Break

- Thank you for not using your cell phones during the lectures.

- Brain rot: A condition of mental fogginess, lethargy, reduced attention span, and cognitive decline that results from an overabundance of screen time.

"It keeps me from looking at my phone every two seconds."

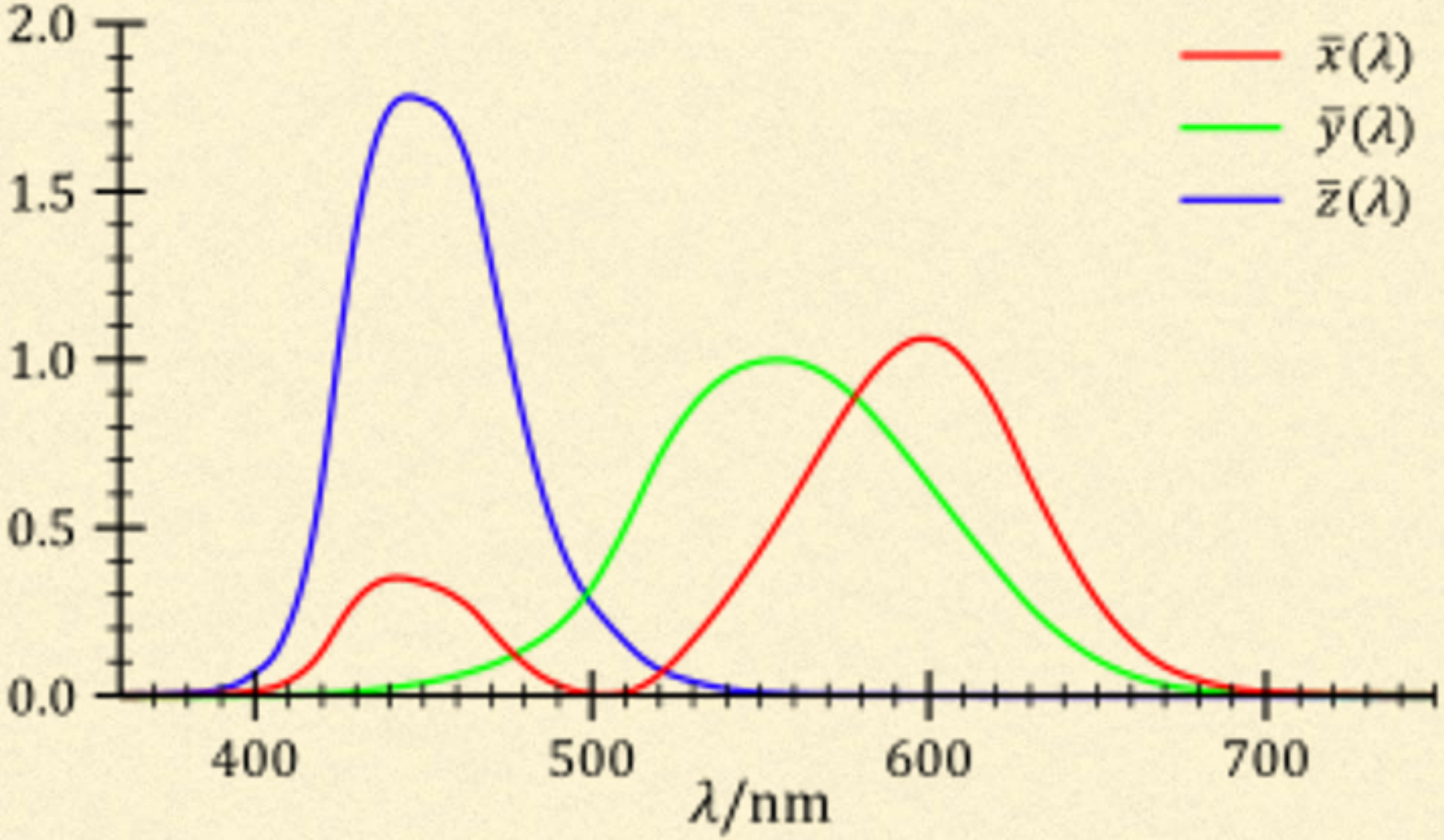
Liam Walsh/The New Yorker

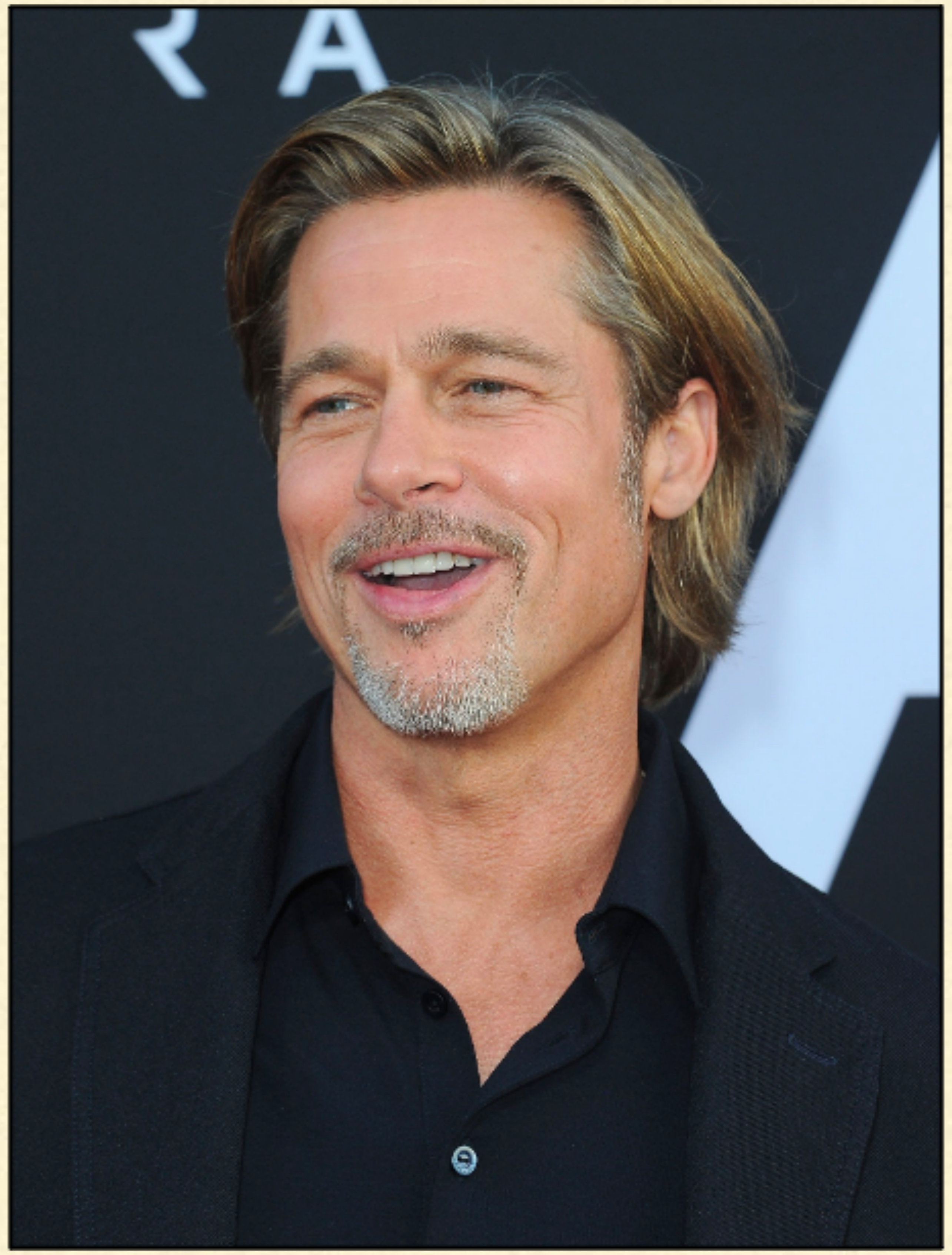
UNDERWATER COLORIMETRY

BASIC COLORIMETRY - II

