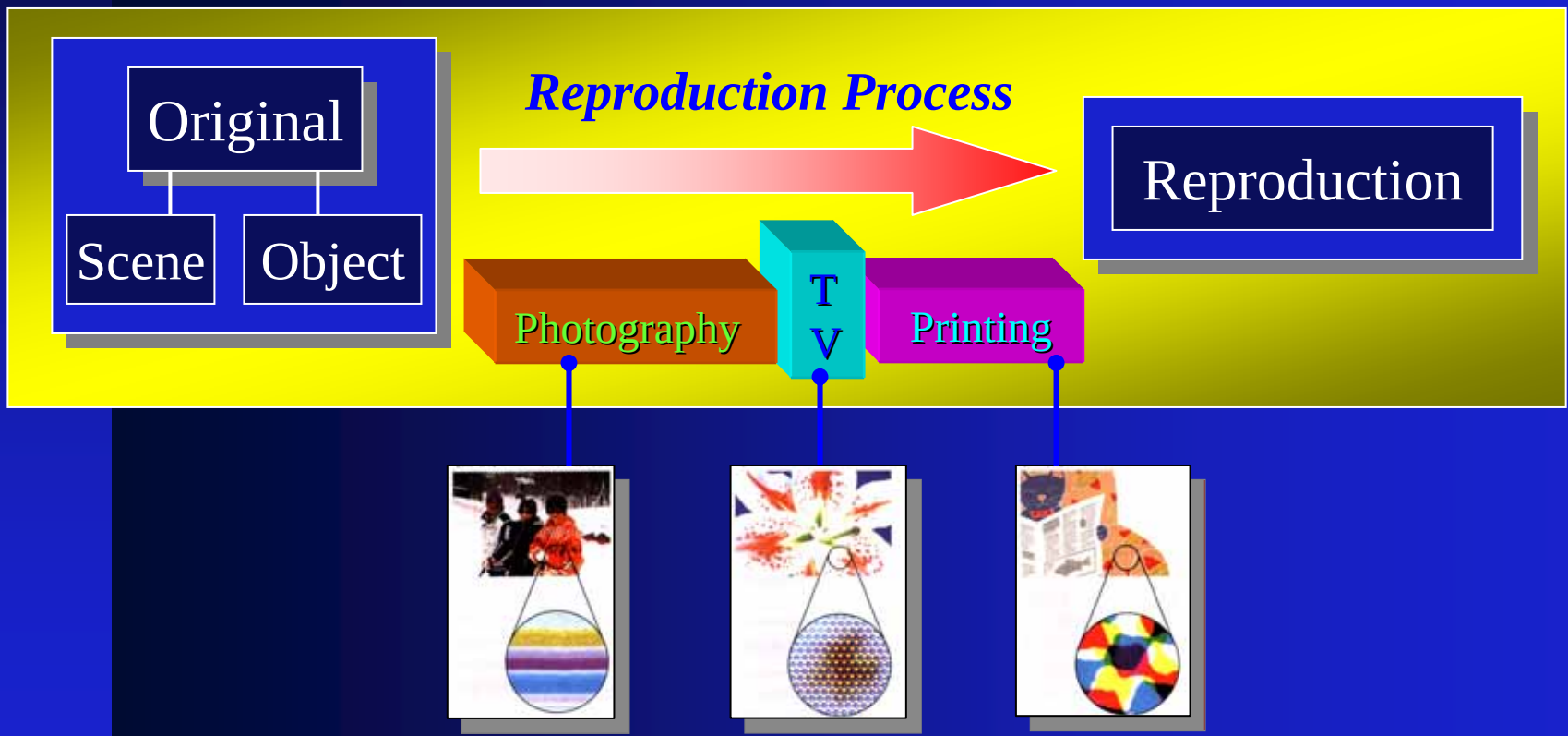
一次色:
[C]
[M]
[Y]

二次色:
[R]
[G]
[B]

三次色:
[K]

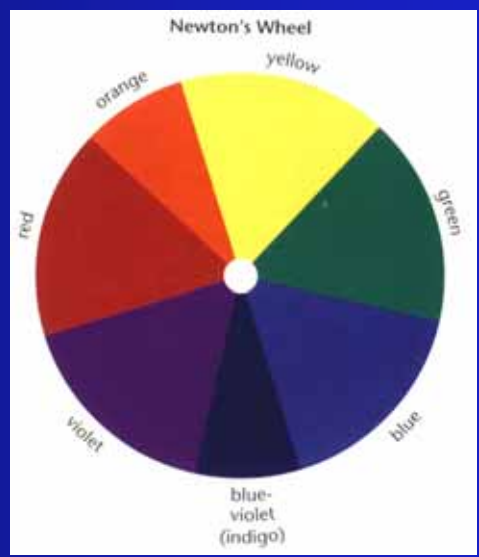
彩色複製；色彩再現 (Color Reproduction)

- A reproduction of producing a color image from some form of original scene or object.
- The process includes making photographic color transparencies and prints, television images, computer displays and printed reproductions.



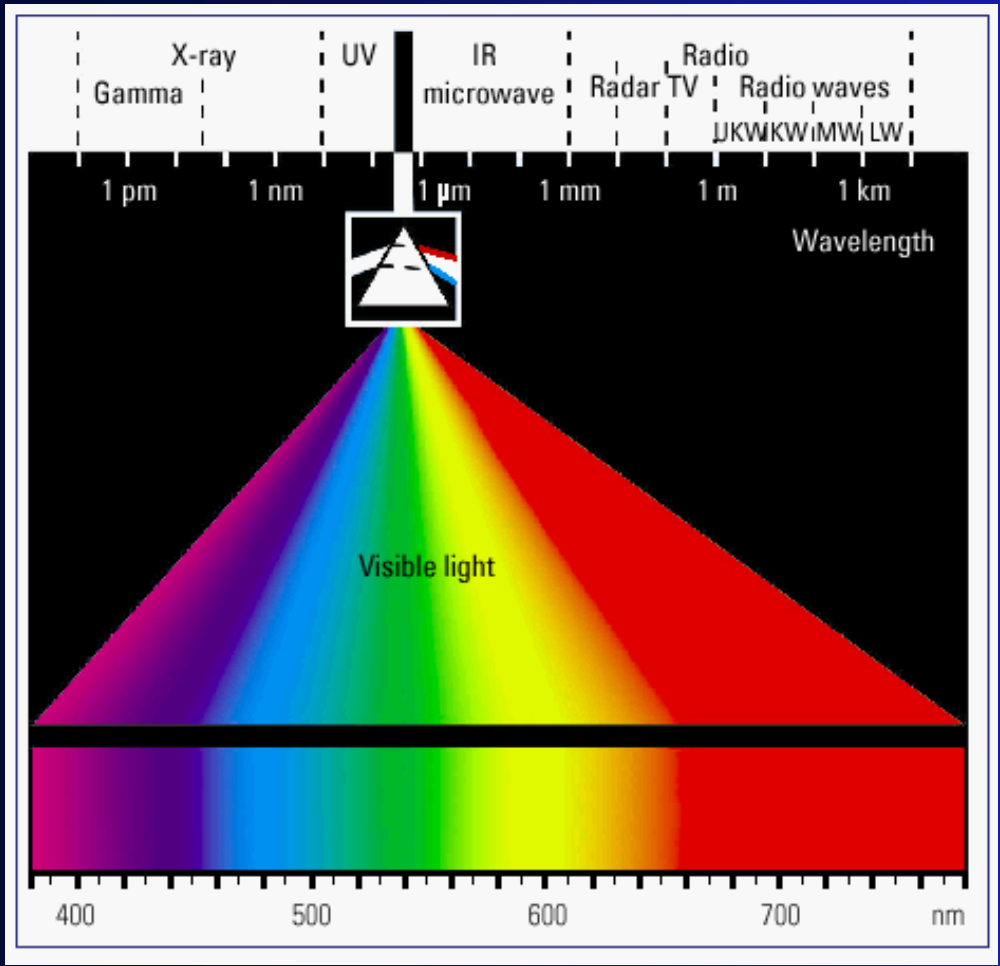
牛頓 Newton（1642~1727）

- 推翻希臘古典模式:白與黑為色彩的基本原色
- 利用三棱鏡與透鏡進行分光實驗,將色與光之研究整理成『光學』一書
- 將白光分解為七色光,將七色光聚集後還原為白光
- 『光不是顏色』(“The rays are not colored.”)
- 建立色相環(hue circle)
- 奠立色彩科學理論的基礎研究



色彩的發生(1) :物理學角度

色光是被破壞與分解的白光



Visible light

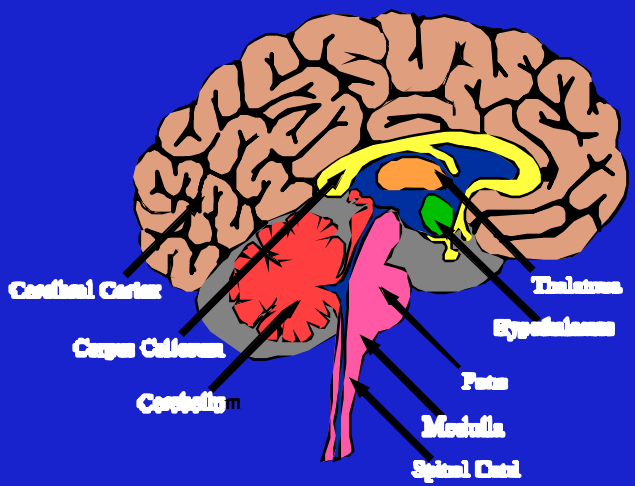
Red
Orange
Yellow
Green
Blue
Blue-violet

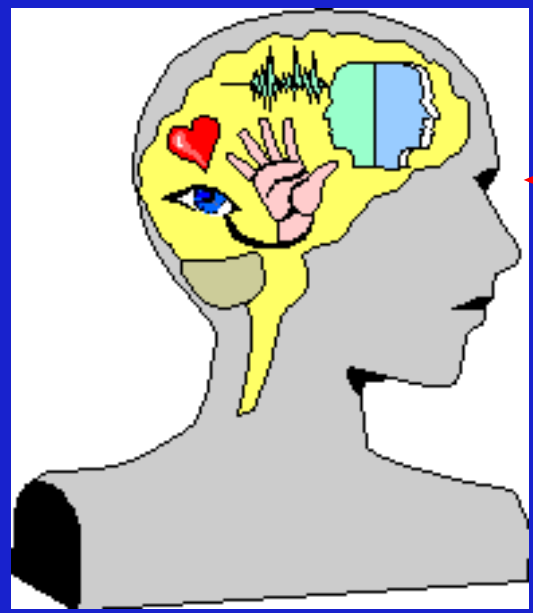
Violet

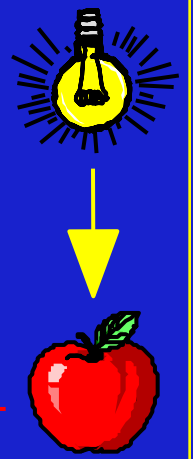
(nm:10^{-9}m)

色彩的發生(2) ：生理學角度

光不是色彩，我們藉由人腦感知(see)色彩



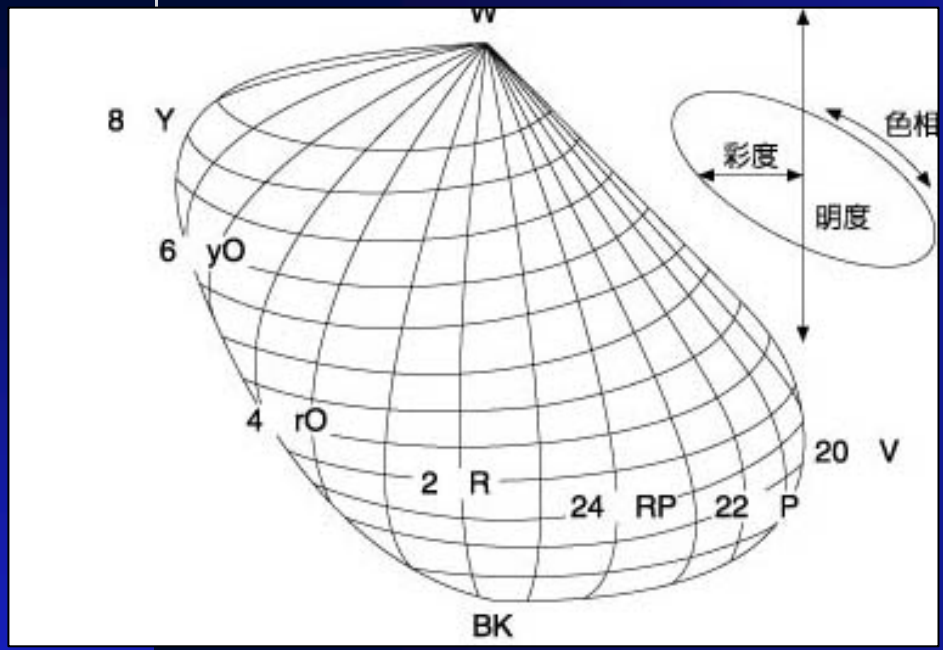




- 色彩三要素： 物體, 光源, 人眼

色彩構成

- 色彩三屬性： 色相(hue), 明度(lightness), 彩度(chroma)



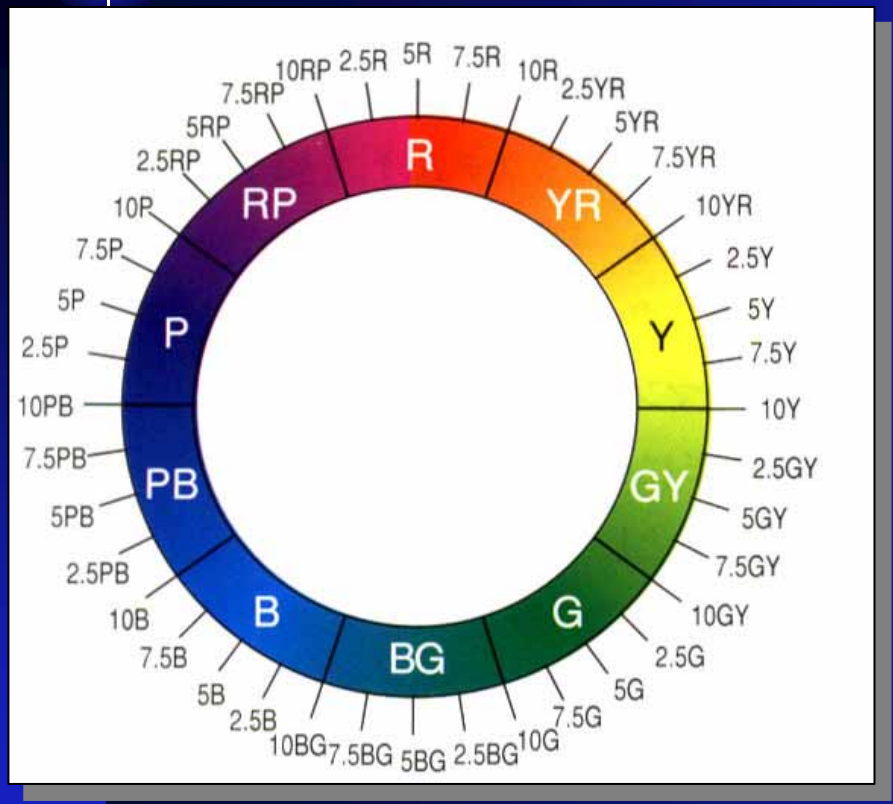
- PCCS色立體

- Munsell色立體模型

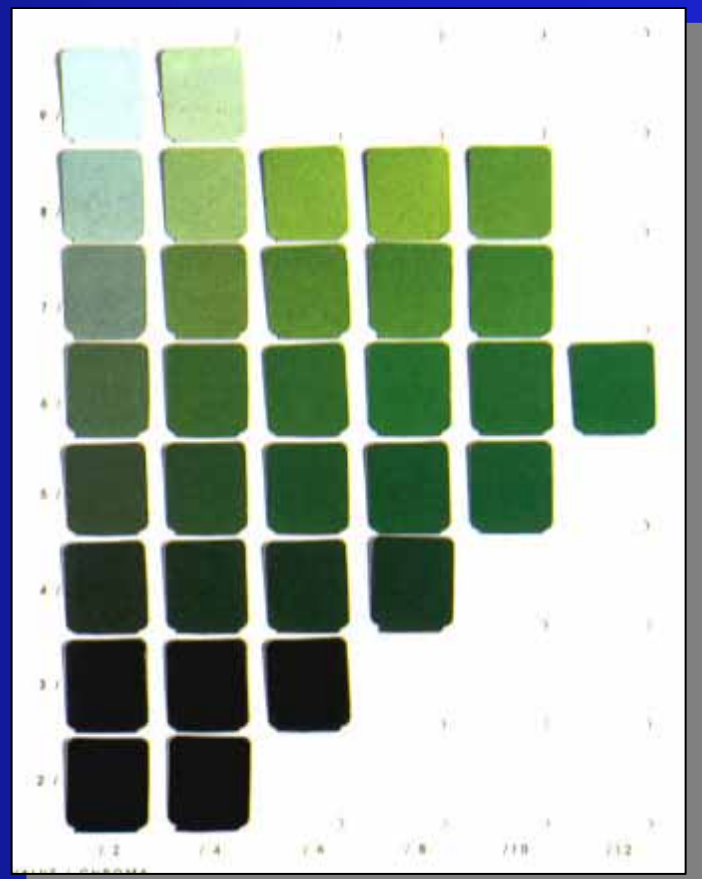
Color Solid | Color Tree | Hue Page | Hue=Color Name

色彩體系

Munsell color system



Hue Circle

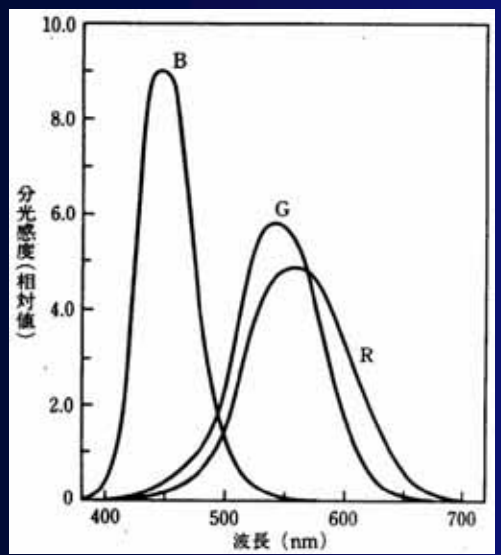


Hue Page

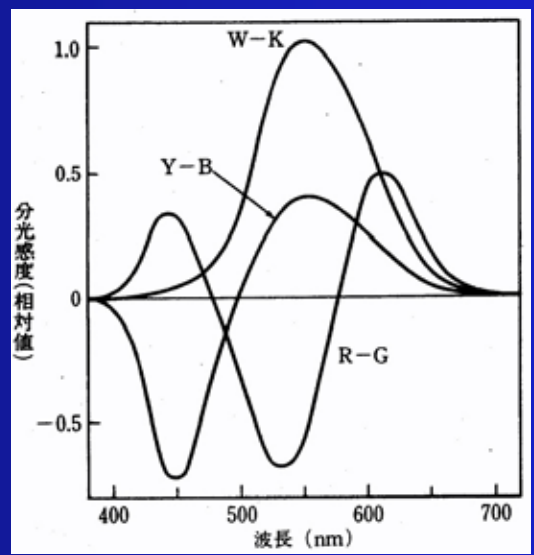
色知覺理論(I)：三原色說*v. s.* 對立色說

- 三原色說 (Young , Helmholtz)：『人眼內含有三種感受紅(R)，綠(G)，藍(B)色彩的受光器，色覺是由各受光器對光產生的應答』

- 對立色說 (Hering)：『人眼內含有三種感受紅–綠（R–G)，黃–藍(Y–B)，白–黑（W–K)色彩的受光器，色覺是由各受光器對光產生的應答』



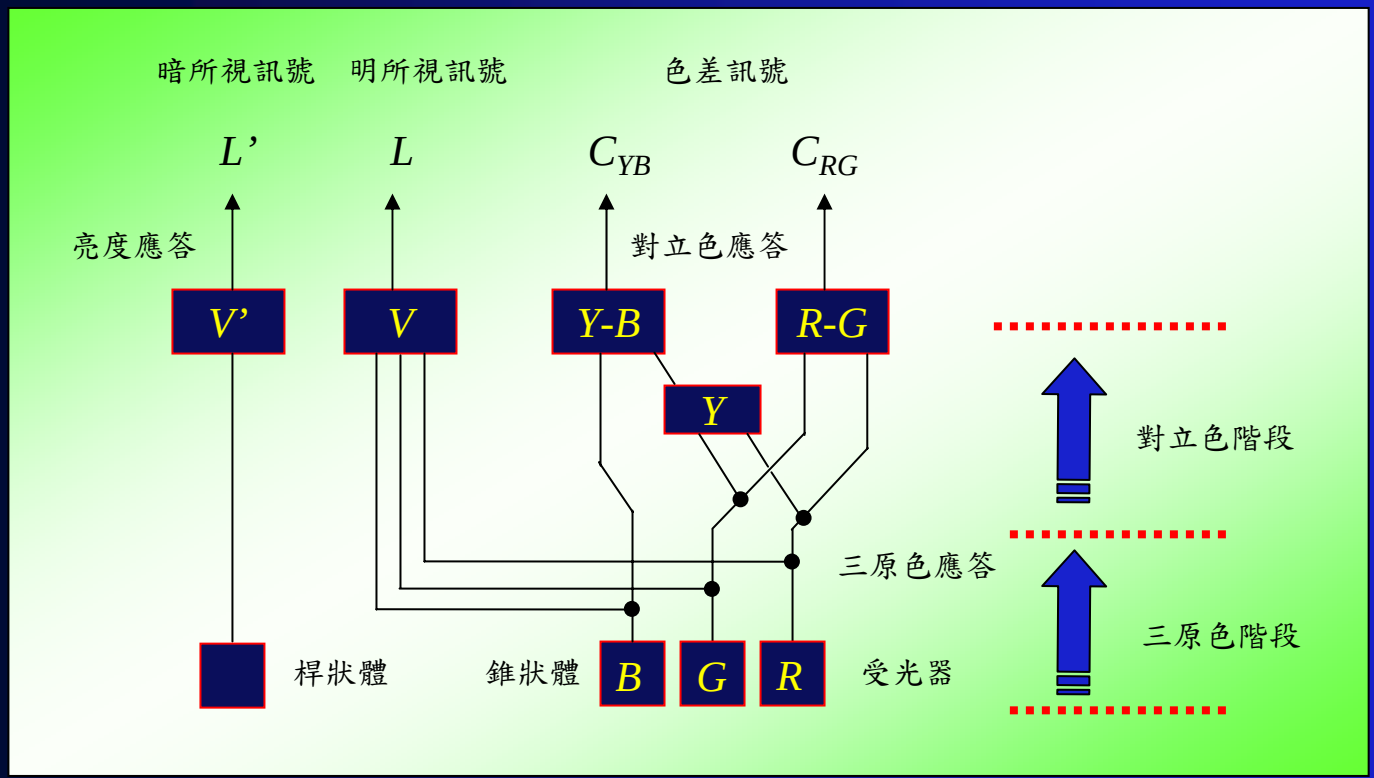
三原色說 (trichromatic theory)



對立色說 (opponent-colors theory)

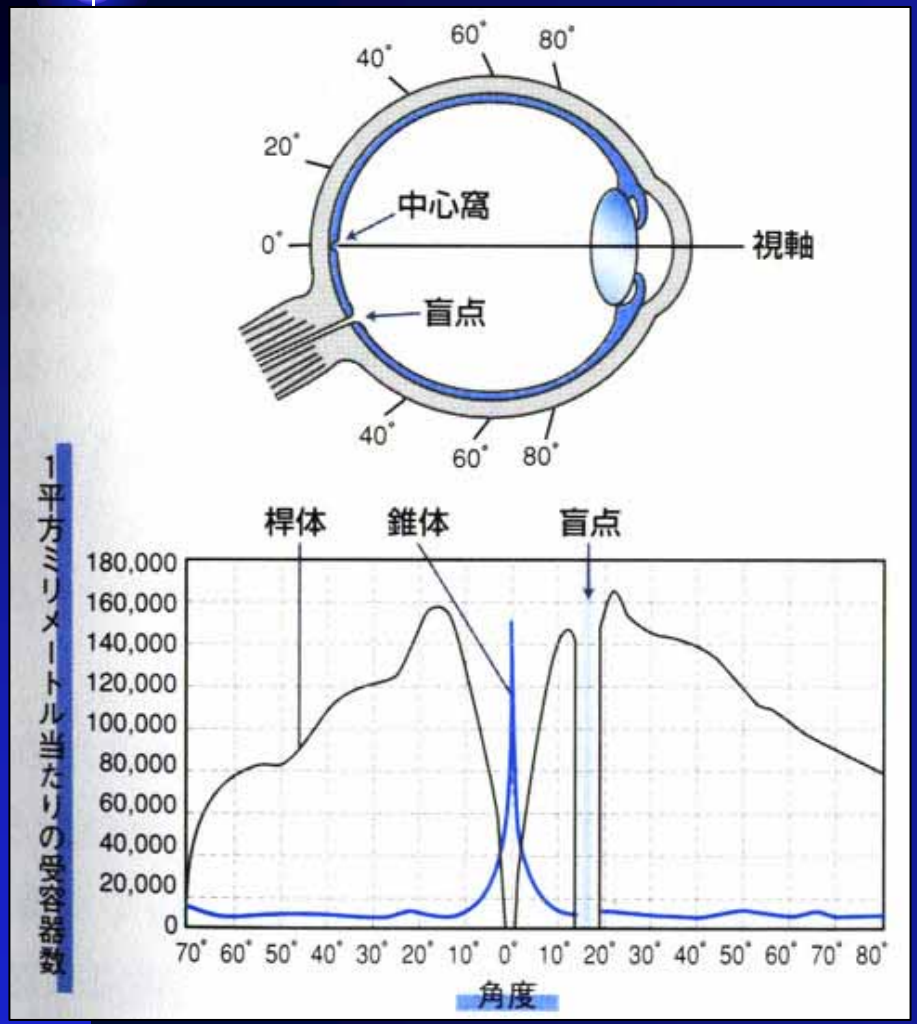
色知覺理論(II):階段說

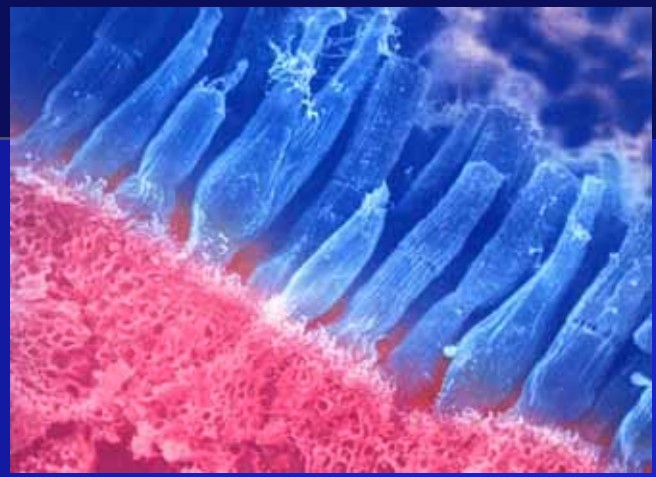
- 階段說（Adams, Goth etc.）：『網膜上產生之應答會因網膜厚度方向位置而有所不同，錐狀細胞的初期階段為三原色應答，後期階段轉換為對立色應答。人眼並非在三原色應答與對立色應答之間作一選擇，而是最初以三原色應答感覺色彩，再變換成為對立色應答後傳入腦部 』

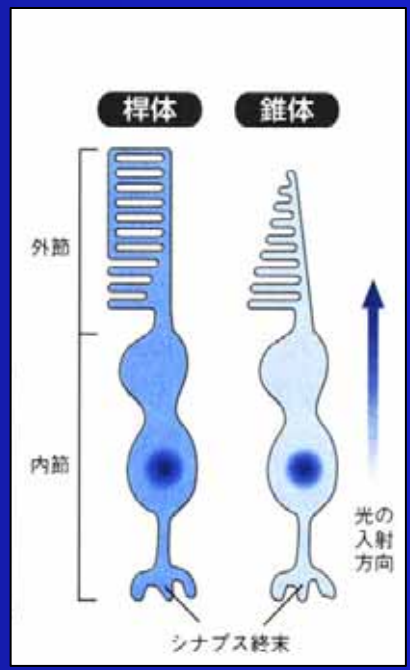


階段說 (stage theory)

錐狀體與桿狀體


40°
60°
80°
20°
中心窩
0°
視軸
盲点
40°
60°
80°
桿体
錐体
盲点
1平方ミリメートル当たりの受容器数
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80°
角度




桿体
錐体
外節
内節
光の入射方向
シナプス終末

色彩3色表示

$$L = \int_{vis} P(\lambda)\cdot l(\lambda)d\lambda$$

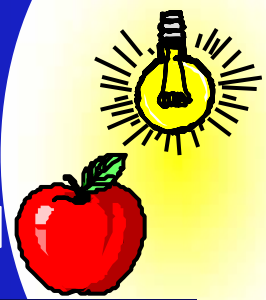
$$M = \int_{vis} P(\lambda)\cdot m(\lambda)d\lambda$$

$$S = \int_{vis} P(\lambda)\cdot s(\lambda)d\lambda$$

4.

色刺激頻譜分布$P(\lambda)$
(color stimulus spectral distribution)

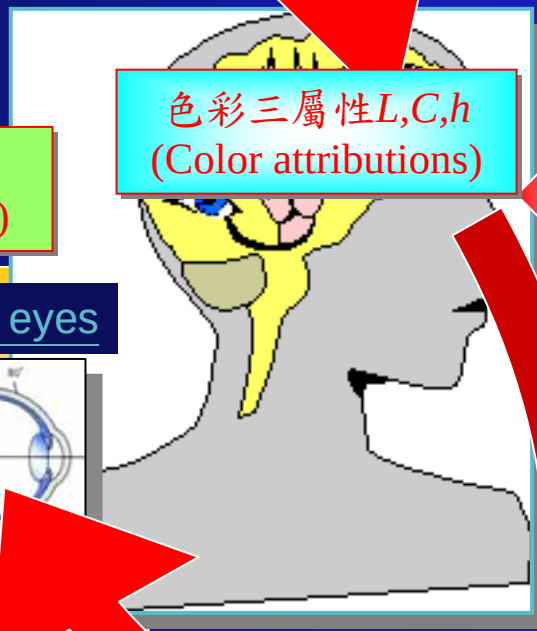
Color stimulus



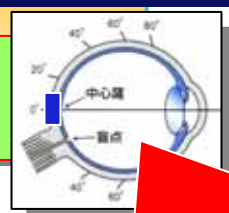
1.

Red apple

色彩三屬性L,C,h
(Color attributions)



Human eyes

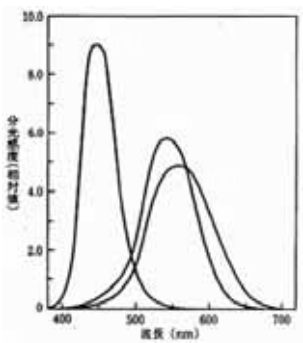


2.

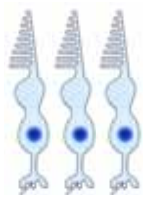
3.

應答量L,M,S
(Signal responses)

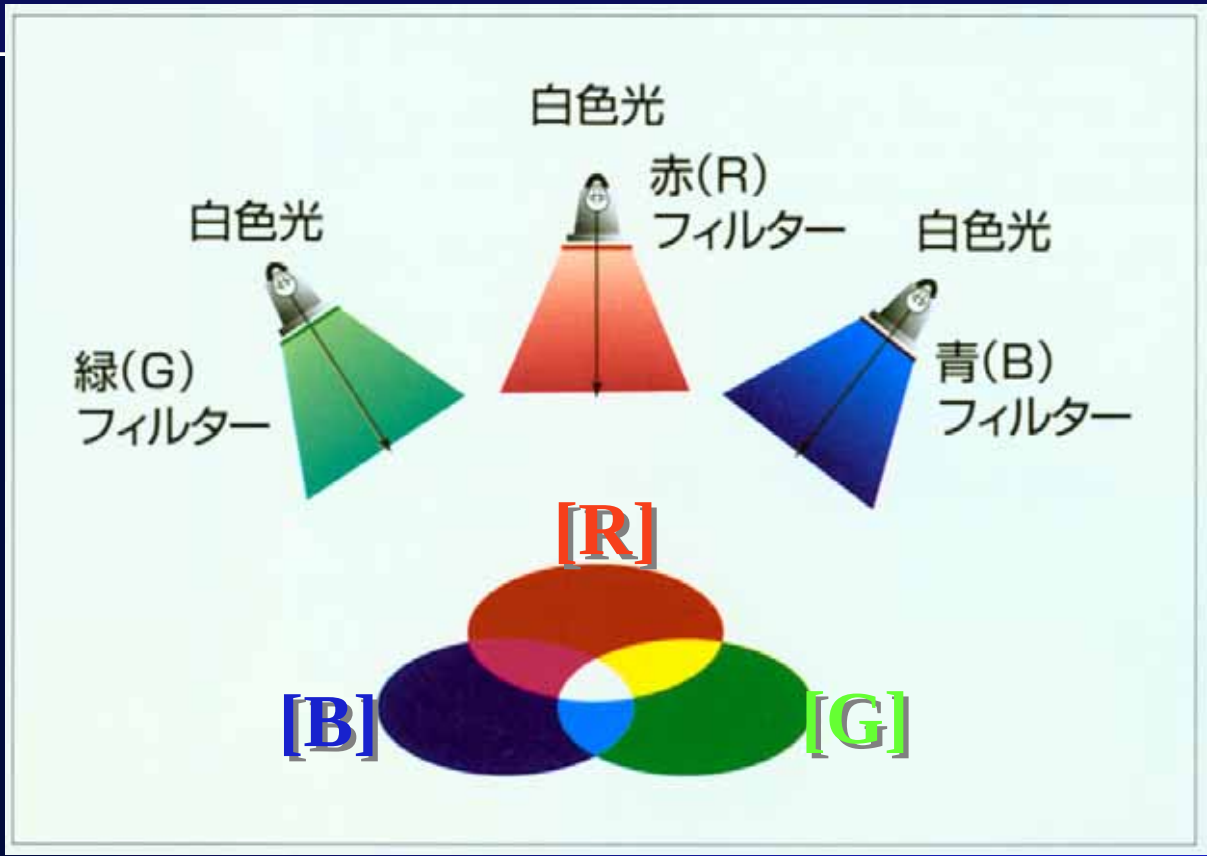
錐狀體頻譜感度$l(\lambda)$, $m(\lambda)$, $s(\lambda)$
(cone spectral sensitivity)