Dr. Derya Akkaynak | dakkaynak@univ.haifa.ac.il

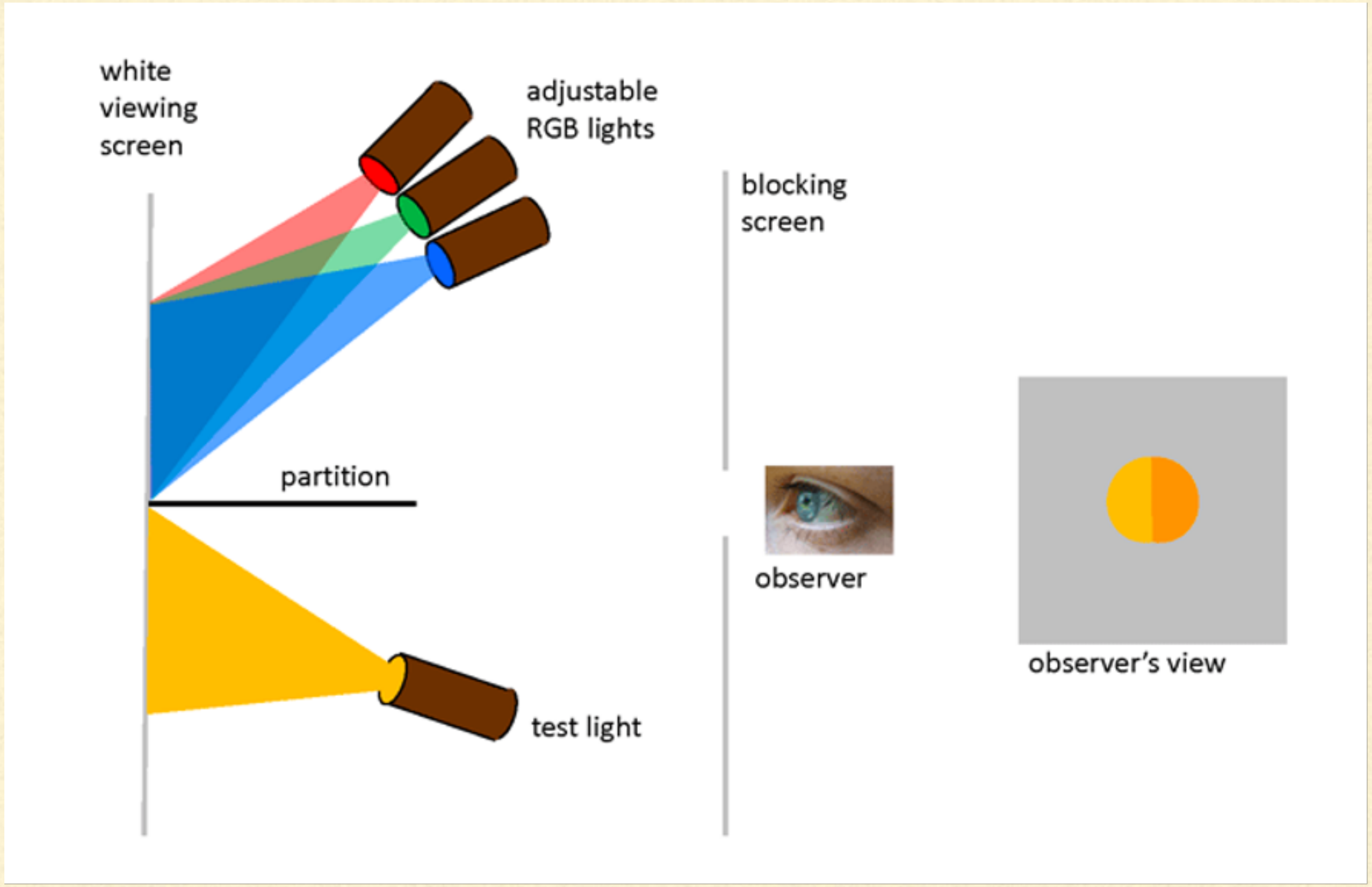
CIE 1931 STANDARD OBSERVER





Spectral sensitivity of a human with "normal" color vision

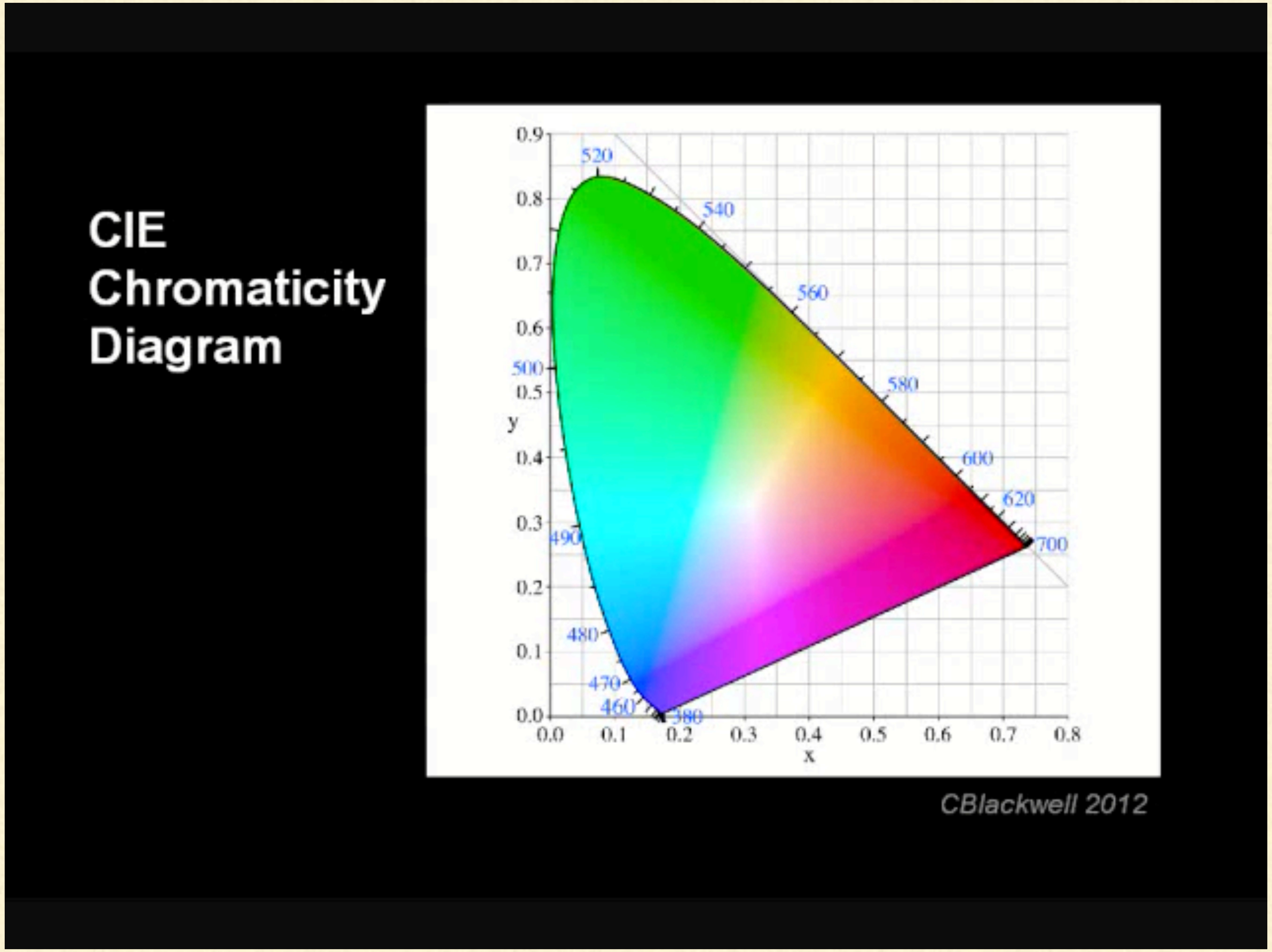