Cone cells



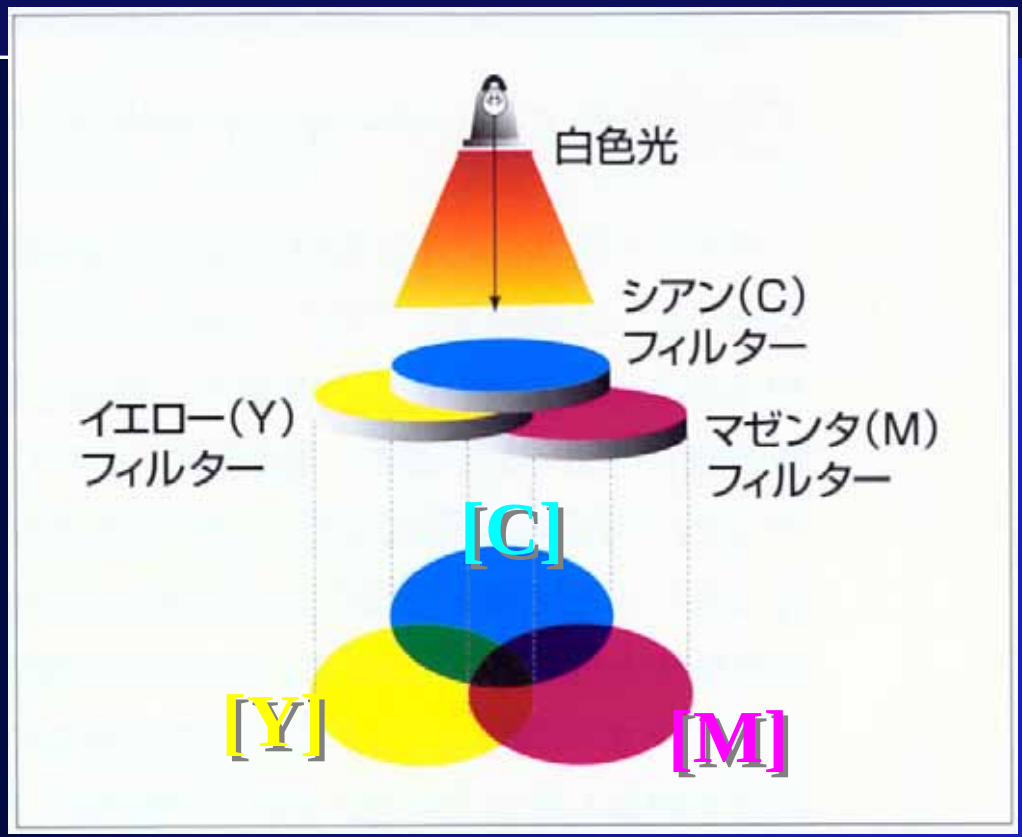
加法混色原理



$$[F]=R[R]+G[G]+B[B]$$

- R,G,B代表[R],[G],[B]色光的混合量

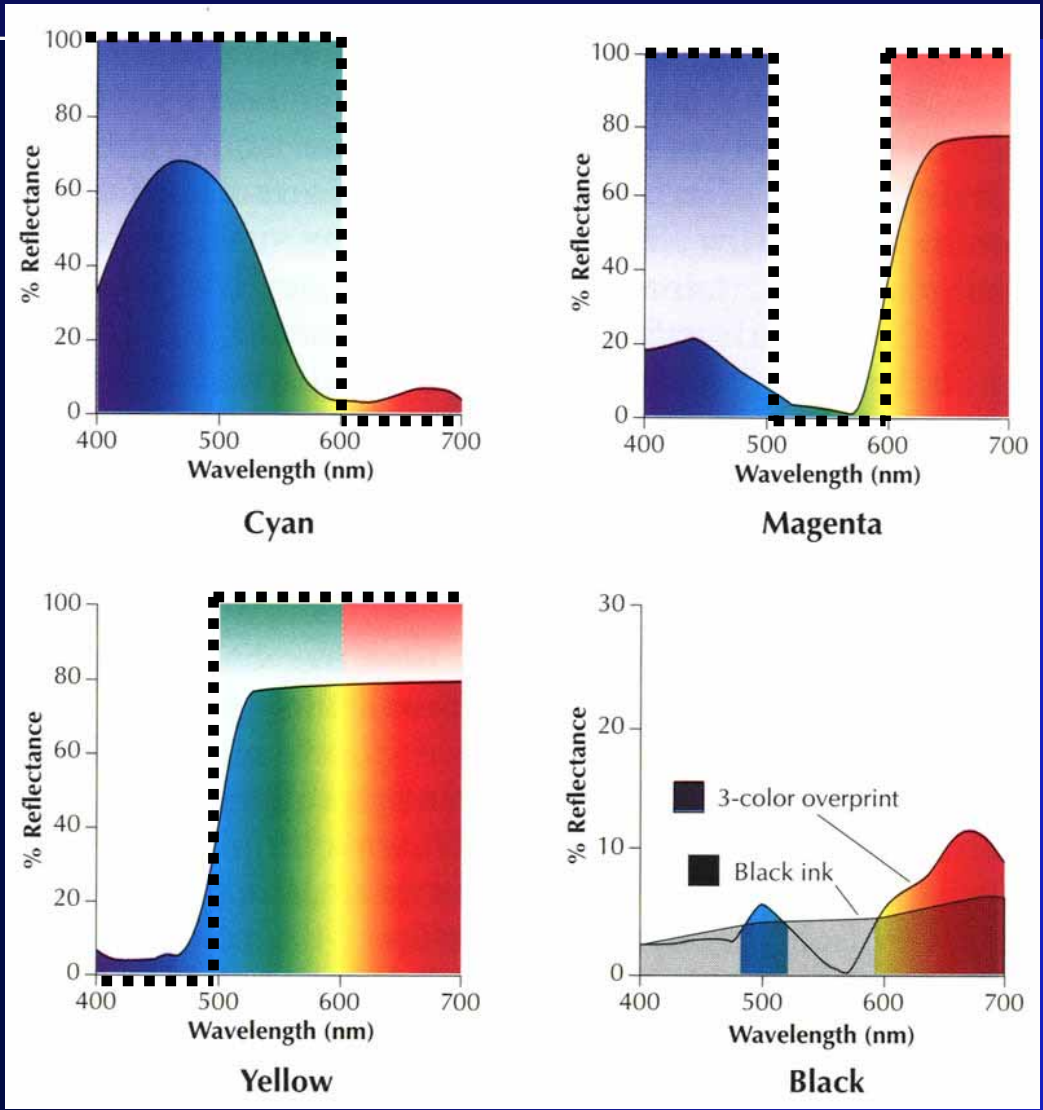
減法混色原理



$$[F] = [C]^{c} * [M]^{m} * [Y]^{y}$$ ➡ 近似乘法計算運作

- *c,m,y*分別代表彩色濾光片中[C],[M],[Y]色素的混合量

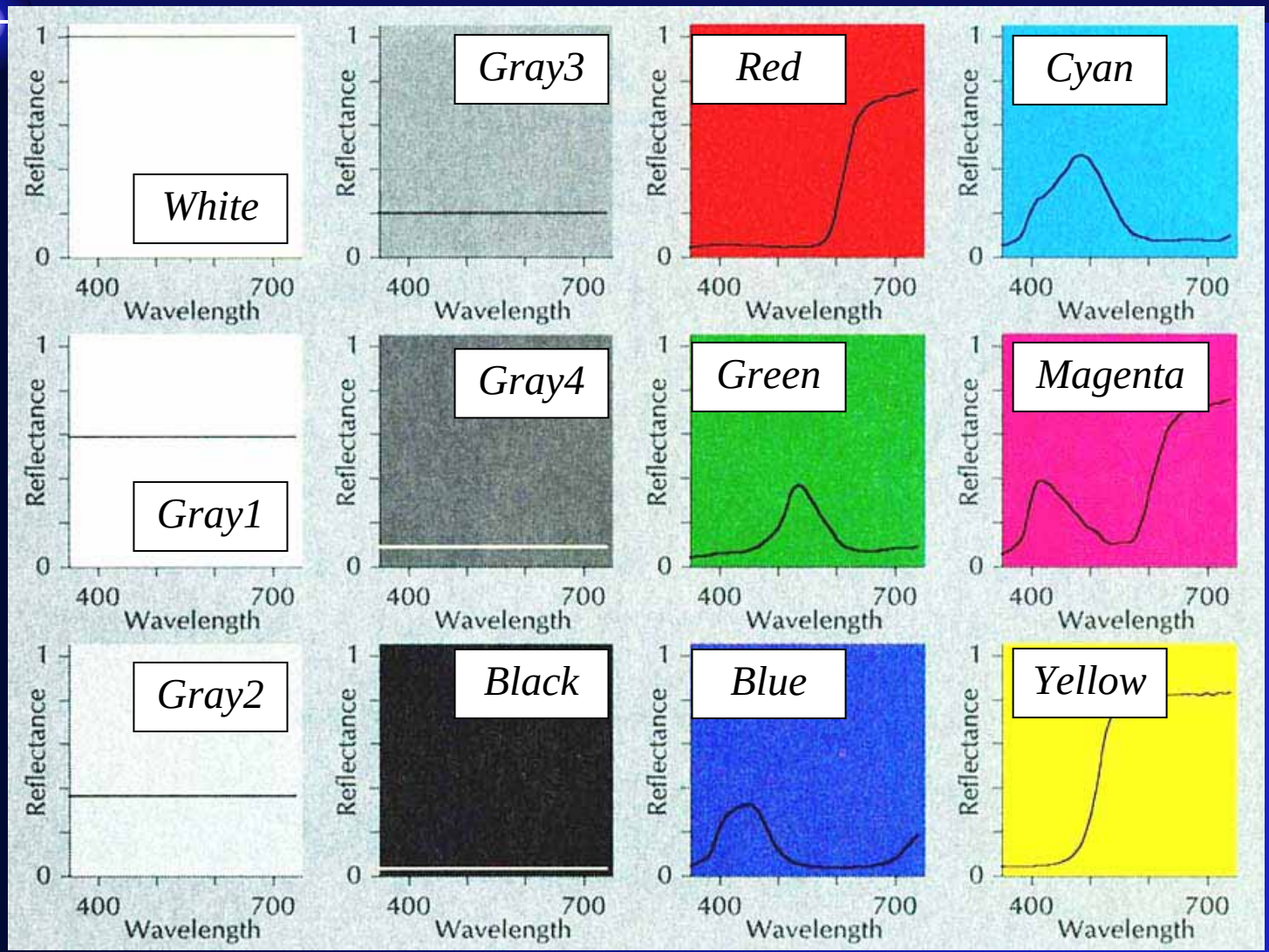
C,M,Y,K油墨頻譜反射率



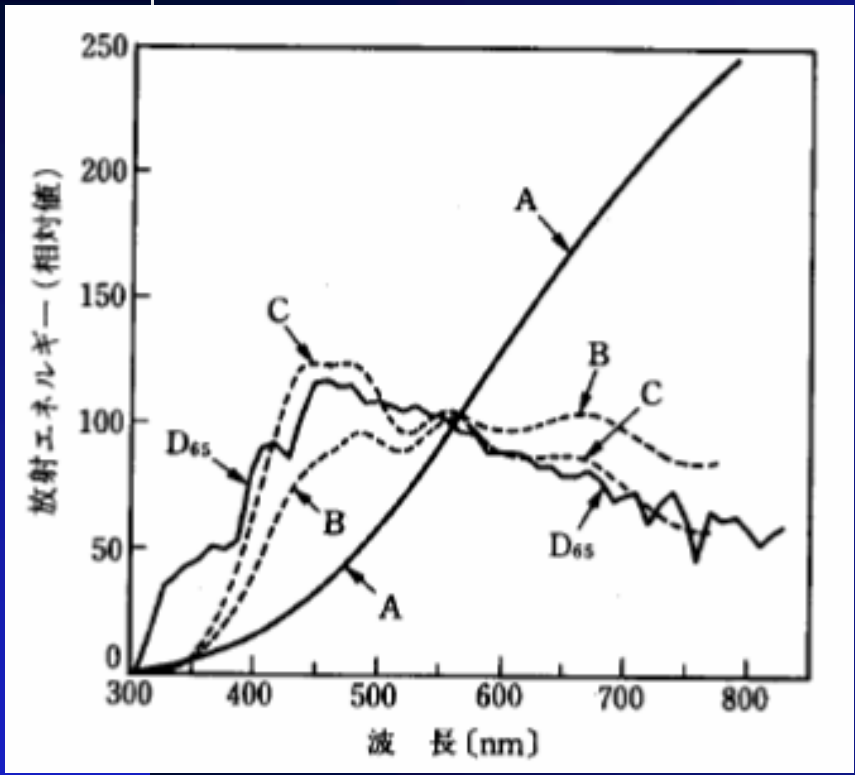
物體頻譜反射率

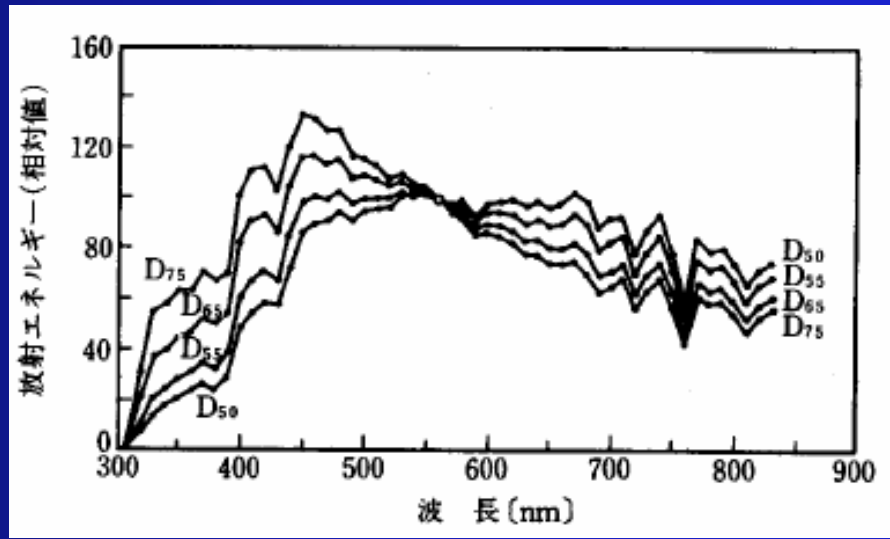
Reflectance :反射率

Transmission : 穿透率

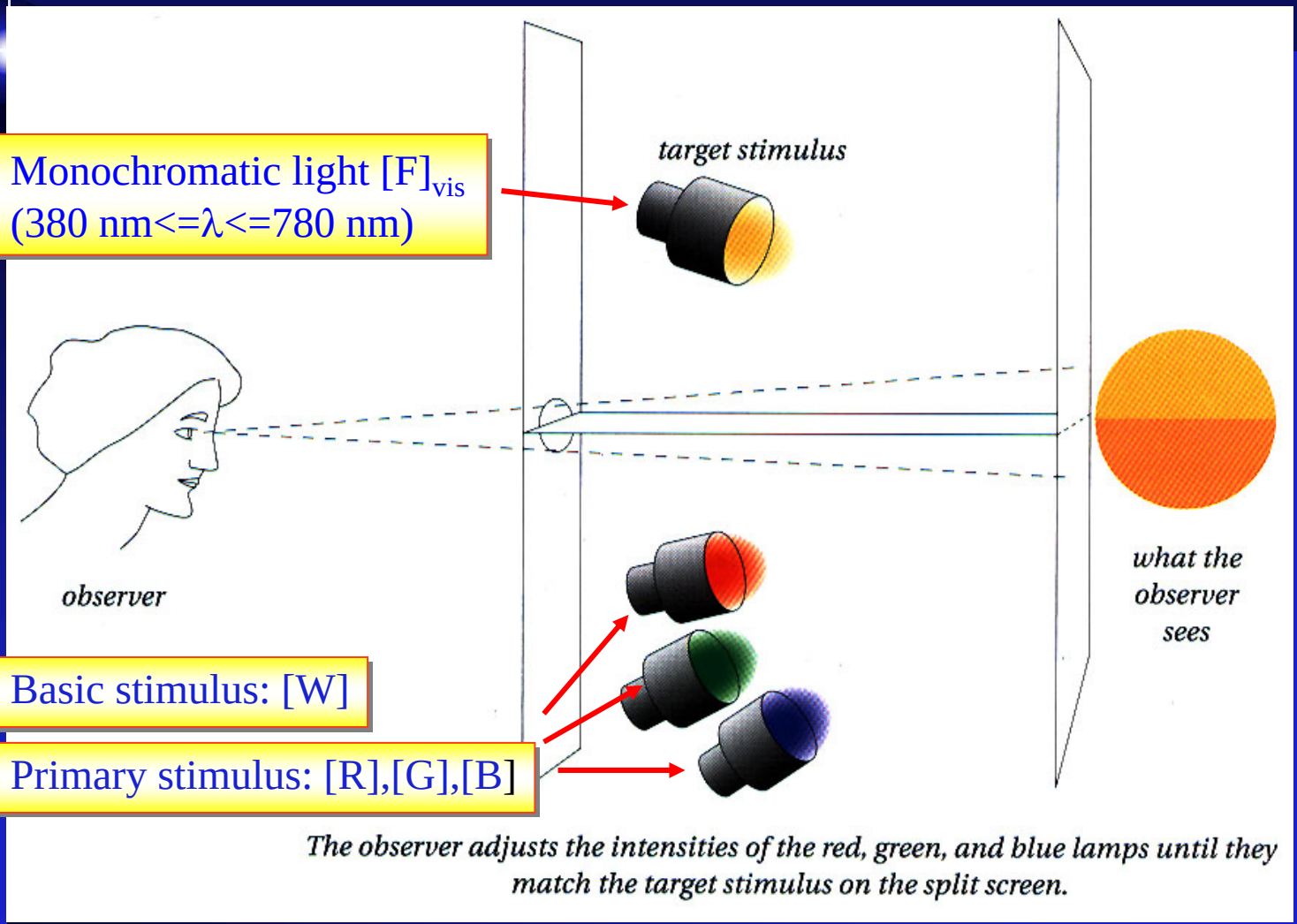


照明光頻譜能量分布


250
200
150
100
50
0
300
400
500
600
700
800
放射エネルギー（相対値）
波　長（nm）
A
B
C
D65
B
C
D65
A


160
120
80
40
0
300
400
500
600
700
800
900
放射エネルギー（相対値）
波　長（nm）
D75
D65
D55
D50
D50
D55
D65
D75

RGB 配色函數→由"配色實驗" 求得



(配色函數:Color Matching Functions ; CMFs)

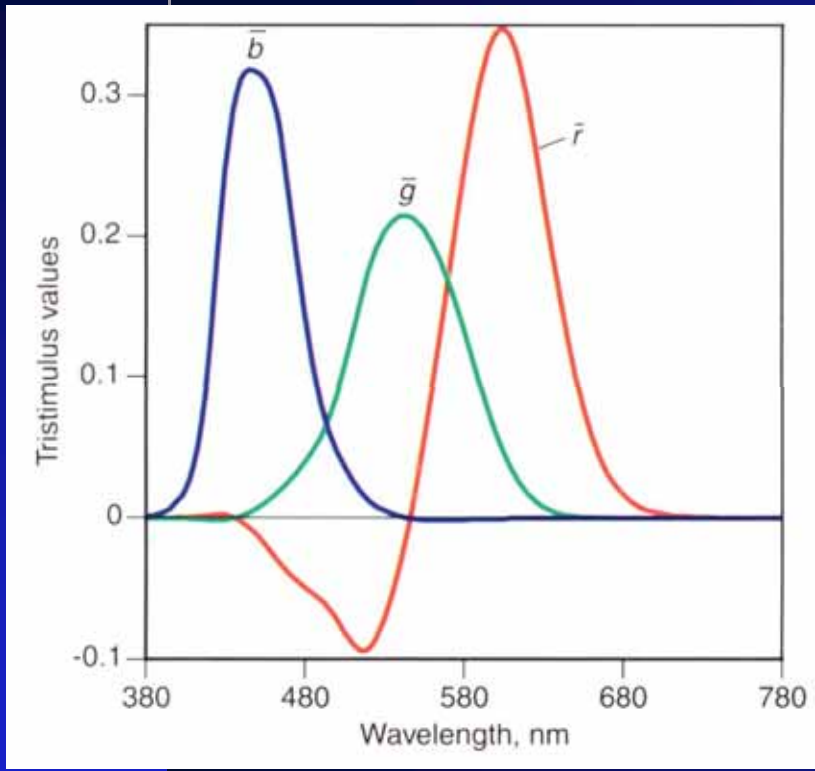
RGB 配色函數

在混色系統中，一旦配色函數確定，任意色刺激的三刺激值即能確定，但配色函數隨基礎刺激、原刺激的不同而異，因此在相互比較測色結果時，必須事先進行標準化。為此，國際照明委員會(CIE)於1931年根據以下的基準制定了標準配色函數。

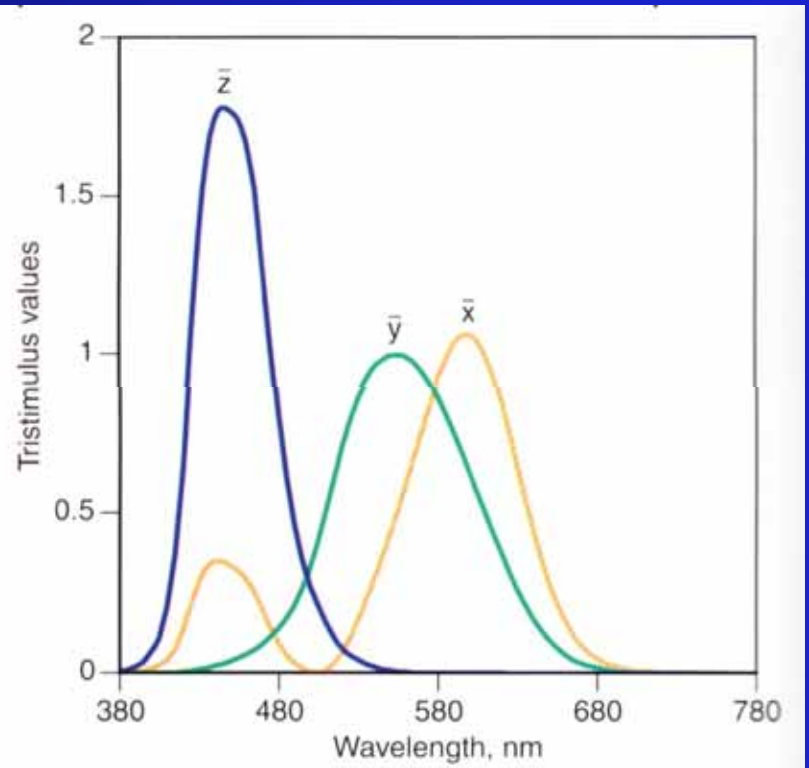
- 原刺激[R],[G],[B]定義為:
  λ_R =700.0 nm，λ_G =546.1 nm，λ_B =435.8 nm的單色光
  - 基礎刺激為等能量光譜的白色刺激。這時，原刺激[R],[G],[B]的亮度係數關係為1.0000 : 4.5907 : 0.0601（光度量單位）

RGB配色函數 v.s. XYZ配色函數

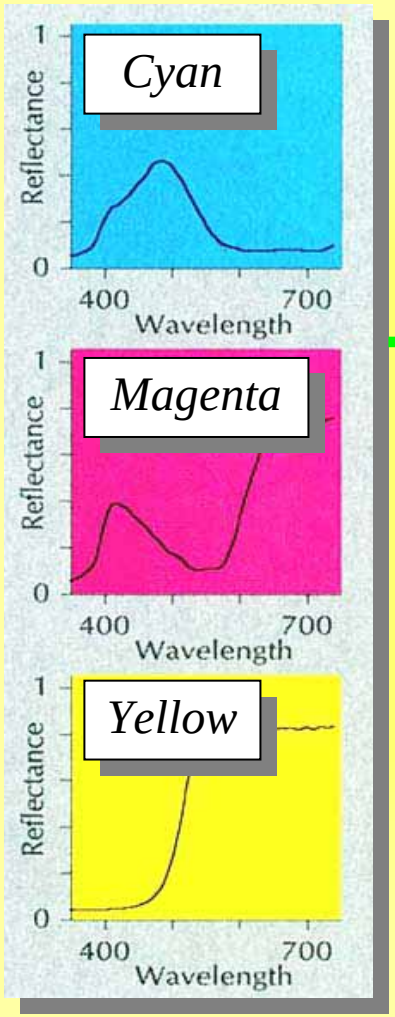
- RGB配色函數



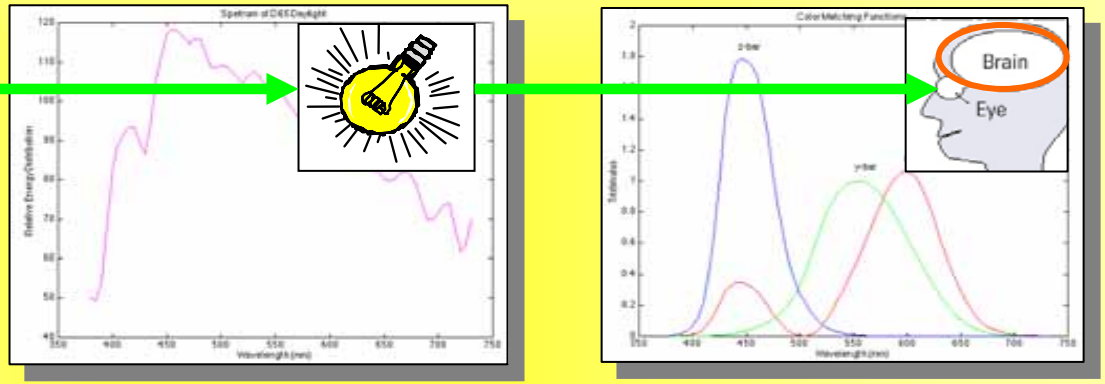
- XYZ配色函數



色彩定量化描述



- 色感(色彩感覺)發生於視覺腦



- 色感為{物體/光源/視覺特性}三者的綜合作用

三刺激值計算

物體反射率　光源能量分布　配色函數

Tristimulus values

三刺激值

$$X = k\int_{vis} R(\lambda)\bullet P(\lambda)\bullet \bar{x}(\lambda)d\lambda$$

$$Y = k\int_{vis} R(\lambda)\bullet P(\lambda)\bullet \bar{y}(\lambda)d\lambda$$

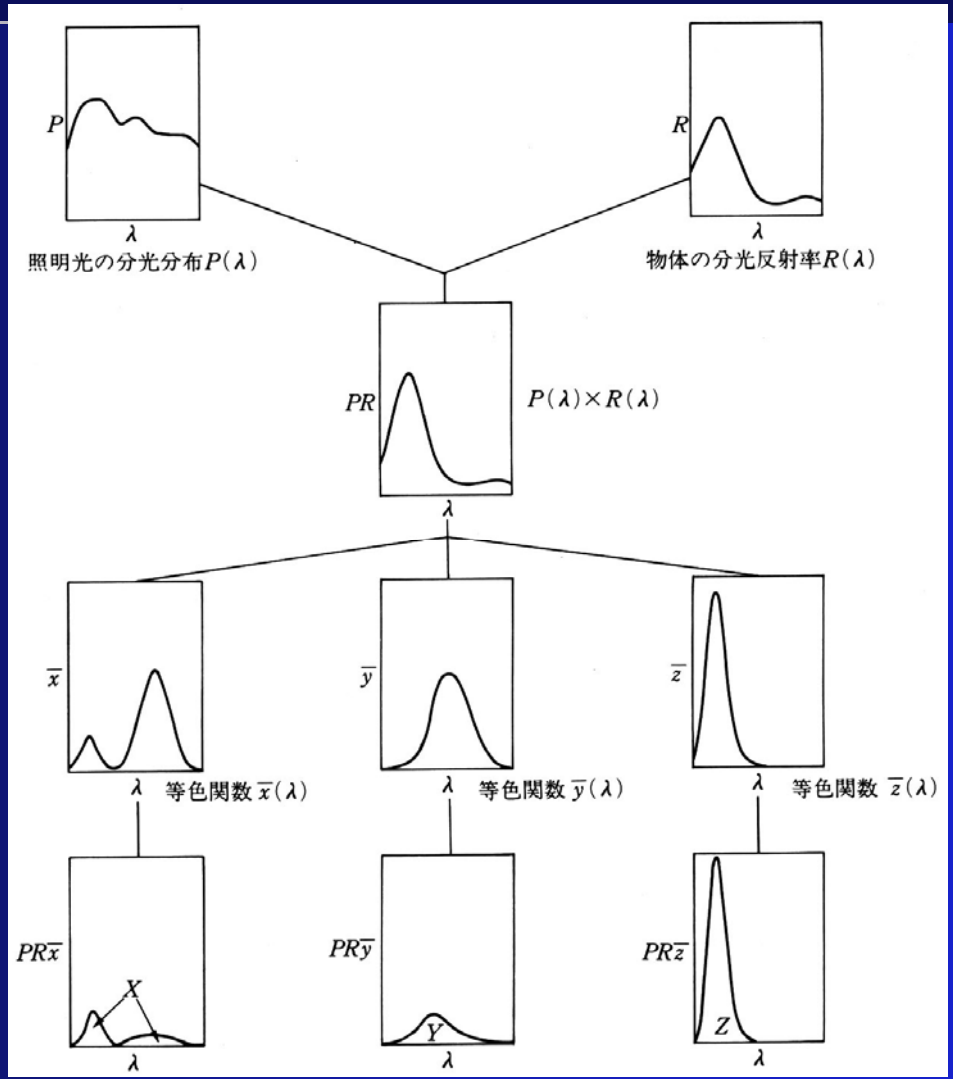
$$Z = k\int_{vis} R(\lambda)\bullet P(\lambda)\bullet \bar{z}(\lambda)d\lambda$$

正規化係數

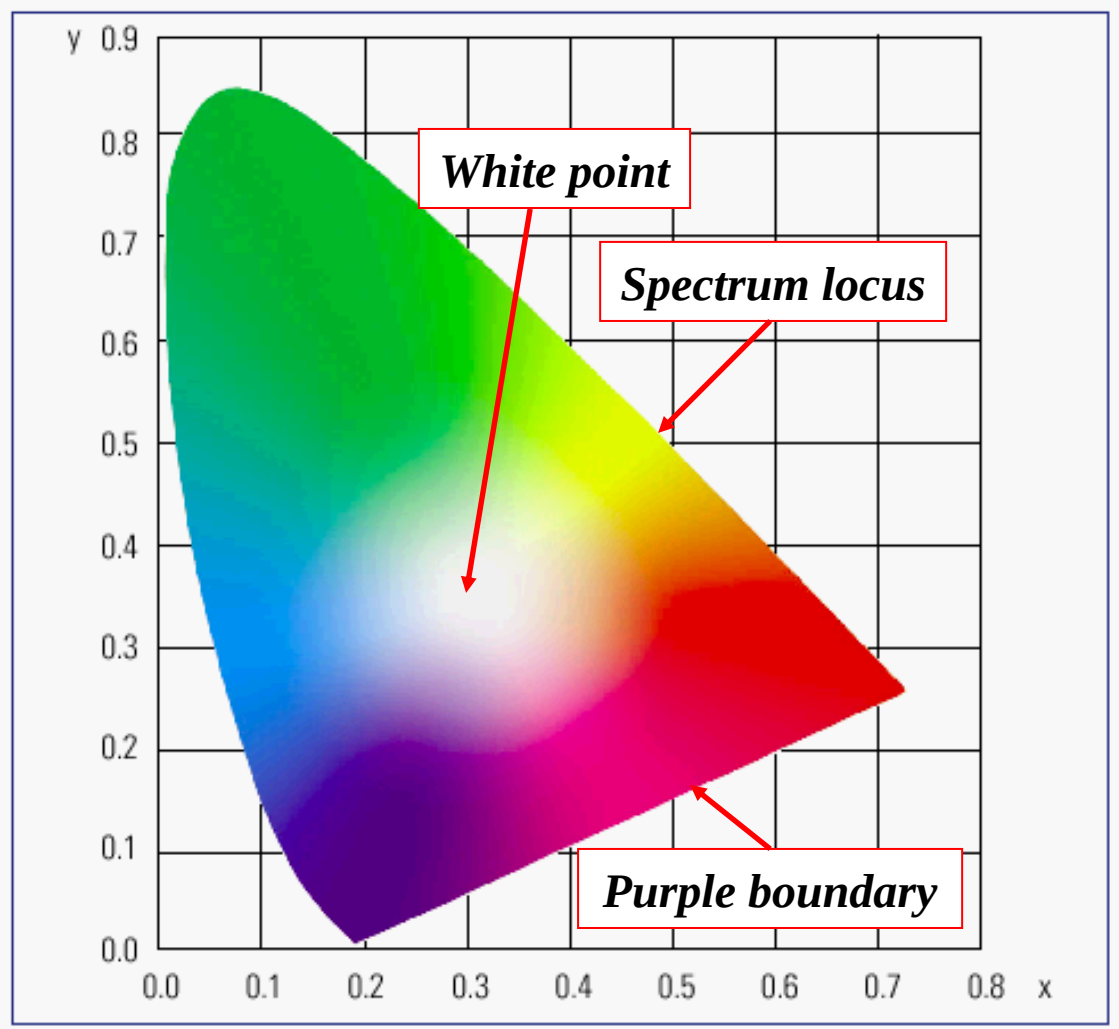
$$k = \frac{100}{\int_{vis} P(\lambda)\bullet \bar{y}(\lambda)d\lambda}$$

三刺激值計算(cont')

三刺激值XYZ=物體光譜反射率(穿透率),照明光光譜分布與CIE配色函數三者在可見波長範圍內積分作用後所得的積分面積



CIE *xy* 色度圖



- chromaticity
- chromaticity diagram
- chromaticity coordinates

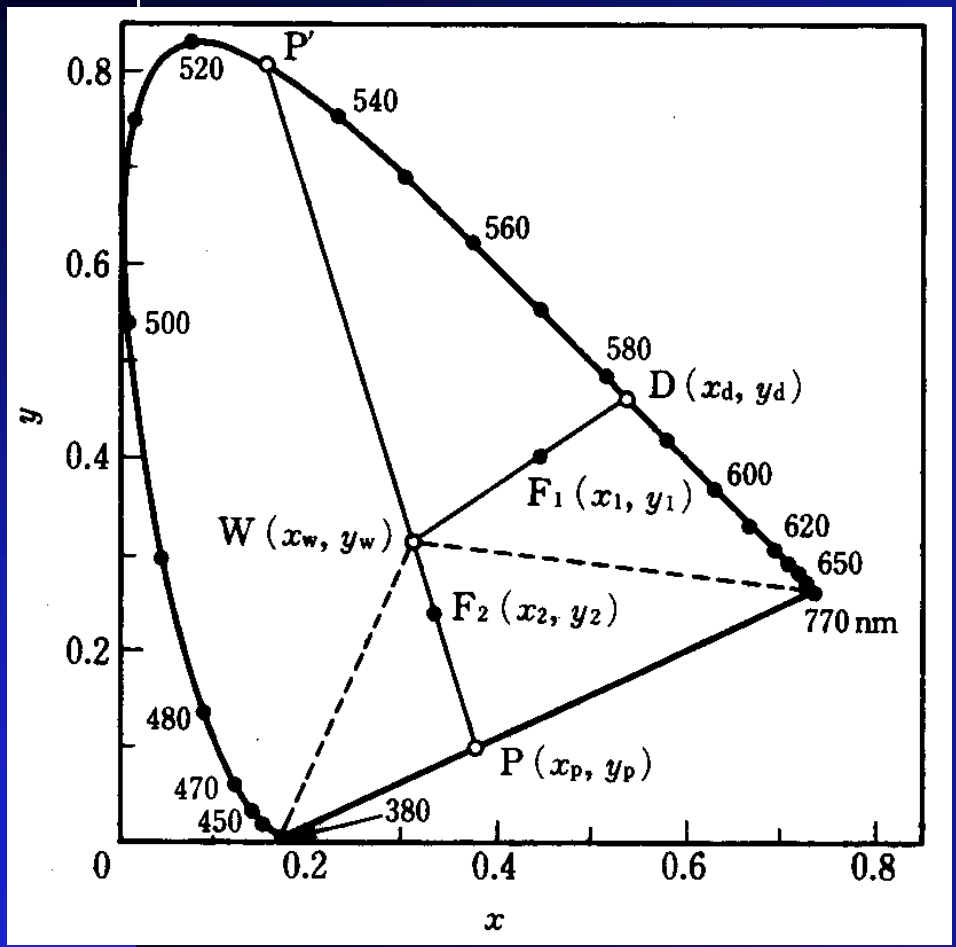
色度座標(*x*,*y*)

$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$

$$x+y+z=1$$

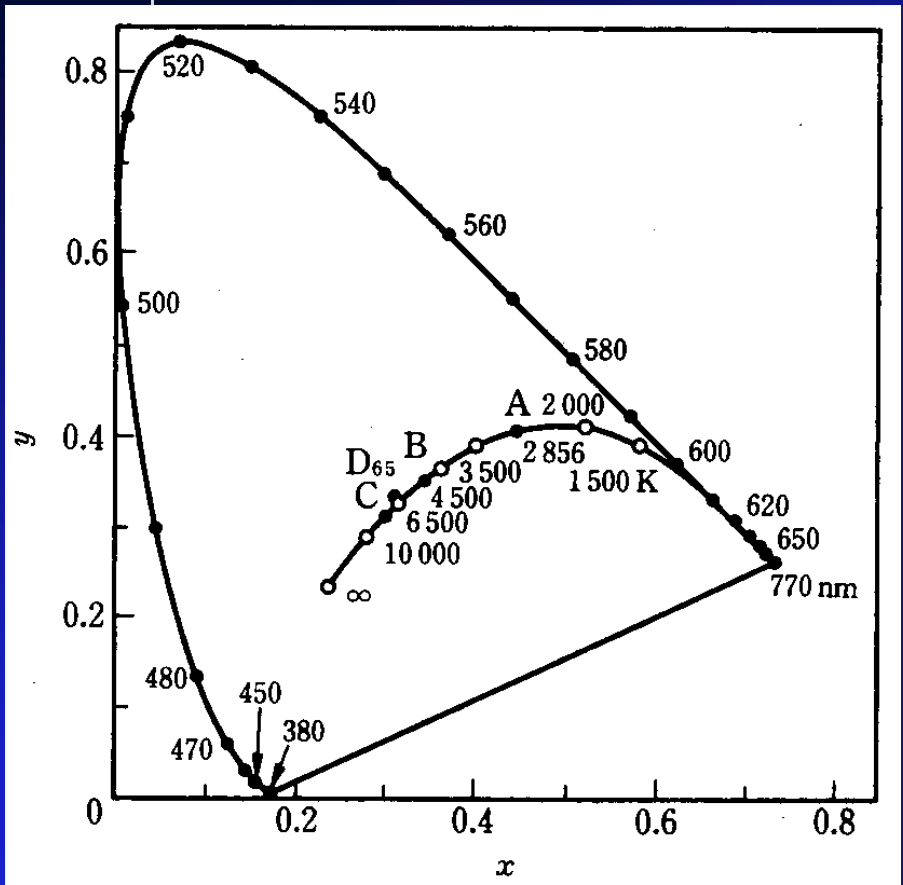
主波長(互補主波長)與刺激純度

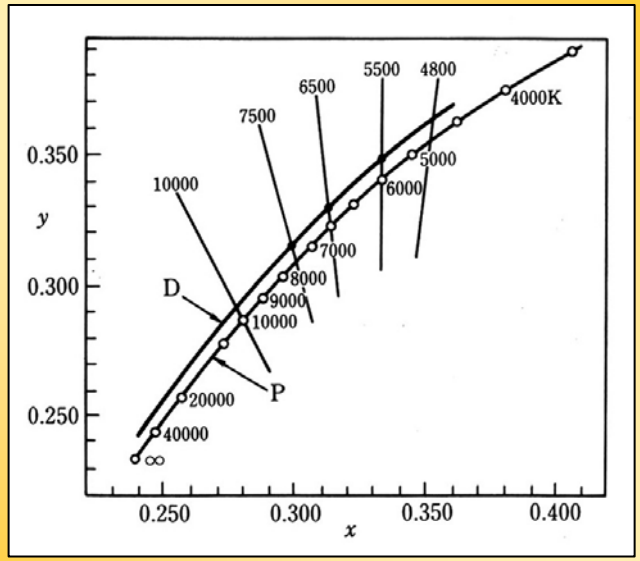


- Dominant Wavelength (l_d)
- Complementary Wavelength (l_c)
- Excitation Purity (P_e)

黑體軌跡 (blackbody locus)

- Absolute Temperature (Kelvin)
- Color Temperature (CT)
- Corrected Color Temperature (CCT)
- Blackbody locus
- Isotemperature line (等色溫線)
- Reciprocal color temperature (倒數色溫)





CIE日光軌跡 (D)與黑體軌跡 (P)
(直線代表等色溫線)

標準照明體與輔助標準照明體

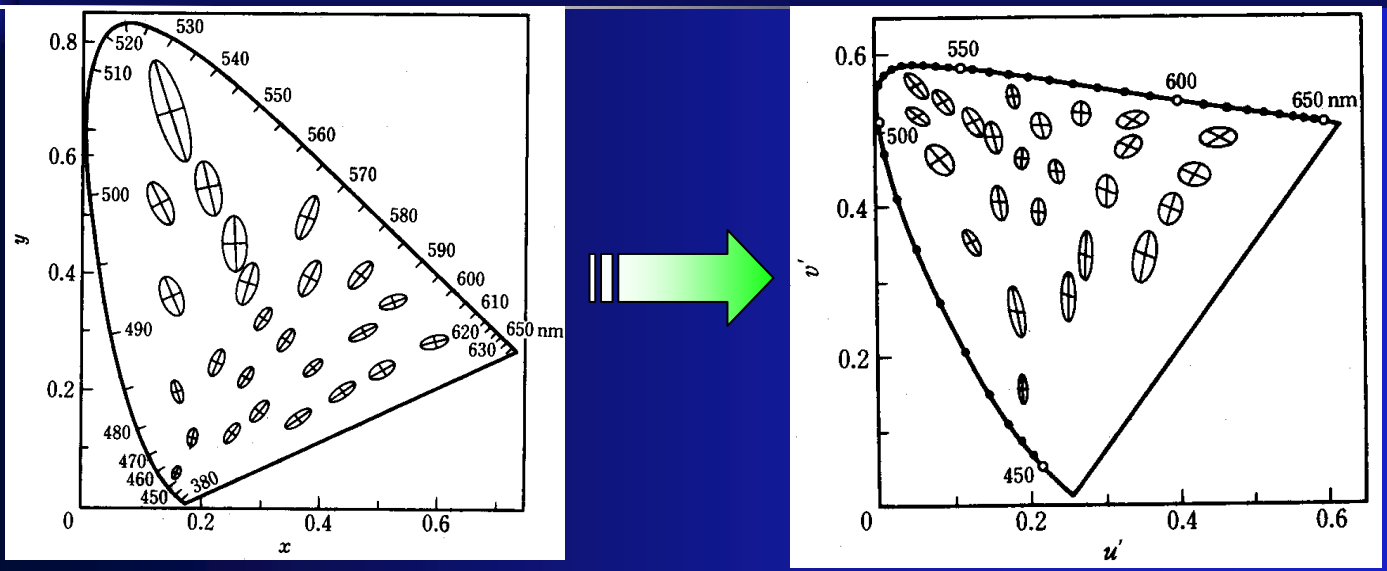
1. 標準照明體/標準光源
   - 標準照明體A和標準光源A (CCT=2856K)
   - 標準照明體C和標準光源C (CCT=6774K)
   - 標準照明體D_{65}和常用光源D_{65} (CCT=6500K)

2. 輔助標準光/輔助標準光源
   - 輔助標準照明體B (CCT=6874K)
   - 輔助標準照明體D_{50}, D_{55}, D_{75} (CCT=5003,5503,7504K)

CIE標準照明體: CIE standard illuminant　　常用光源: daylight simulator

CIE標準光源: CIE standard source

均等色度圖: CIE u'v'色度圖



$$u' = \frac{4x}{-2x+12y+3} = \frac{4X}{X+15Y+3Z}$$

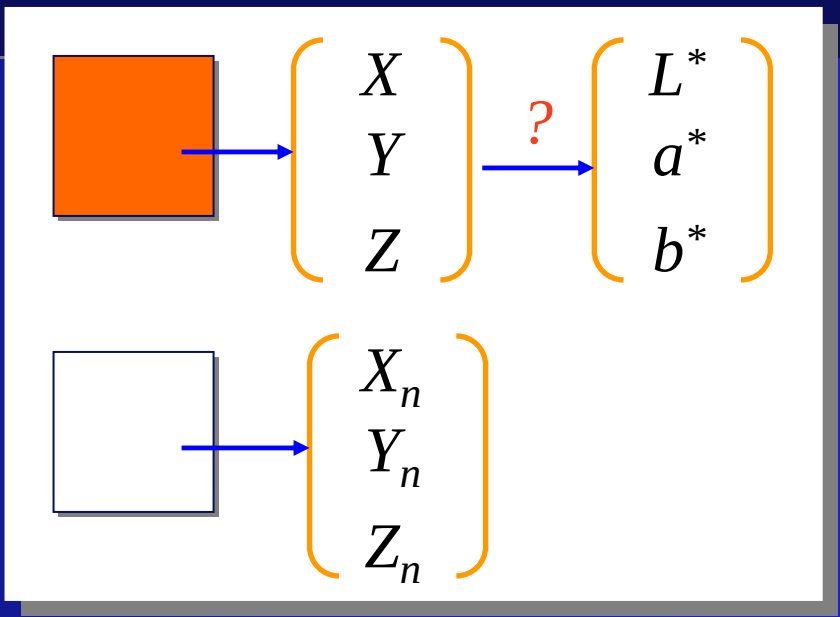
$$v' = \frac{9y}{-2x+12y+3} = \frac{9Y}{X+15Y+3Z}$$

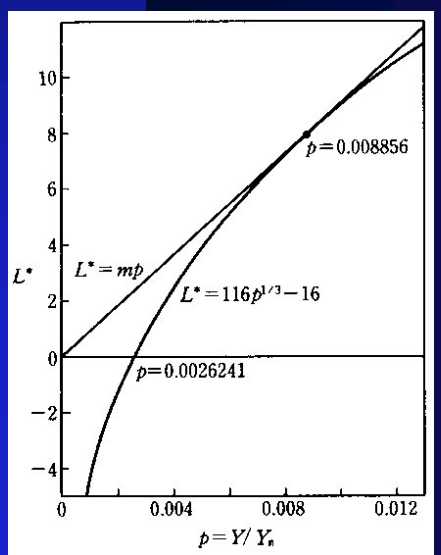
均等色彩空間: CIE*XYZ*→CIE*LAB*變換

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left\{ f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right\}$$

$$b^* = 200\left\{ f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right\}$$



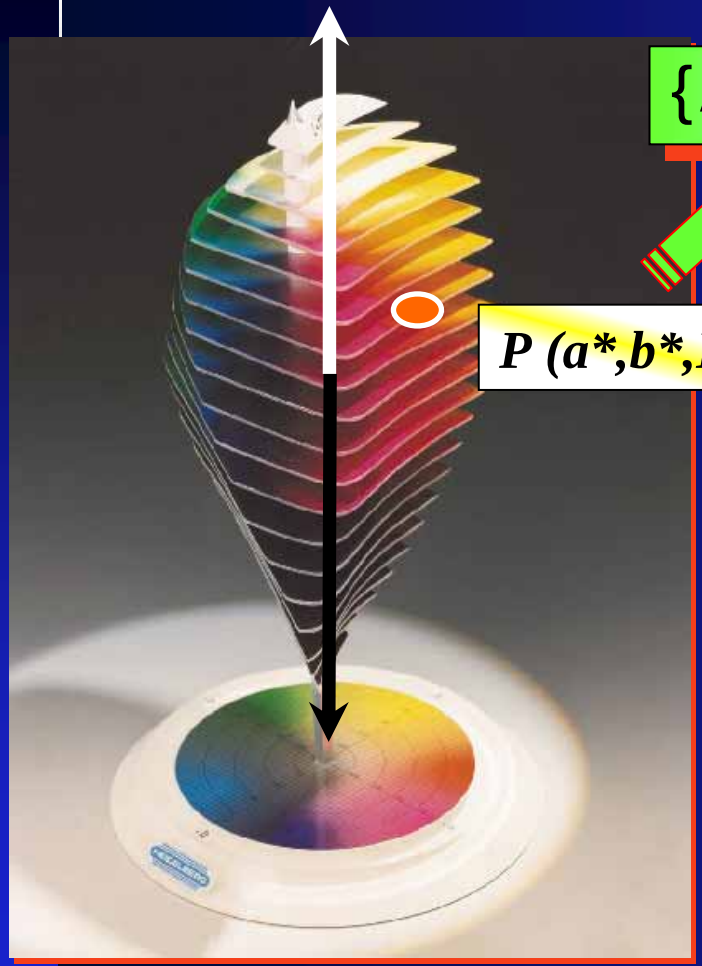


$$\begin{cases} f\left(\frac{I}{I_n}\right) = \left(\frac{I}{In}\right)^{1/3}, & \frac{I}{I_n} > 0.008856 \\ f\left(\frac{I}{I_n}\right) = 7.787\left(\frac{I}{I_n}\right) + \frac{16}{116}, & \frac{I}{I_n} \le 0.008856 \\ \textit{where} \quad f\left(\frac{I}{I_n}\right) \quad \textit{is} \quad f\left(\frac{X}{X_n}\right), f\left(\frac{Y}{Y_n}\right), f\left(\frac{Z}{Z_n}\right) \end{cases}$$

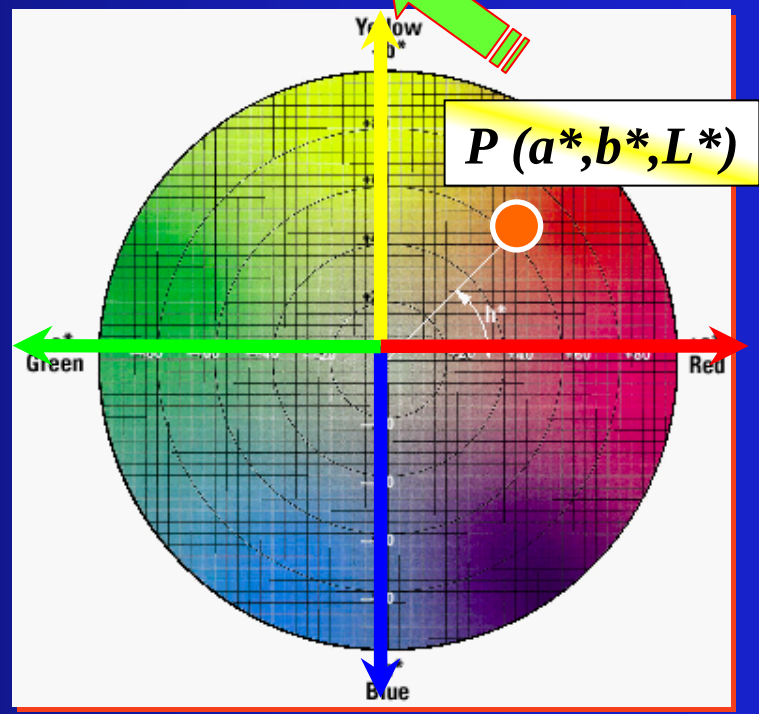
CIE LAB 均等色彩空間

$$h = \tan^{-1}\left(\frac{b^*}{a^*}\right), \quad C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2}$$