COLOR MATCHING EXPERIMENTS



Try for yourself!

https://rgbcmyk.com.ar/1931/

HOW WAS THE CIE 1931 STANDARD OBSERVER DERIVED?



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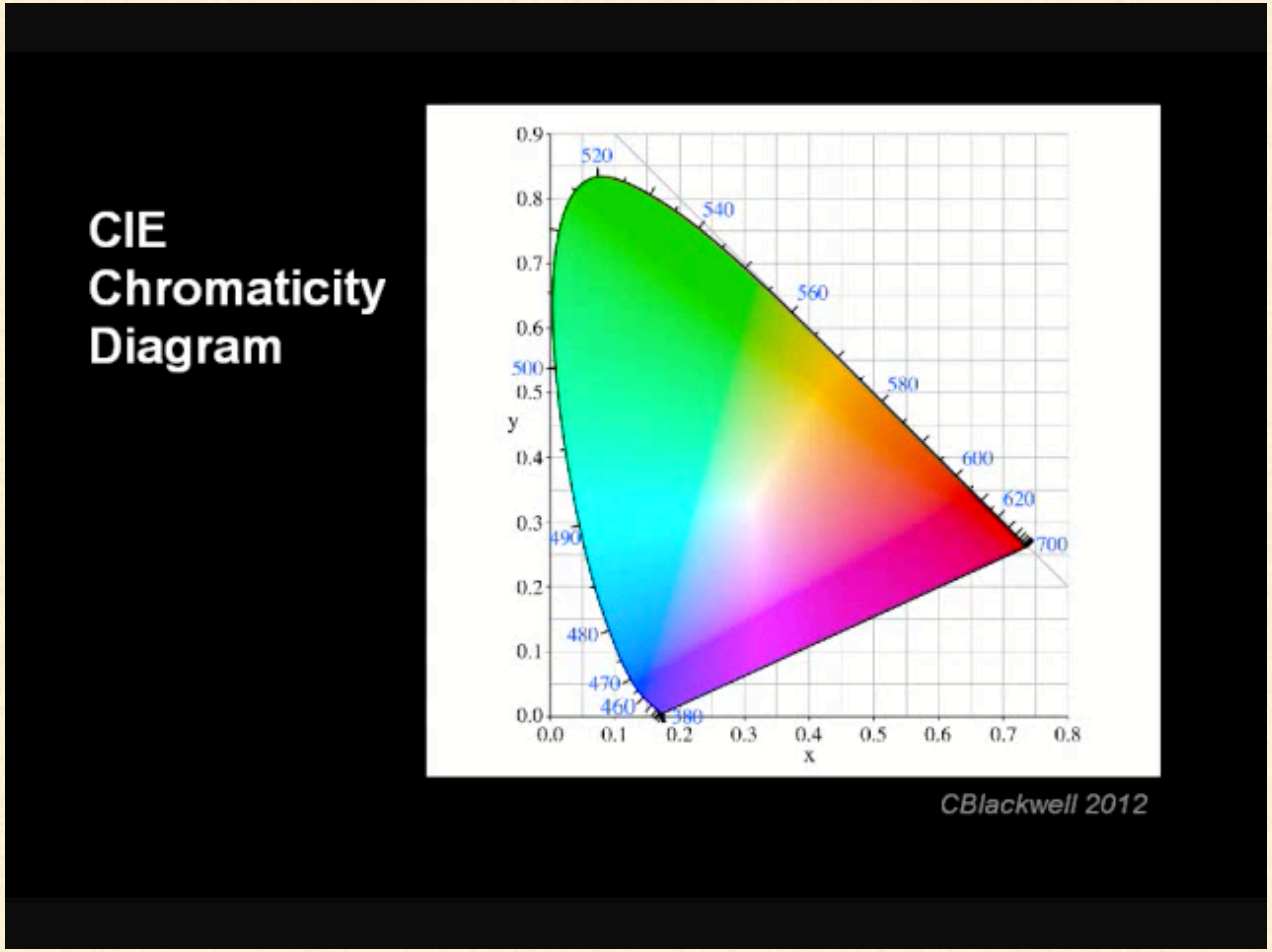

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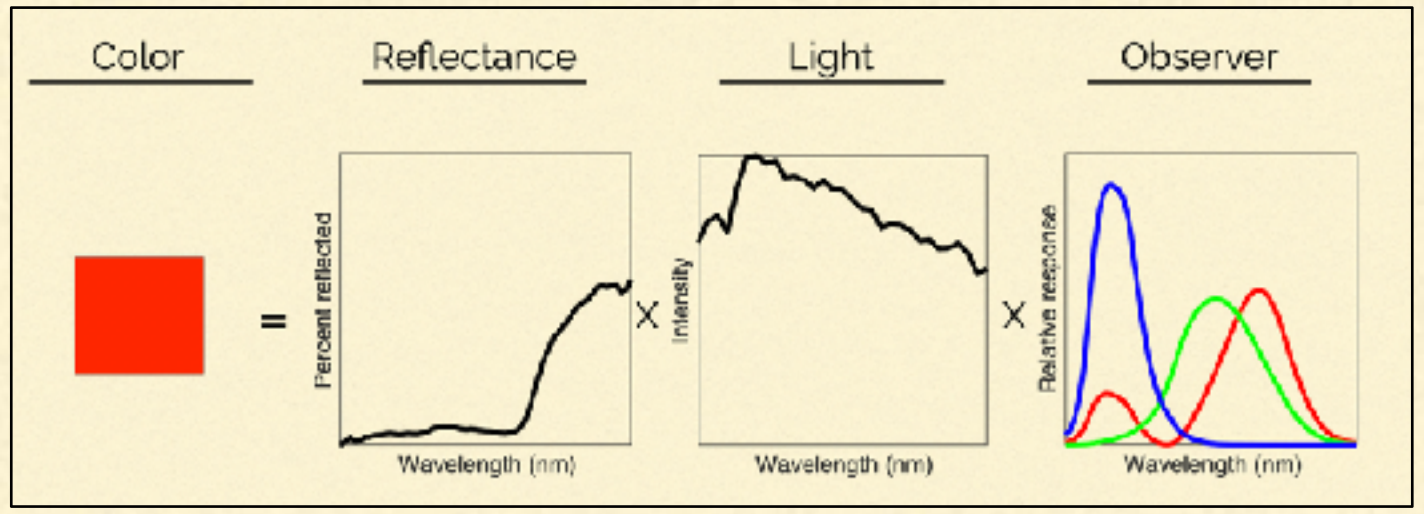
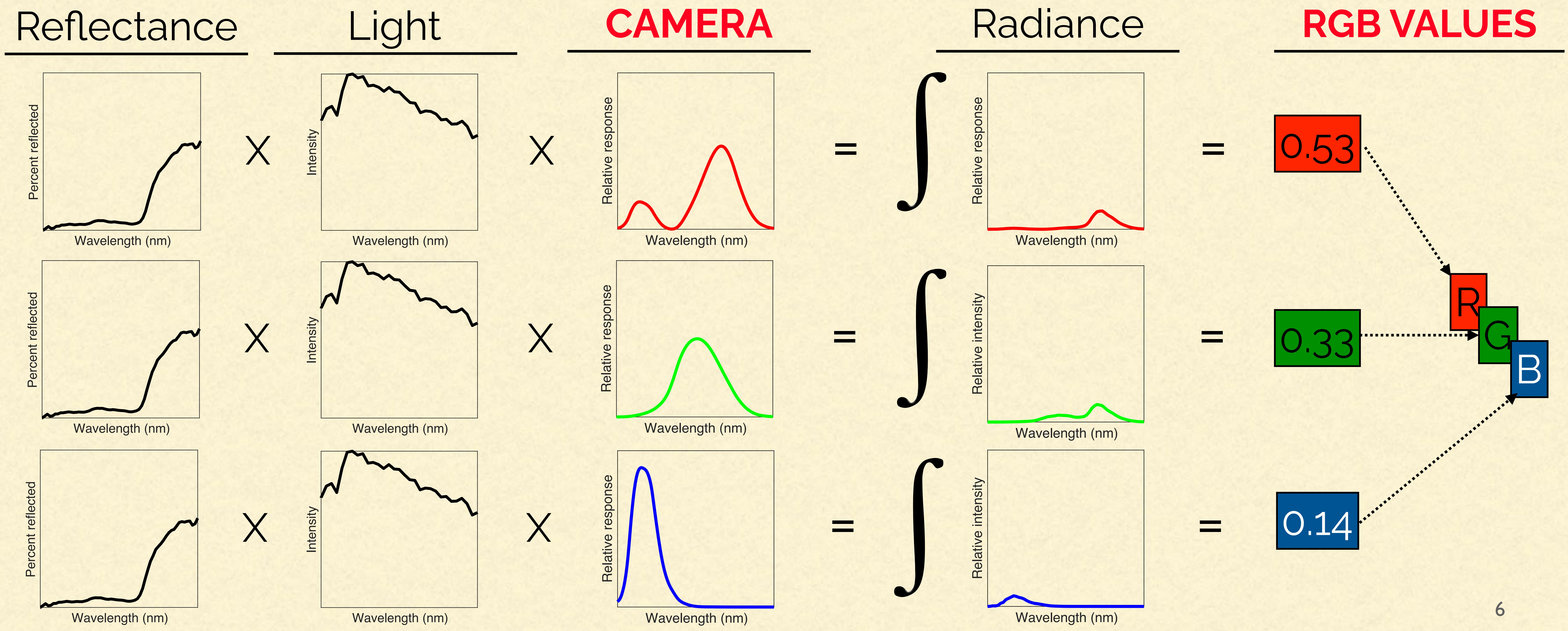
RGB Values