{*Hue, Lightness, Chroma*}

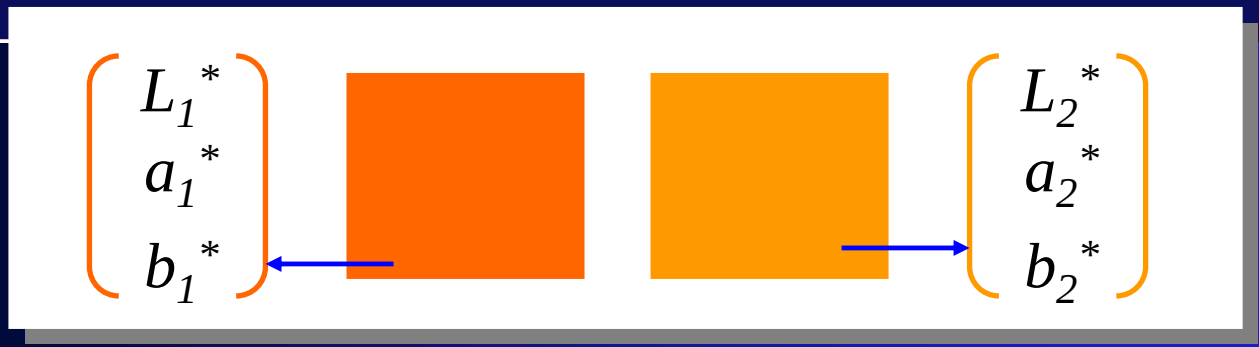


P (a*,b*,L*)



P (a*,b*,L*)

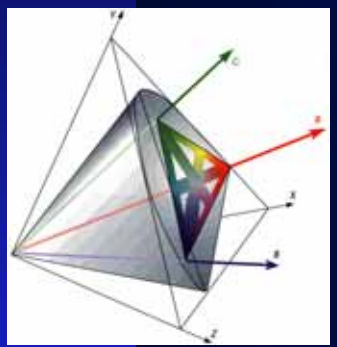
色差ΔE_{ab}^{*} (1976)



$$\Delta E_{ab}^{*}=\left\{\left(\Delta L^{*}\right)^{2}+\left(\Delta a^{*}\right)^{2}+\left(\Delta b^{*}\right)^{2}\right\}^{1/2}$$

$$\begin{cases}\Delta L^{*}=L_1^{*}-L_2^{*}\\ \Delta a^{*}=a_1^{*}-a_2^{*}\\ \Delta b^{*}=b_1^{*}-b_2^{*}\end{cases}$$

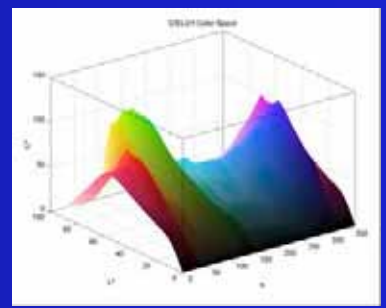
顯示器色彩工程
~ Part 2 色度學在顯示器上的應用 ~



世新大學 資訊管理學系

助理教授 陳鴻興

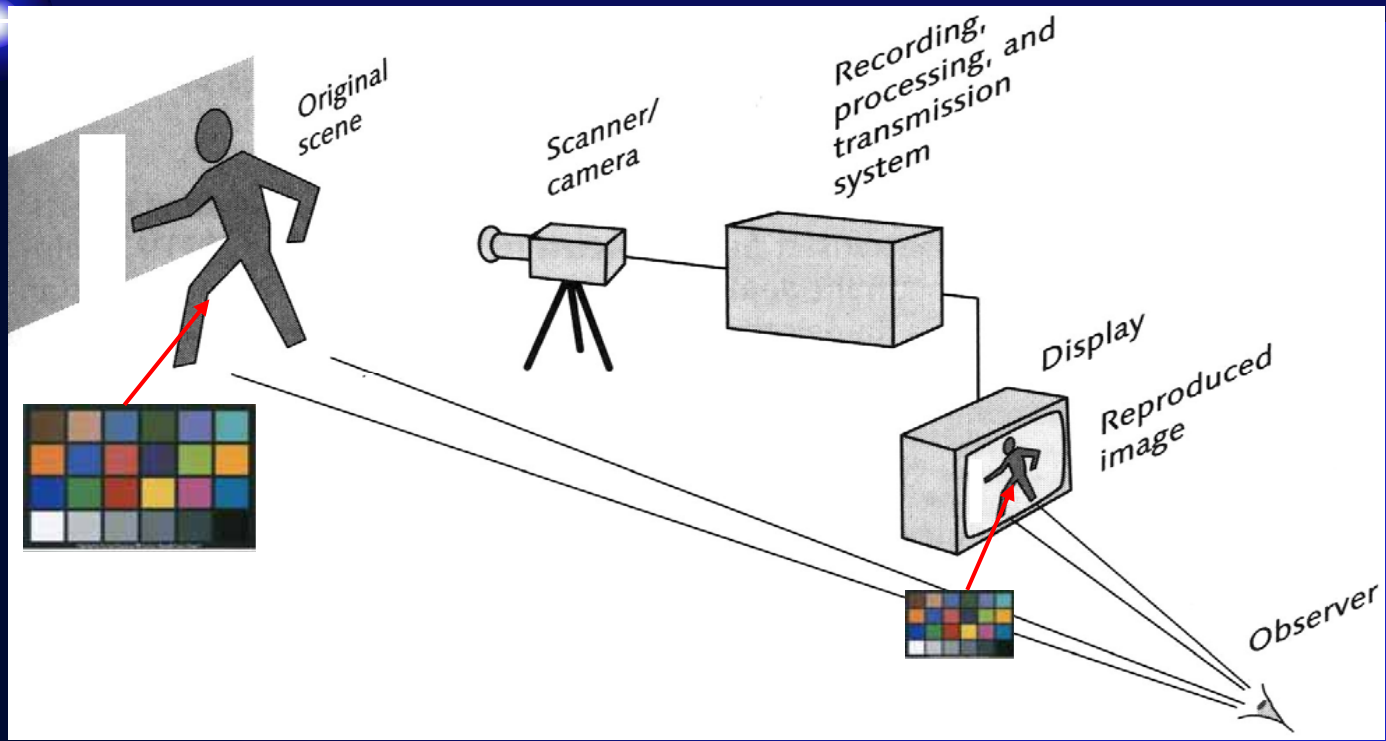
2005/October/26



http://cc.shu.edu.tw/~bridge/color_speech

E-mail: bridge@cc.shu.edu.tw

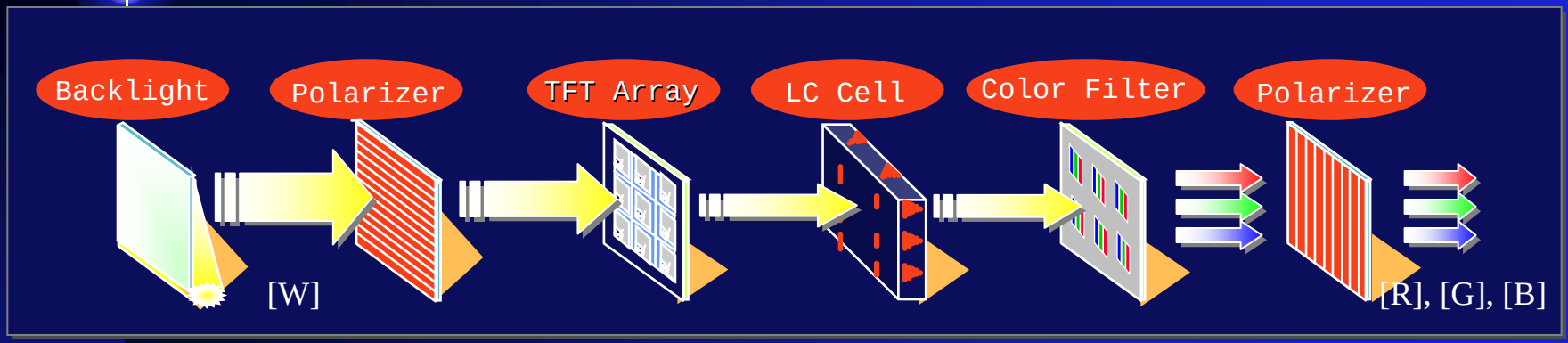
視訊系統的構成



- In video, luminance from the scene in transformed by the function similar to square root into a nonlinear (Optoelectronic conversion function) .
- The nonlinear signal is transformed back to luminance at the display. In CRT, a 2.5-power function is intrinsic (Optoelectronic transfer function).

加法混色設備的色彩描述

以LCD系統內部元件為例



Panel Tr η = η_T x η_P x η_{CF} x η_{ITO} x η_{LC}

其中 η ：Panel 透過率 (4.9~9%)

η_T ：TFT畫素開口率 (48~80%)

η_P ：偏光板的透光率 (~ 38%)

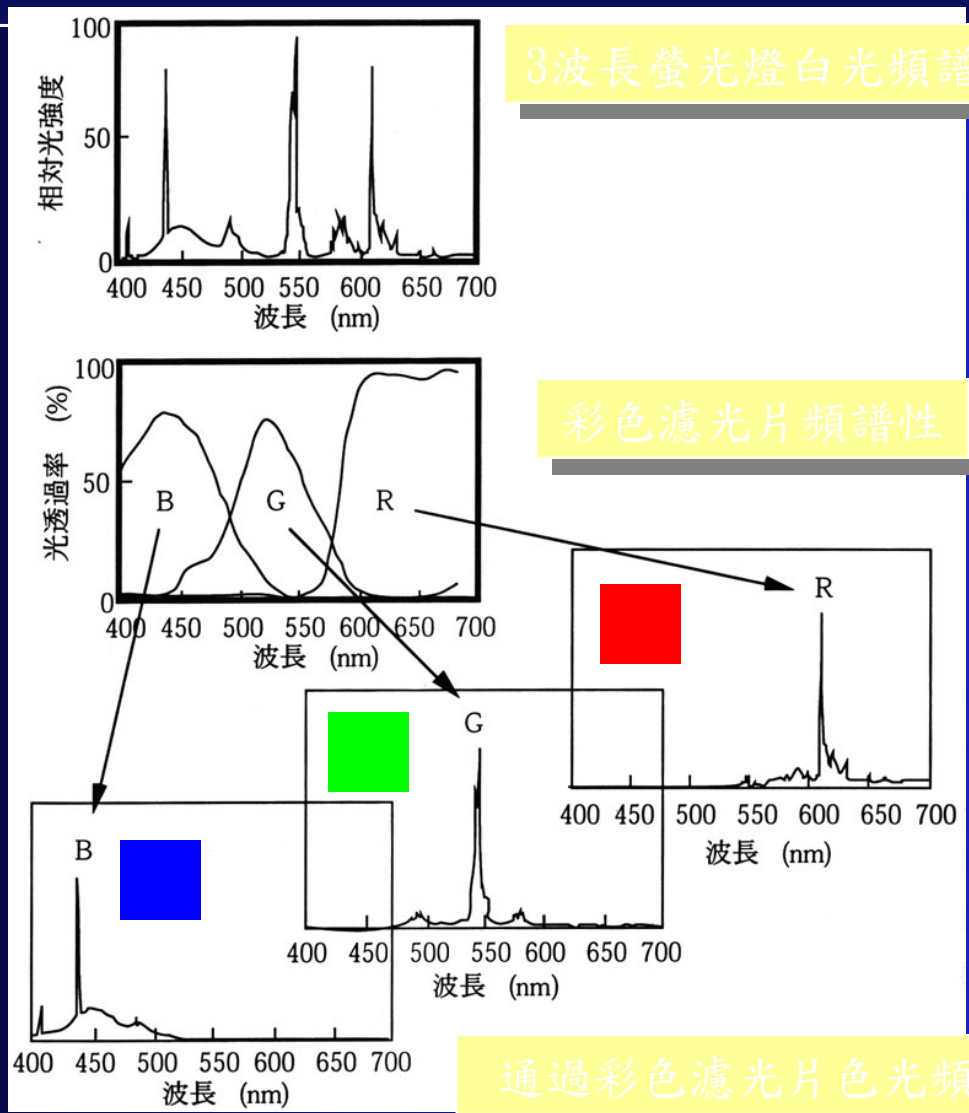
η_{CF} : Color Filter 的透光率 (26~38%)

η_{ITO} : ITO 的透光率 (~ 95%)

η_{LC} ：液晶材料的透光率 (~ 100%)

加法混色設備的色彩描述(cont')

以LCD系統內部元件頻譜為例

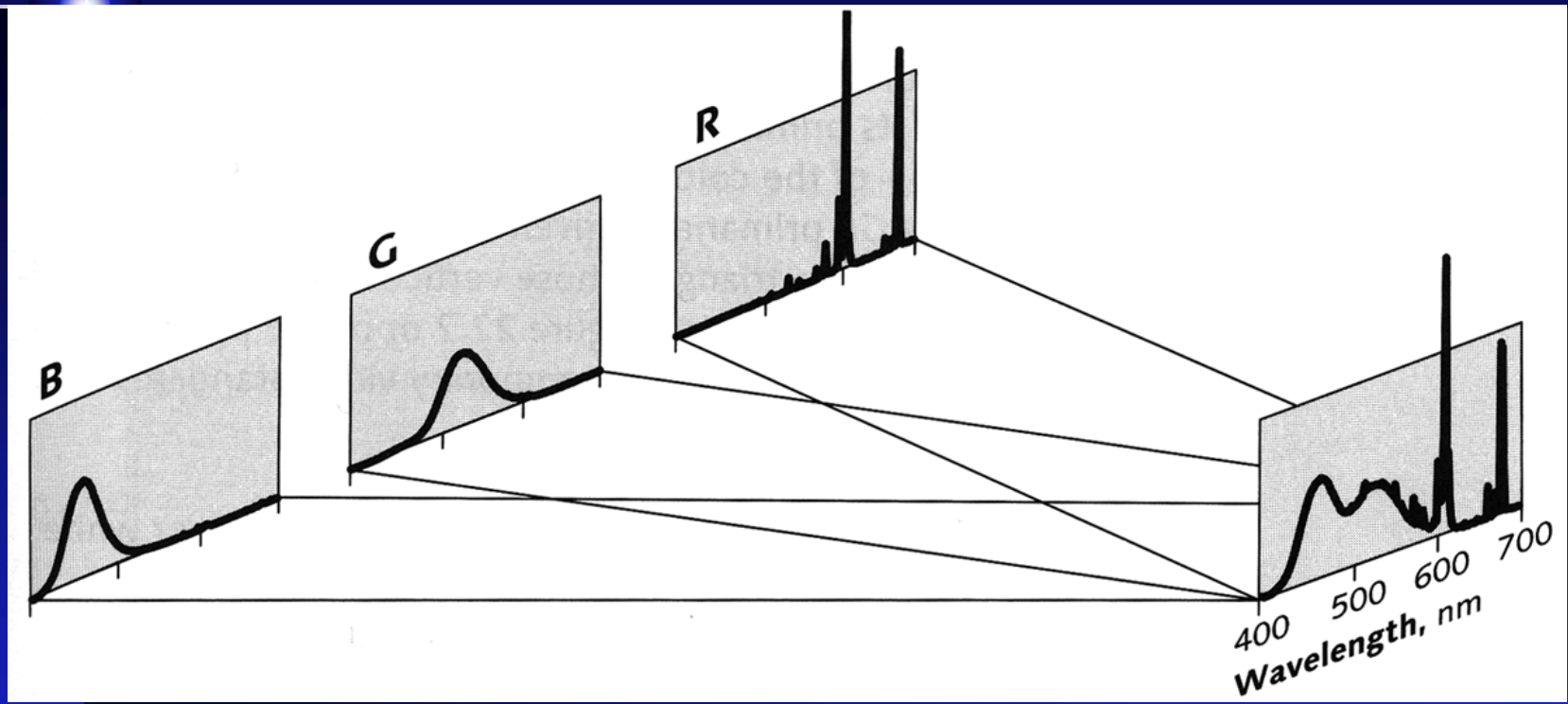


3波長螢光燈白光頻譜

彩色濾光片頻譜性

通過彩色濾光片色光頻譜

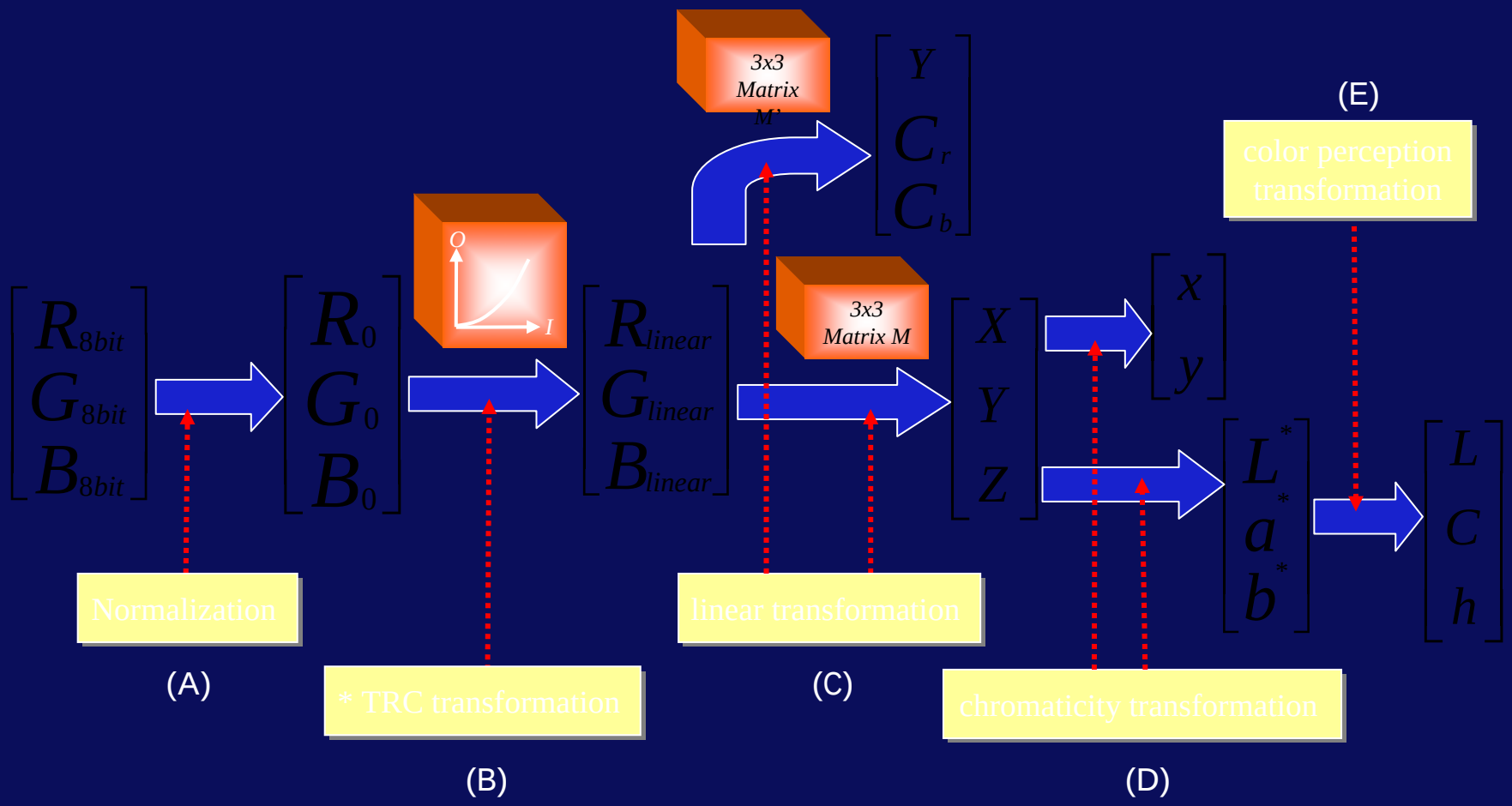
加法混色複製



Additive reproduction

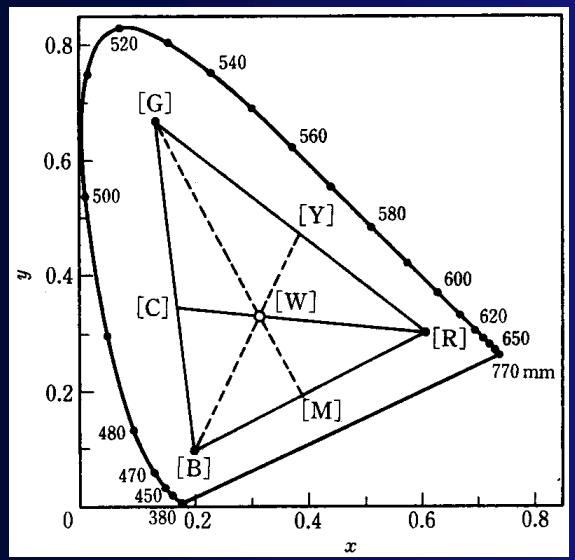
- The colors of the mixtures are determined by the colors of the primaries.
- Each primaries has independent, direct path to the image.