$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)d\lambda$$

κ: exposure-related constant



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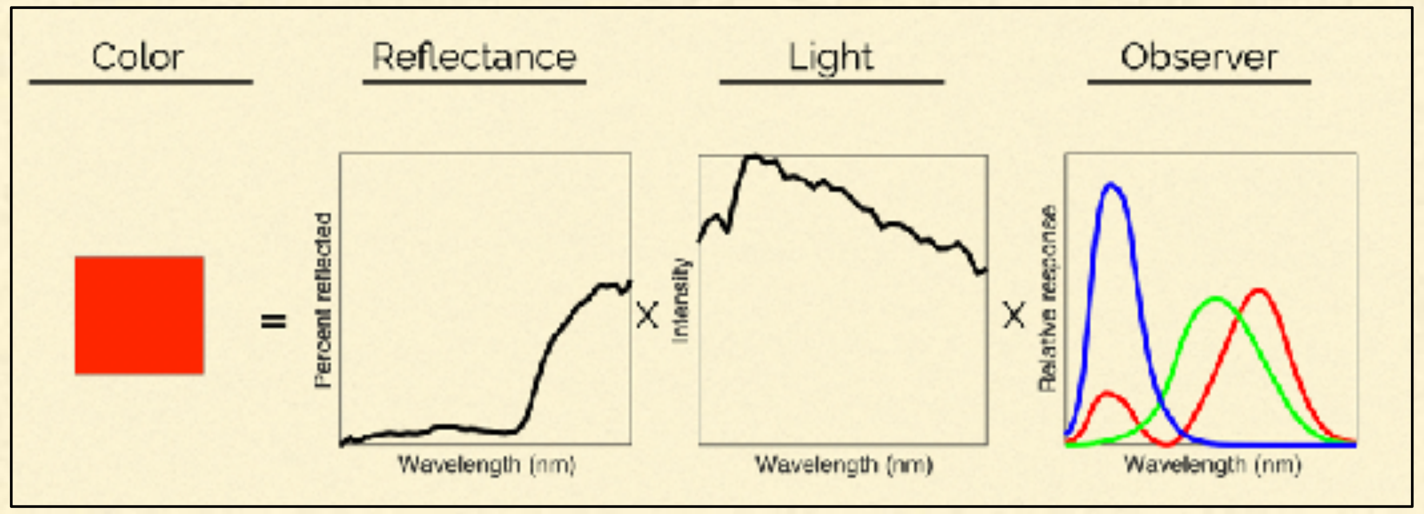