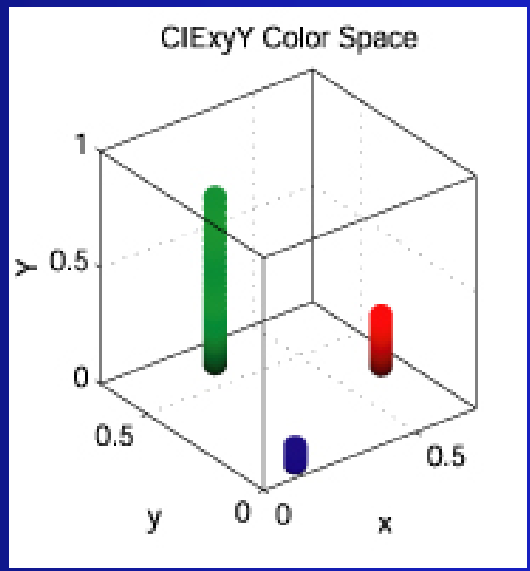
顯示系統色彩變換流程


3x3
Matrix
M'
Y
C_r
C_b
(E)
color perception
transformation
O
I
3x3
Matrix M
R_{8bit}
G_{8bit}
B_{8bit}
R_0
G_0
B_0
R_{linear}
G_{linear}
B_{linear}
X
Y
Z
x
y
L^*
a^*
b^*
L
C
h
Normalization
(A)
* TRC transformation
(B)
linear transformation
(C)
chromaticity transformation
(D)
* TRC: Tone Reproduction curve

加法混色設備的色彩描述 (cont')

Digital Camera, Video Camera, Display, TV, Projector





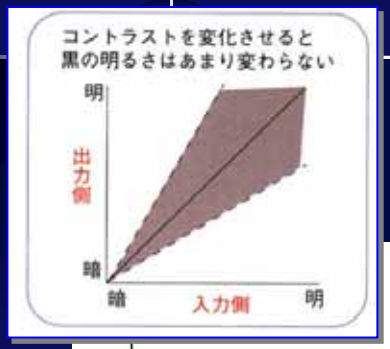
$$[F] = R[R] + G[G] + B[B]$$

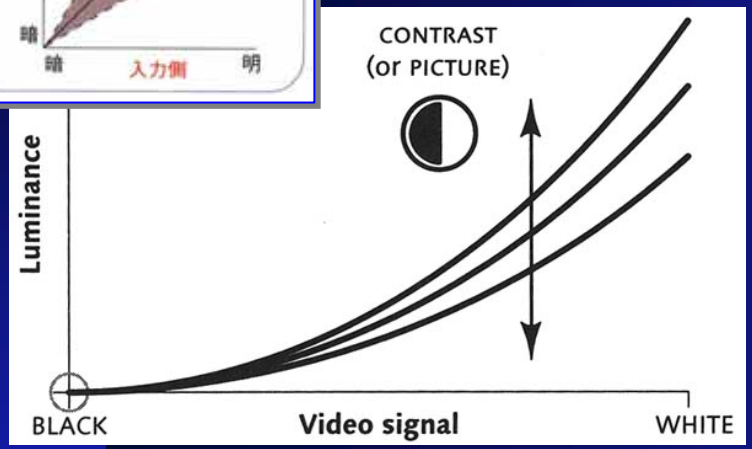
- [F]代表混合色光
- *R*,*G*,*B*代表[R],[G],[B]色光的混合量

各種螢幕規格原色色度值

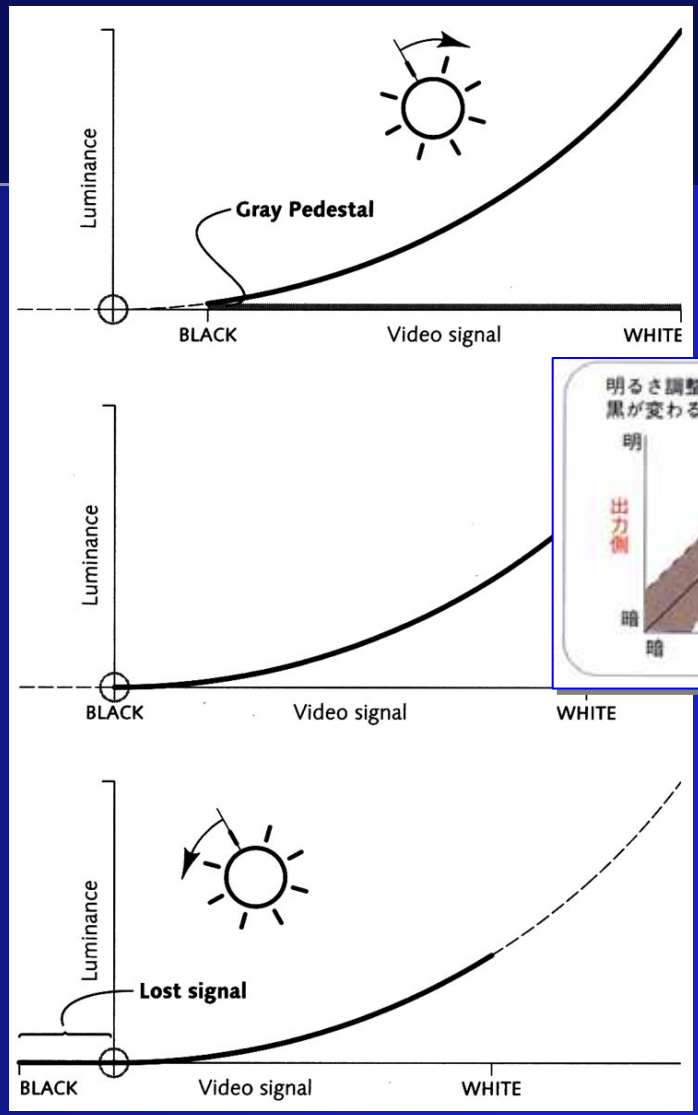
Specification		Red	Green	Blue	White		Area
NTSC	x y	0.670 0.330	0.210 0.710	0.14 0.08	C	0.310 0.316	U.S.A, Japan, Taiwan etc.
ITU-R BT.709-2	x y	0.640 0.330	0.300 0.600	0.150 0.060	D_{65}	0.3127 0.3290	HDTV
EBU Tech.3213	x y	0.640 0.330	0.290 0.600	0.150 0.060	D_{65}	0.3127 0.3290	European
Sony P 22	x y	0.625 0.340	0.280 0.605	0.155 0.070	D_{93}	0.2831 0.2971	(Japan,Sony)

對比調整與明暗調整



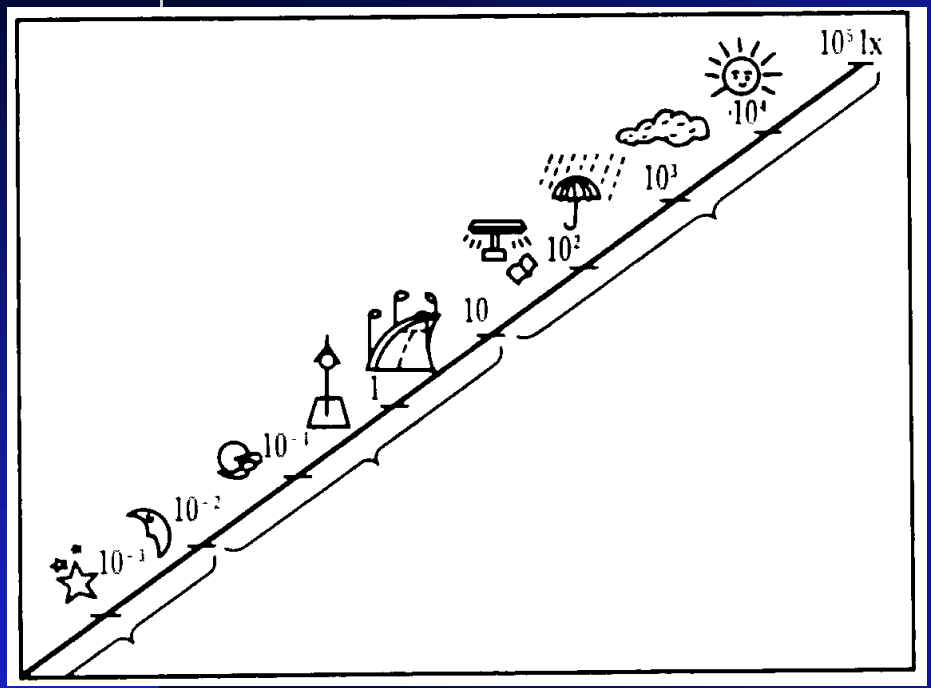


Contrast Adjustment



Brightness Adjustment

動態範圍(dynamic range)



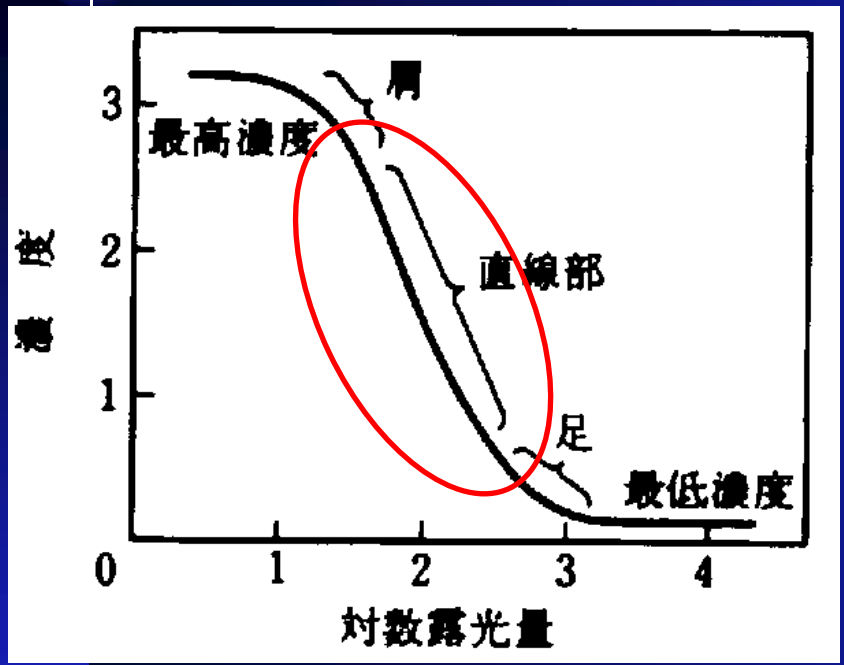
照度目測基準(日本照明學會,1967)

動態範圍$R=P_{max}/P_{min}$

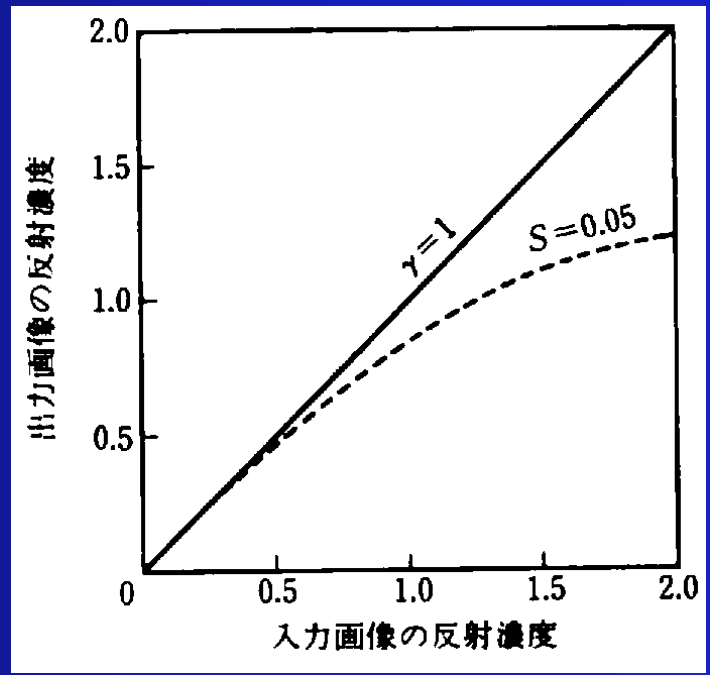
對數動態範圍$\log R=\log(P_{max}/P_{min})$

變數P可以是照度,輝度等型態

表面反射對動態範圍的影響 (for hardcopy)



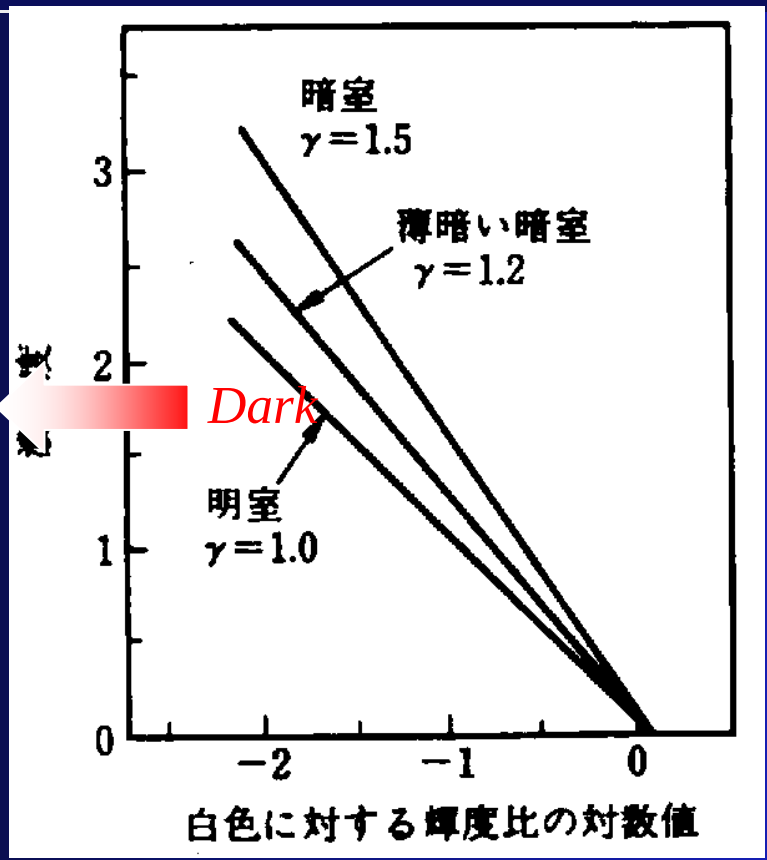
典型的照相特性曲線



表面反射導致相似的反射濃度下降

- 表面反射將導致反射濃度的下降,使動態範圍變窄

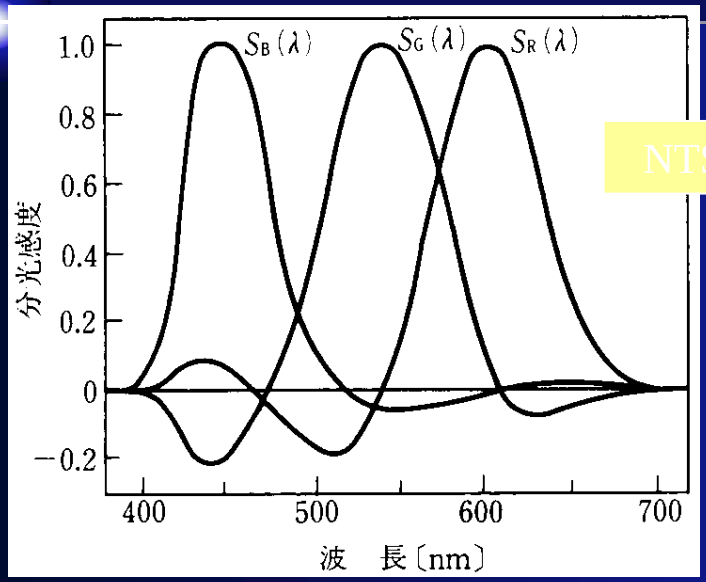
環境明暗對動態範圍的影響 (for softcopy)



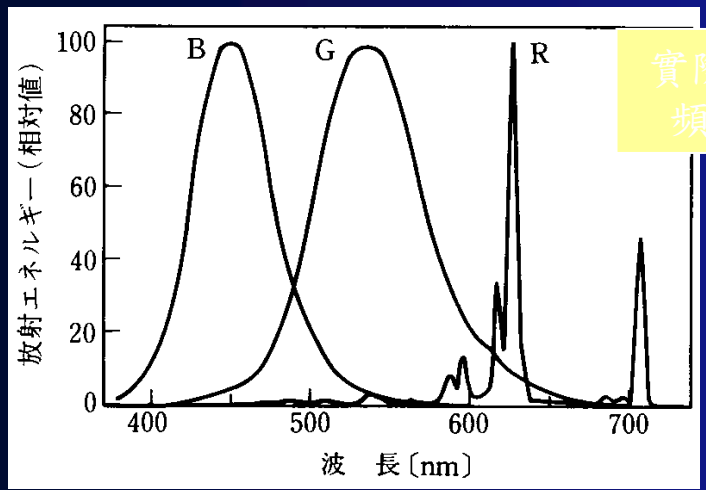
Light ← → Dark

- γ值與環境明暗的關係

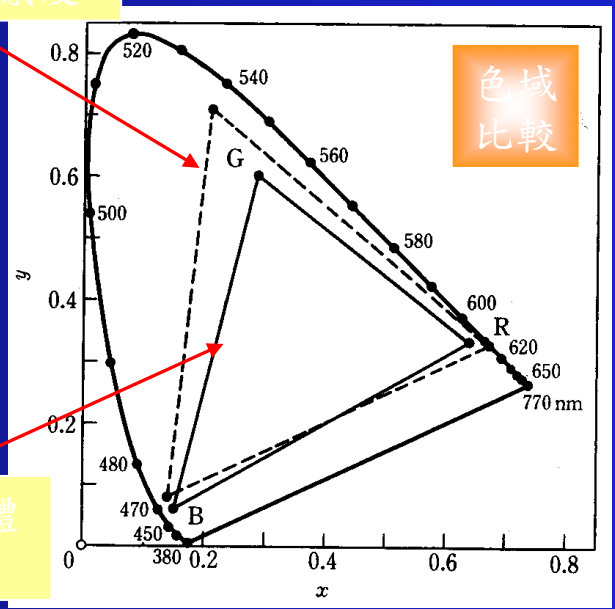
電視螢光體頻譜感度特性



NTSC頻譜感度



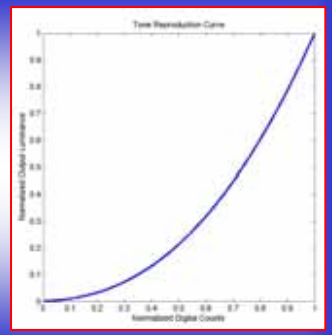
實際螢光體
頻譜感度



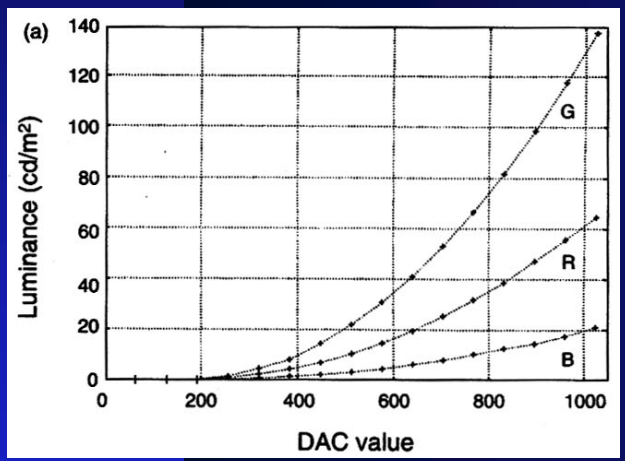
顯示器階調特性

sRGB display TRC
(as a reference)

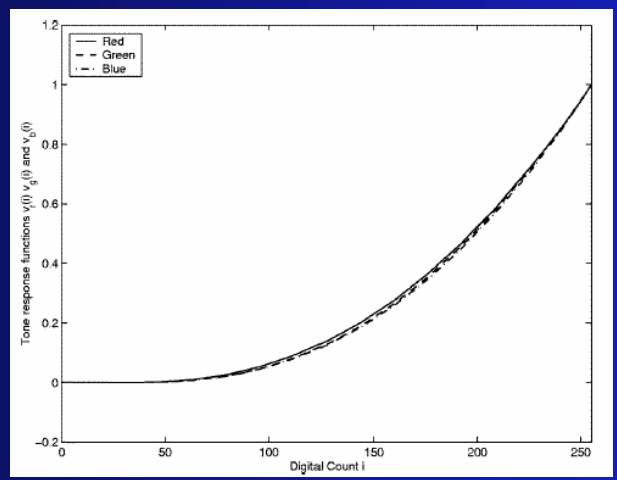
$Y=X^{2.2}$



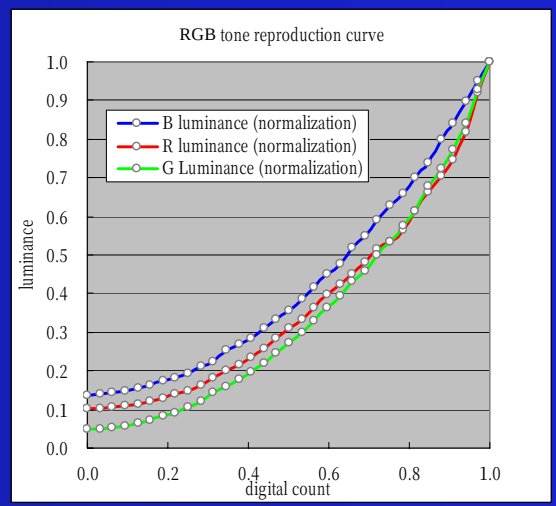
- 橫軸為Digital Counts (0~DC_{max})或Normalized Digital Counts (0~1)
- 縱軸為Luminance (0~Y_{max})或Normalized Luminance (0~1)



CRT階調複製曲線(1)



CRT階調複製曲線(2)



TFT-LCD階調複製曲線

色彩校正技術：黑色浮底校正

黑色浮底(black flare): 當輸入訊號為 (0,0,0)時，LCD 面板上原本應無任何色刺激發生，此時卻溢出少許色刺激的現象

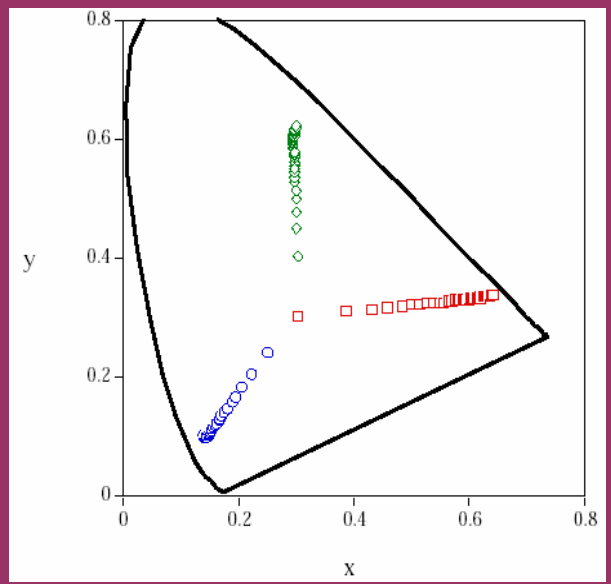
對LCD進行黑色浮底修正，可以將LCD的色彩再現校正到較符合加法混色的情形，其修正模式表示如下：

$$\begin{bmatrix} X_{pixel} \\ Y_{pixel} \\ Z_{pixel} \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix} + \begin{bmatrix} X_{bk} \\ Y_{bk} \\ Z_{bk} \end{bmatrix}$$