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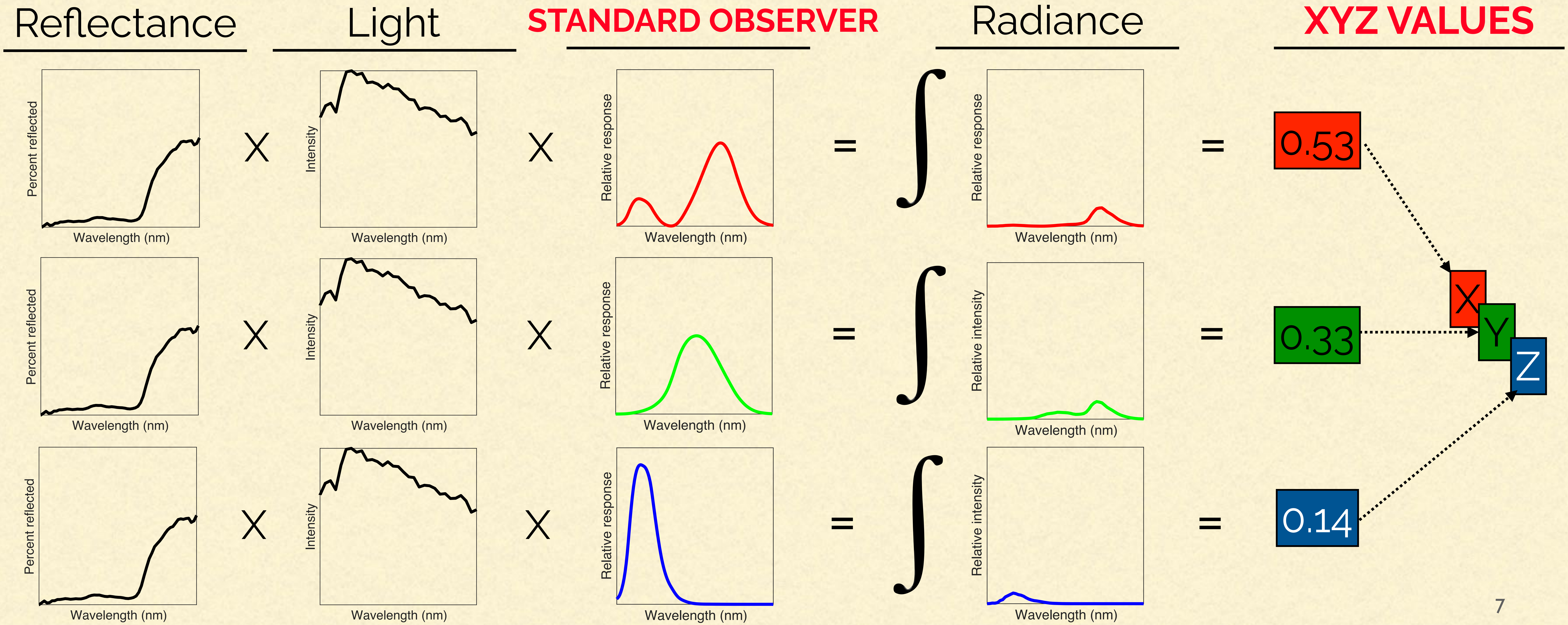

HOW ARE COLORS STANDARDIZED BETWEEN CAMERAS?