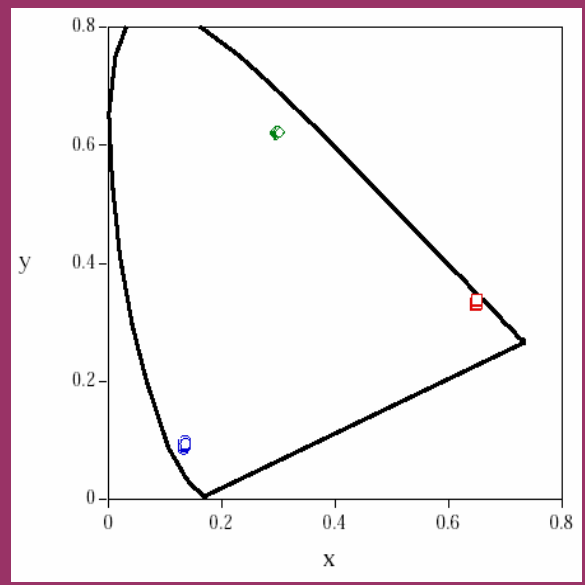
$X_{pixel}, Y_{pixel}, Z_{pixel}$	各畫素之三刺激值
X_i, Y_i, Z_i (i =R,G,B)	R,G,B最大值之三刺激值
r,g,b	三原色訊號比例量
X_{bk}, Y_{bk}, Z_{bk}	黑色浮底三刺激值

色彩校正技術：黑色浮底校正 (cont')

經過黑色浮底後正後的LCD色度結果，大致可以達成色度恆常性



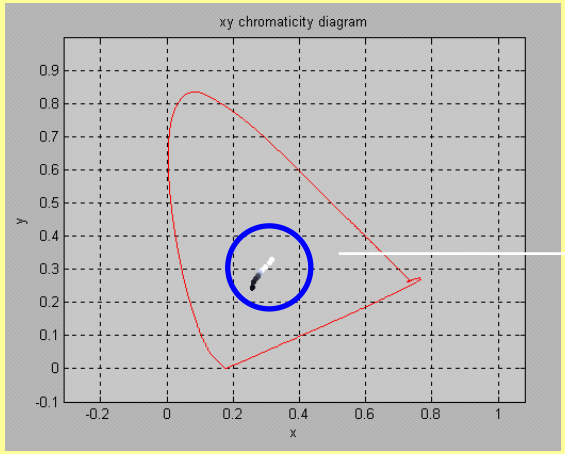
(a) 黑色浮底校正前



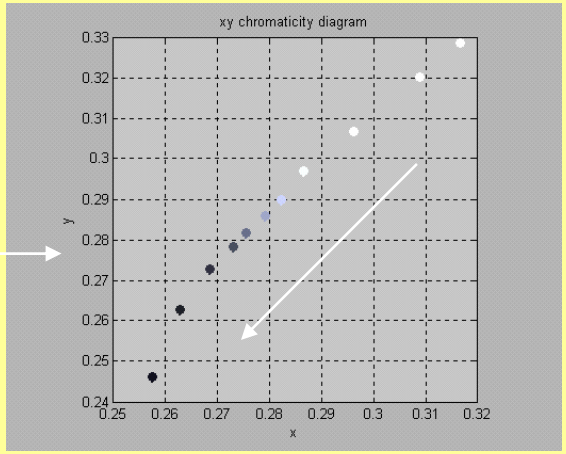
(b)黑色浮底校正後

色彩校正技術：灰色偏移校正

灰色偏移: 對於多數的LCD進行等比例灰階訊號的測量發現，當灰色訊號值由大到小變化呈現時，在CIE-xy色度圖上的表現並非固定的色度位置，而是呈現偏移之軌跡。



(a) CIE-xy色度圖上的表現結果



(b) 輸出訊號由大到小，色度點呈現之色溫逐漸由白色偏移到藍色

色彩校正技術：異色溫下照明之色外貌模擬

(a) A 光源

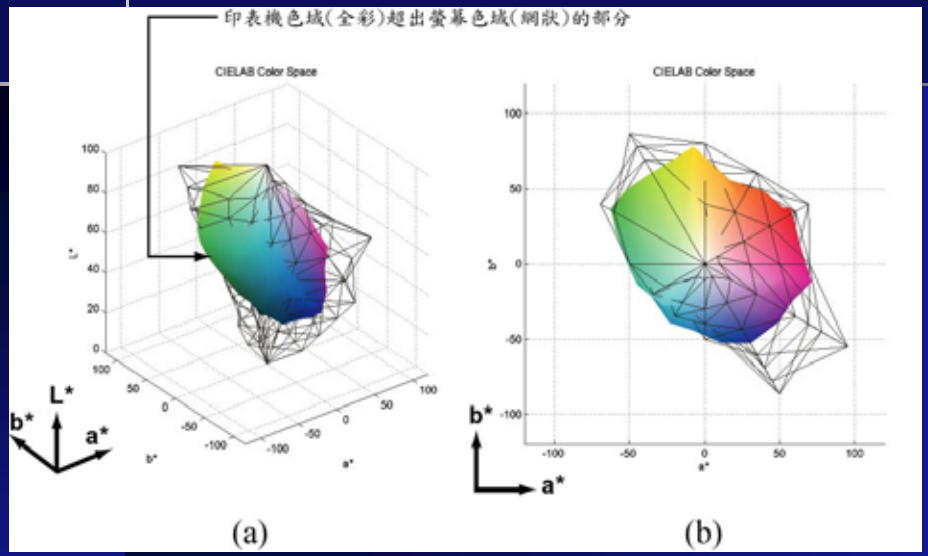
(b) 5,000K

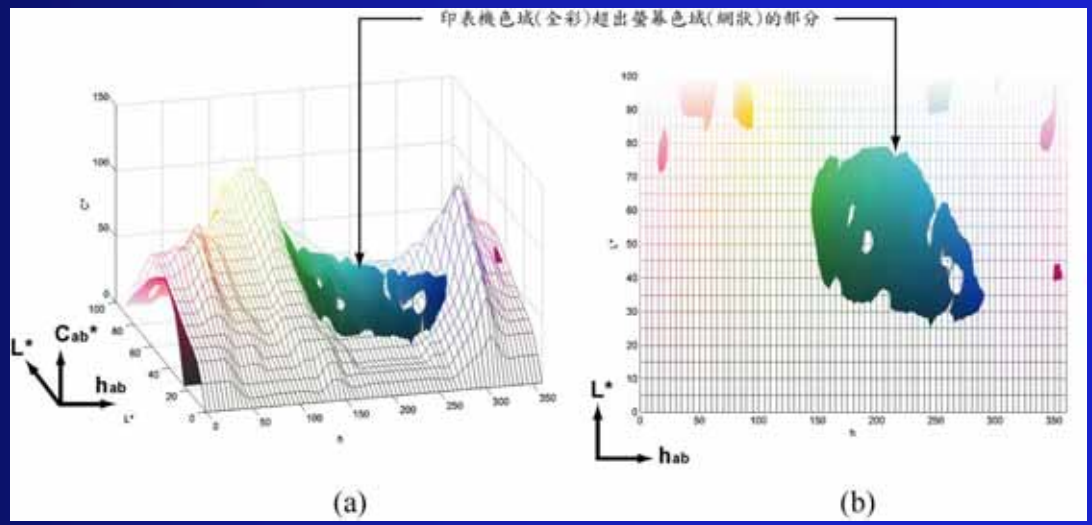
(c) 6,500K (Reference)

(d) 9,300K

- 方法1: 使用實際照明光源照射穿透於各畫素對應之彩色濾光片直接產生色刺激
- 方法2: 利用色彩對照表(RGB-XYZ)或轉換矩陣模擬變換各畫素色刺激值
- 方法3: 利用不同光源頻譜分布與各畫素色光頻譜積分作用,模擬變換各畫素色刺激值

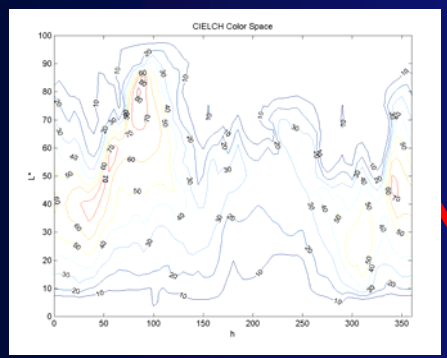
色域視覺化: 顯示器 v.s. 印表機

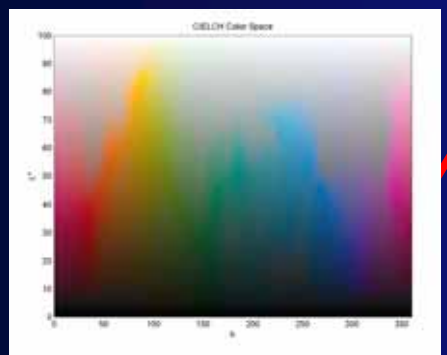


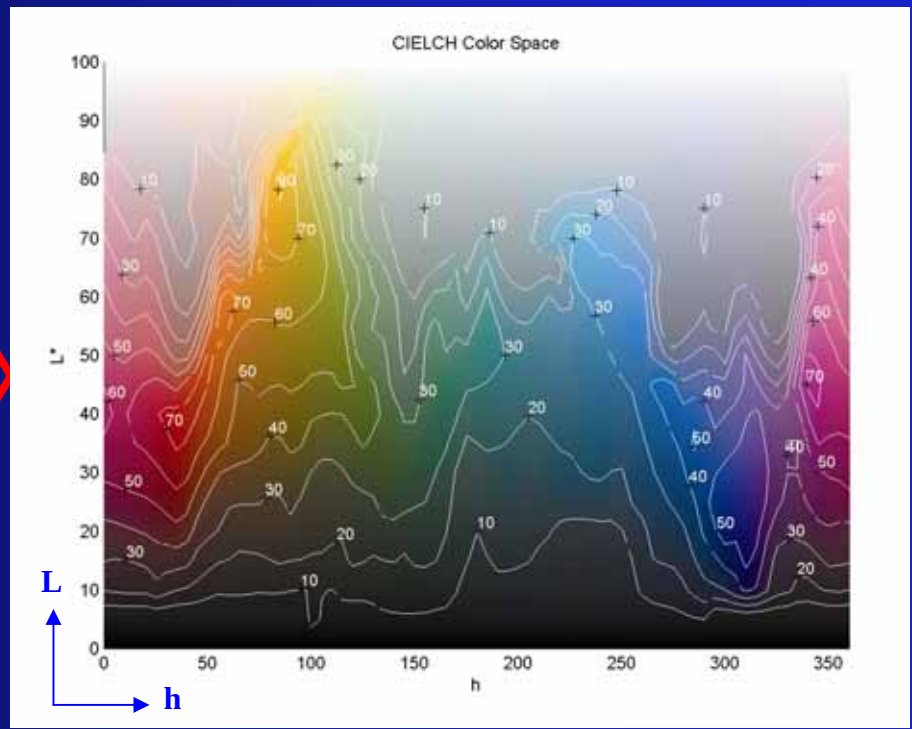


影像彩度等高線表示

二維L-h平面上,以彩度等高線與全彩資訊同時呈現數位影像色域的色相、明度、彩度資訊

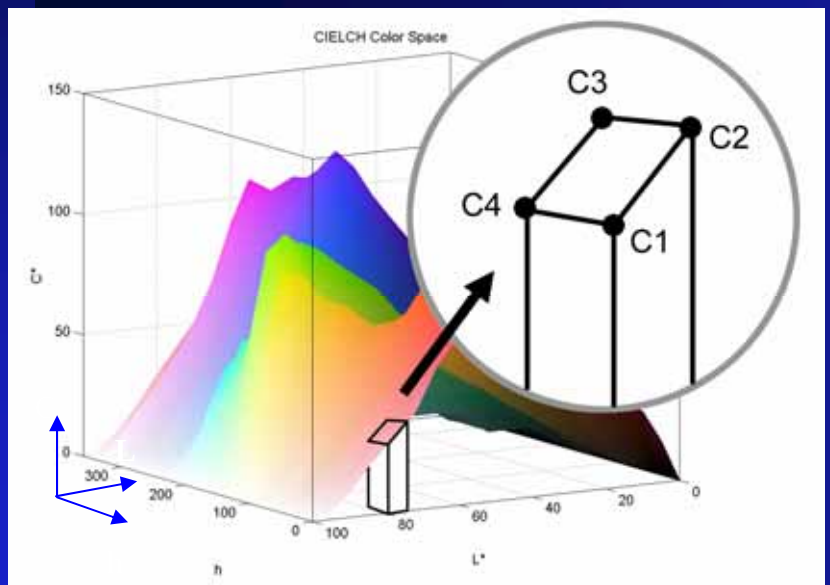






LCh色域體積計算

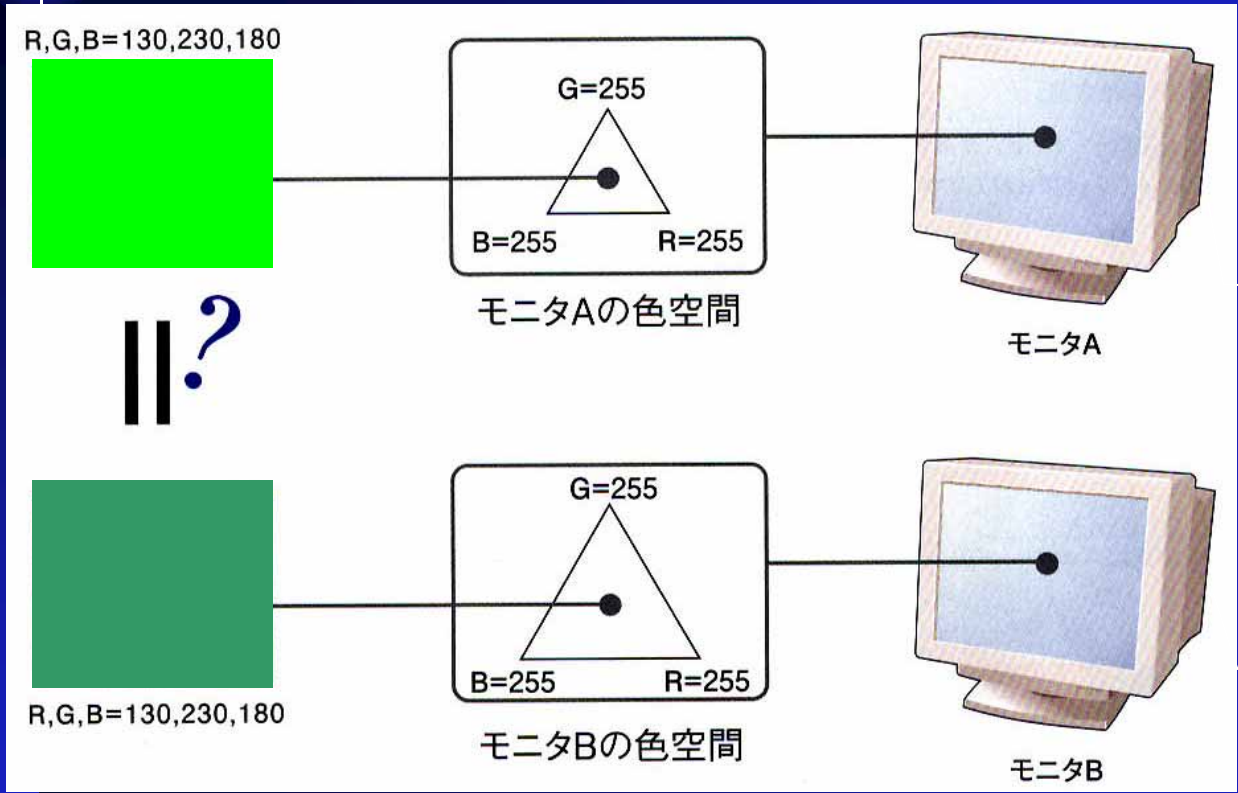
- 色域體積的功能：立即呈現色域大小實際差異，已進行多種色域大
- 色域體積的計算：利用LCh色域立體的彩度(高度)累積量



	色域體積
螢　　幕	**1,411,769**
印 表 機	**861,678**

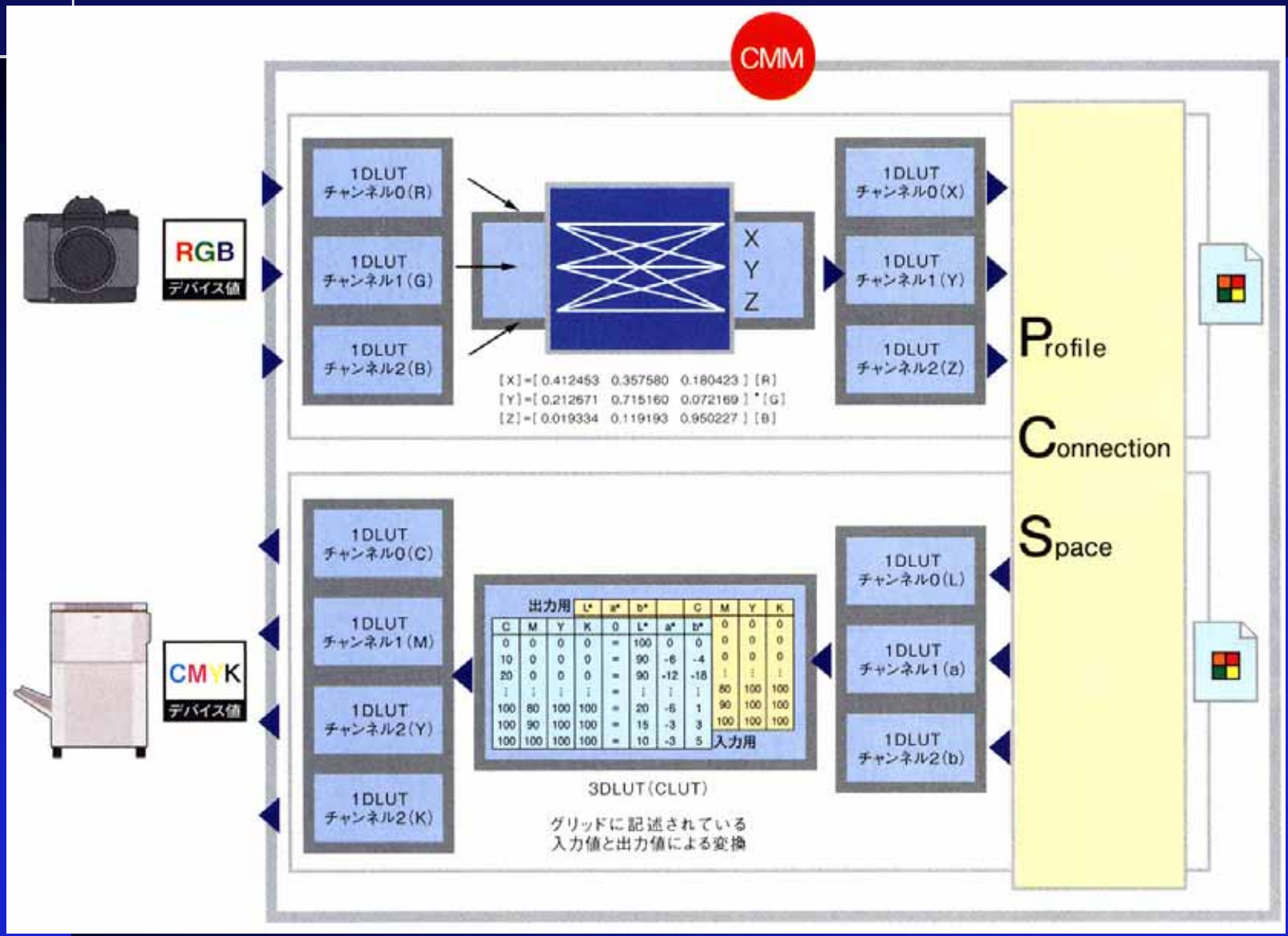
RGB色彩的設備依存性

Q : 同一種RGB彩色訊號為什麼在不同規格的顯示器上顯示的顏色不同?

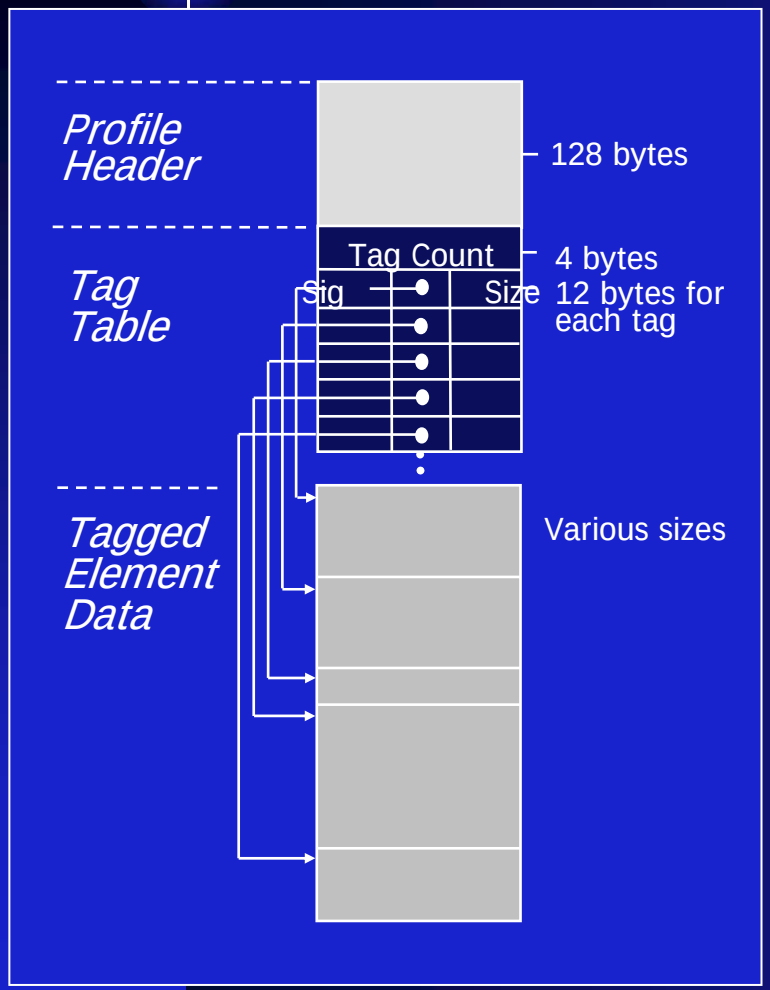


Q : RGB彩色訊號屬於一種設備依存色(device dependent color), 它會隨著設備的不同而改變色彩屬性.

ICC Profiles的計算方法



ICC Profiles 結構



ICC (International Color Consortium; 國際色彩聯盟)

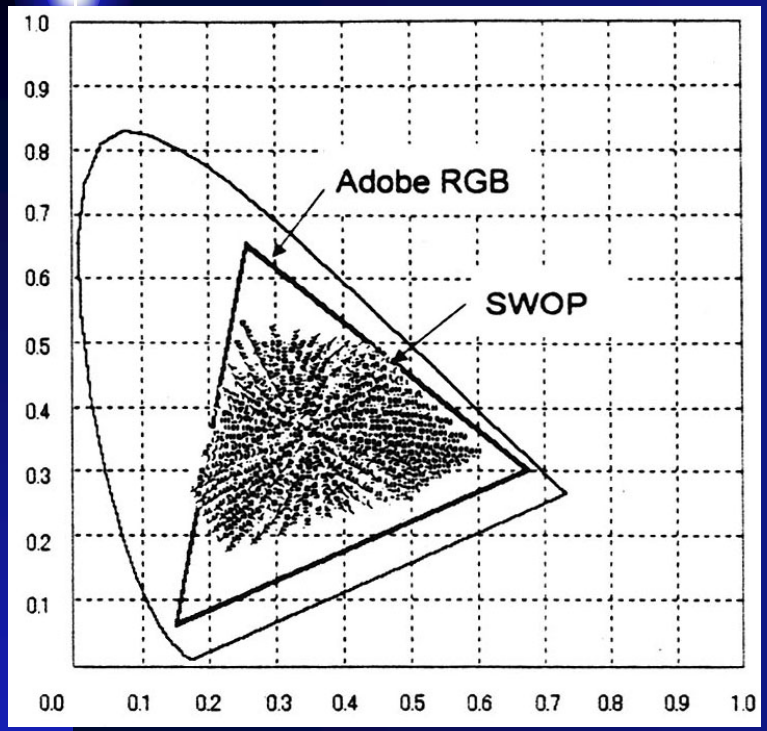
由8家廠商創立(1993年),發展推廣開放的跨媒體色彩管理系統架構

ICC Profiles於PC OS存放位置

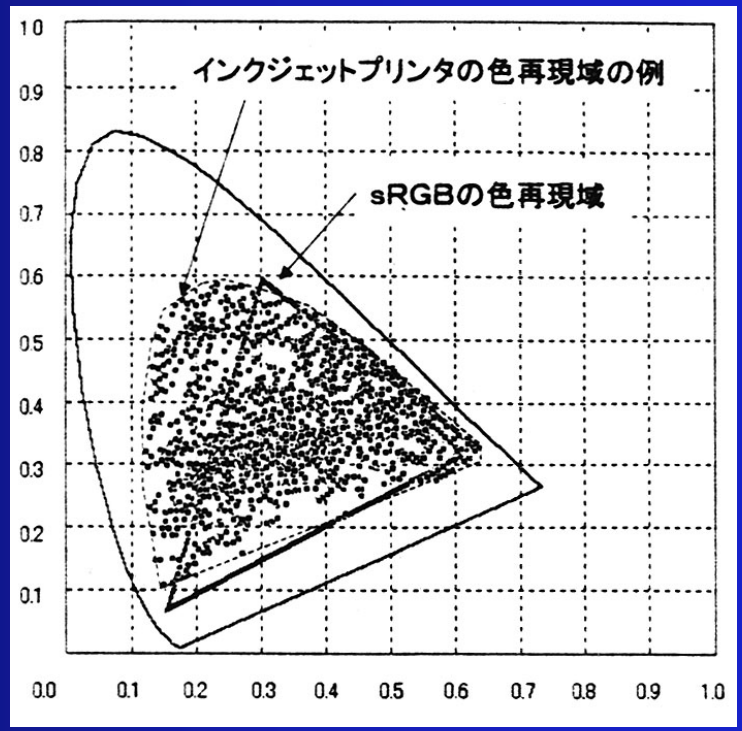
<Windows XP OS>
\windows\system32\spool\drivers\color*.icm

<Mac OS>
\library\colorsync\ColorSyns*.icc

媒體色域比較：softcopy v.s. hardcopy



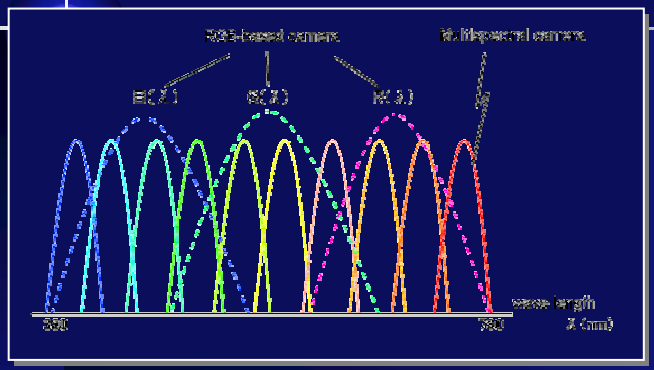
Adobe RGB v.s. SWOP



sRGB v.s. inkjet printer

Multi-spectral imaging system

Natural Vision Research Center (Japan, 2002~)
<http://www-akasaka.nict.go.jp/>



Concept : 3 color system
→ multi-spectral system

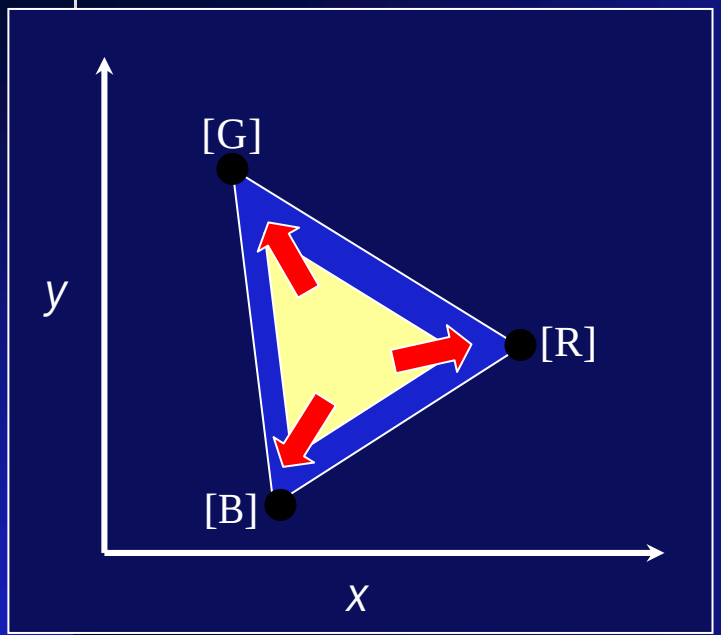
6 band multi-spectral HDTV camera
(for motion picture)

16 band multi-spectral camera
(for still picture)

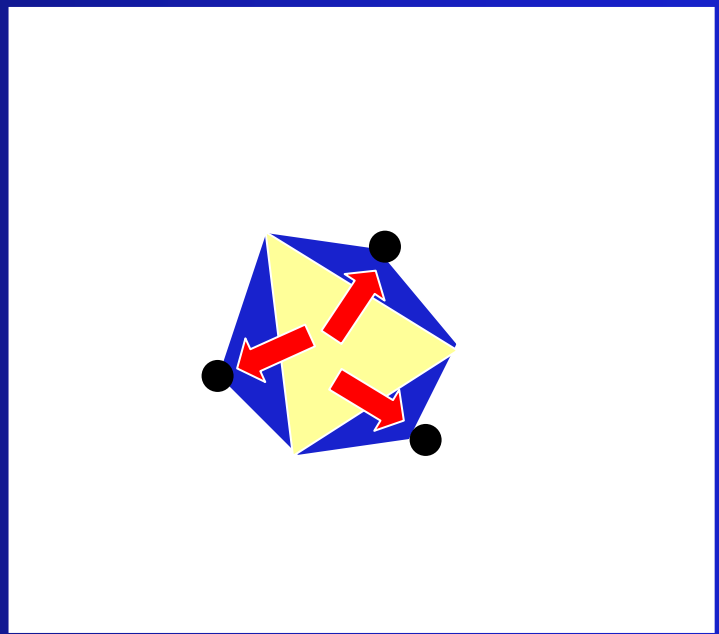
120 inch multi-primary display
(6 primary colors)

廣色域顯示技術的設計

1. 增大原色色度位置 (3原色 → 3原色)



2. 增加原色數目 (3原色 → 多原色)



<Multi-spectral imaging system>

- Multi-primary display
- Multi-spectral camera
- Multi-primary printer (Hi-Fi colors)

廣色域顯示技術的設計

2.

日系色LCD顯示器

日立製造所, Nature vision Project, Japan (2002)

図３　既存装置の色域（３色）

図４　試作装置の色域（４色）

図５　表示画面（自然画像）

図６　表示画面（４原色カラーパッチ）

廣色域顯示技術的設計

2.

LED光源＋入原色LCD顯示器

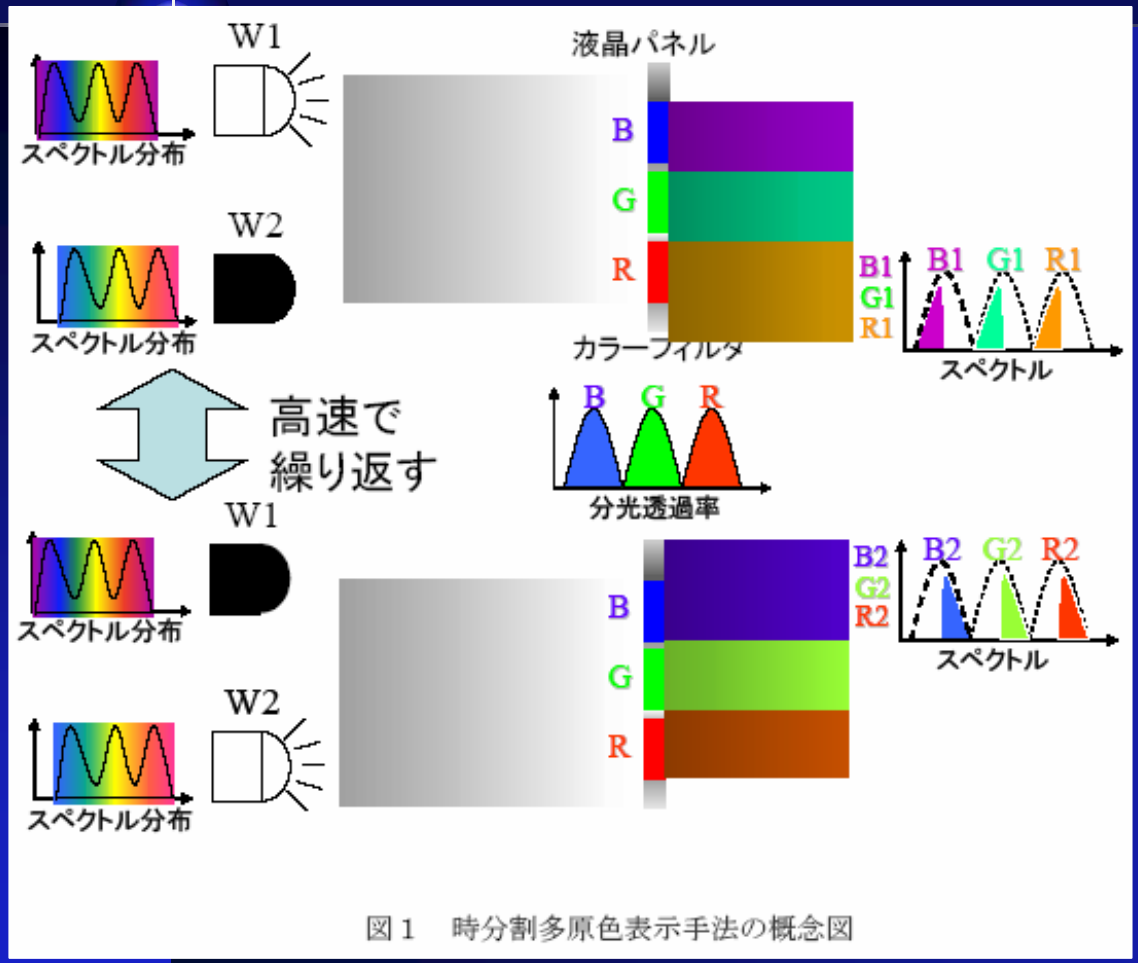


図１　時分割多原色表示手法の概念図

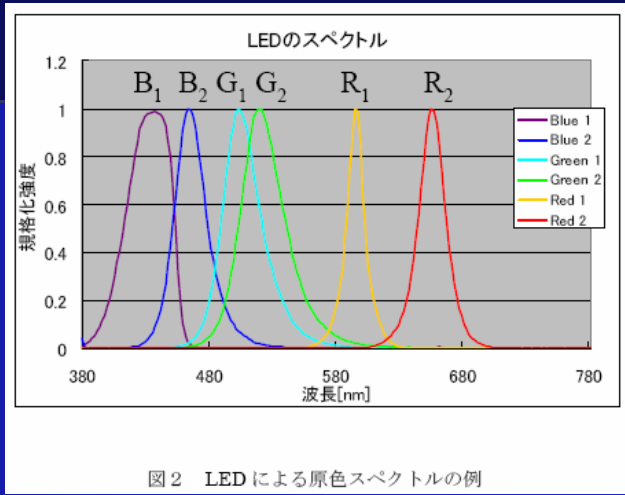


図２　LED による原色スペクトルの例

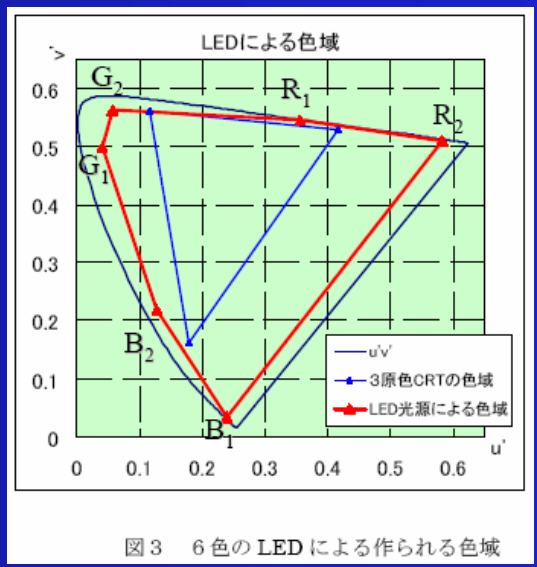
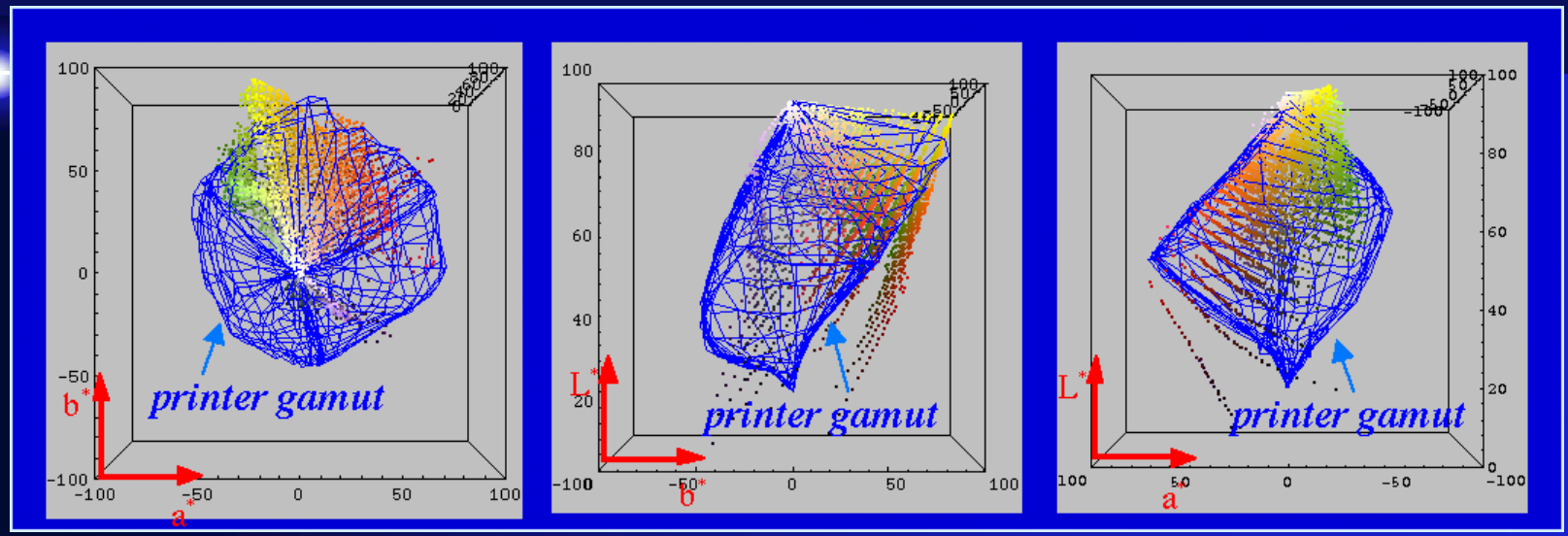


図３　６色の LED による作られる色域

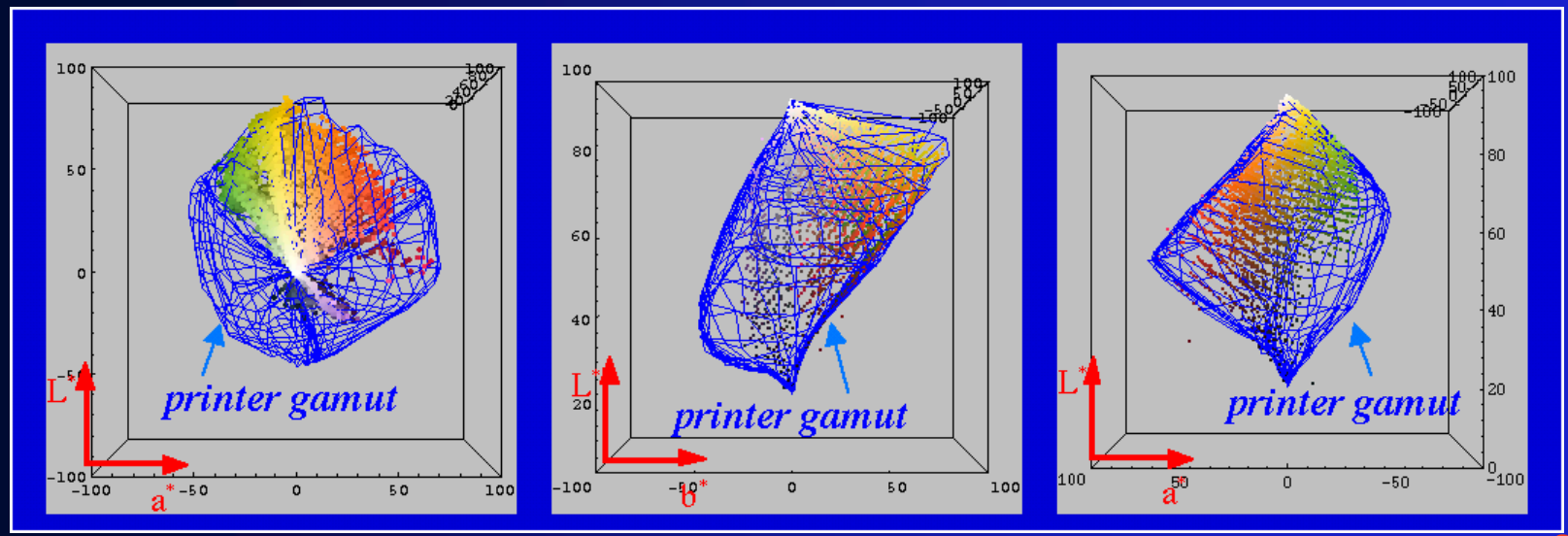
Nature vision Project, Japan (2002)

色域壓縮前後的影像色分布

Before mapping



After mapping



色域壓縮影像結果（2D v. s. 3D）

Original

2D Clipping

2D Image-to-Device

3D Single Focal

3D FLS

3D ILD 30 Focal points

- 3-D image-dependent Gamut Mapping Algorithms, including the processing of multi-focal points & nonlinear tone curve directly performed in CIE-LAB color spaces. (Chen & Kotera, 2000)

(備註: 以色域壓縮後的影像列印色為評量基準)

Conclusions

- 顯示器色彩工程的構成: 色度學(Colormetry),彩色複製學(Color Reproduction), 色彩管理(Color Management)
- 高畫質顯示器色彩技術:色彩訊號變換, 階調特性, 色彩校正, 色域視覺化, 跨媒體色彩管理(色域對映演算)
- 未來顯示器色彩技術: 廣色域色彩再現, 多原色(≥3)顯示器, 舒適的人性化顯示器觀賞環境

Thanks for your attention !!

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10. Color data website <http://www.cvrl.org>

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  平面顯示器、數位相機、彩色印表機相關影像與裝置之色彩分析、色彩校正與色彩管理