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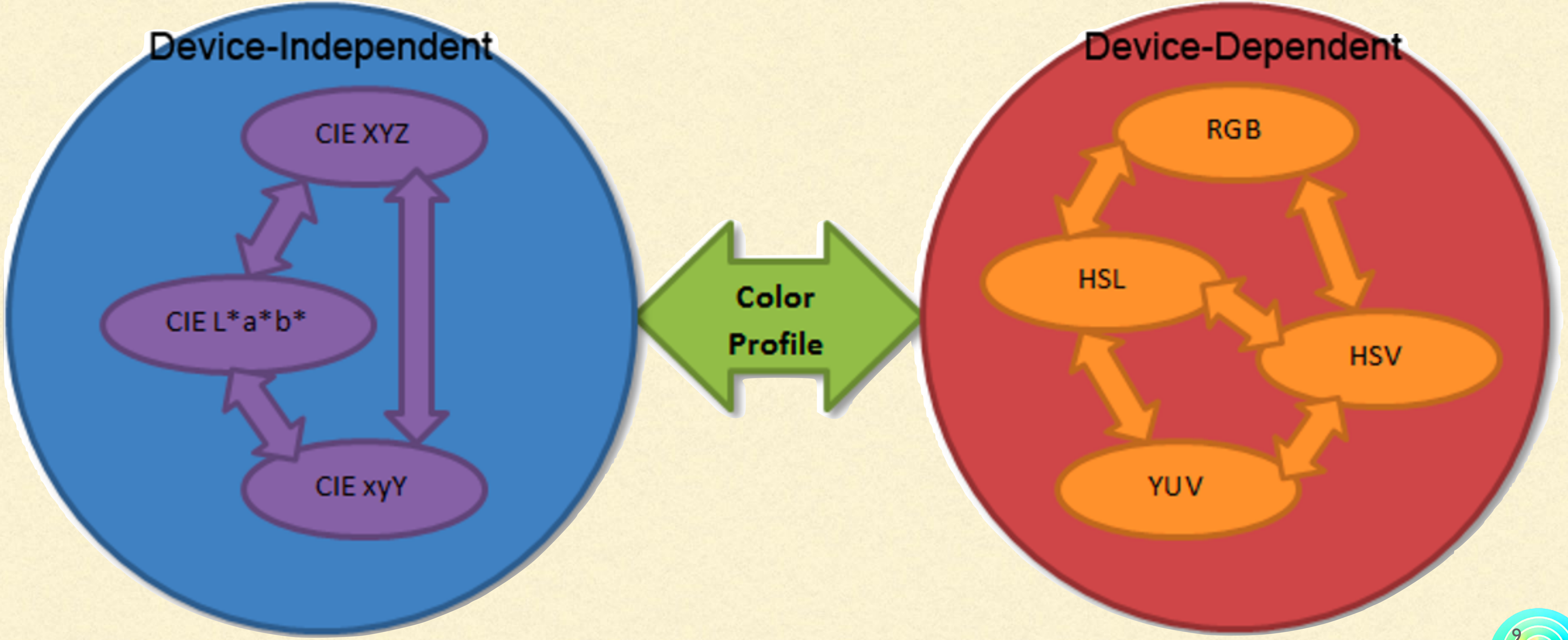
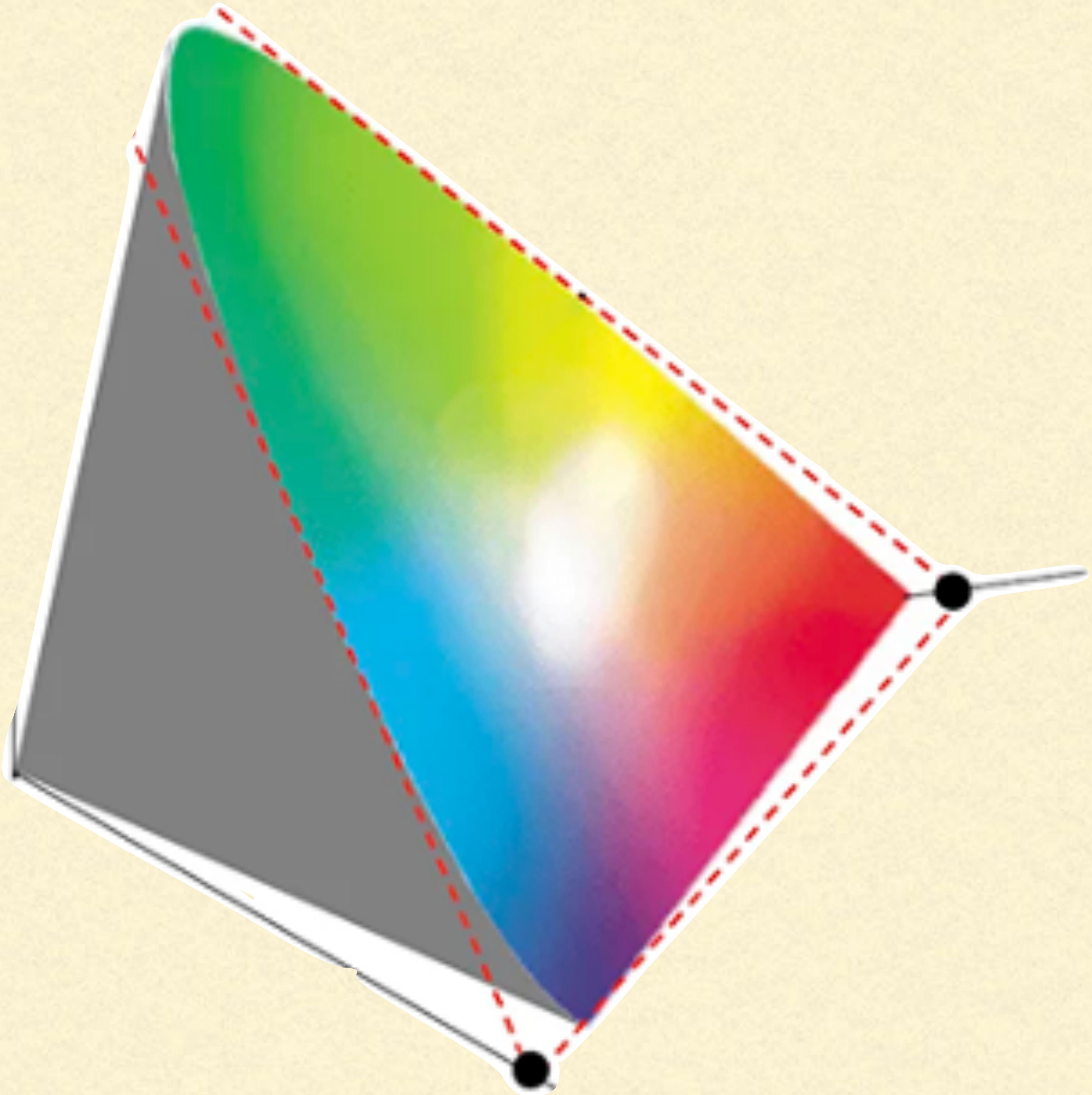
COLOR SPACES



1931 CIE XY CHROMATICITY DIAGRAM

The chromaticity diagram is considered to be a gamut of all colors visible a viewer with the CIE standard observer visual system.



XYZ color solid

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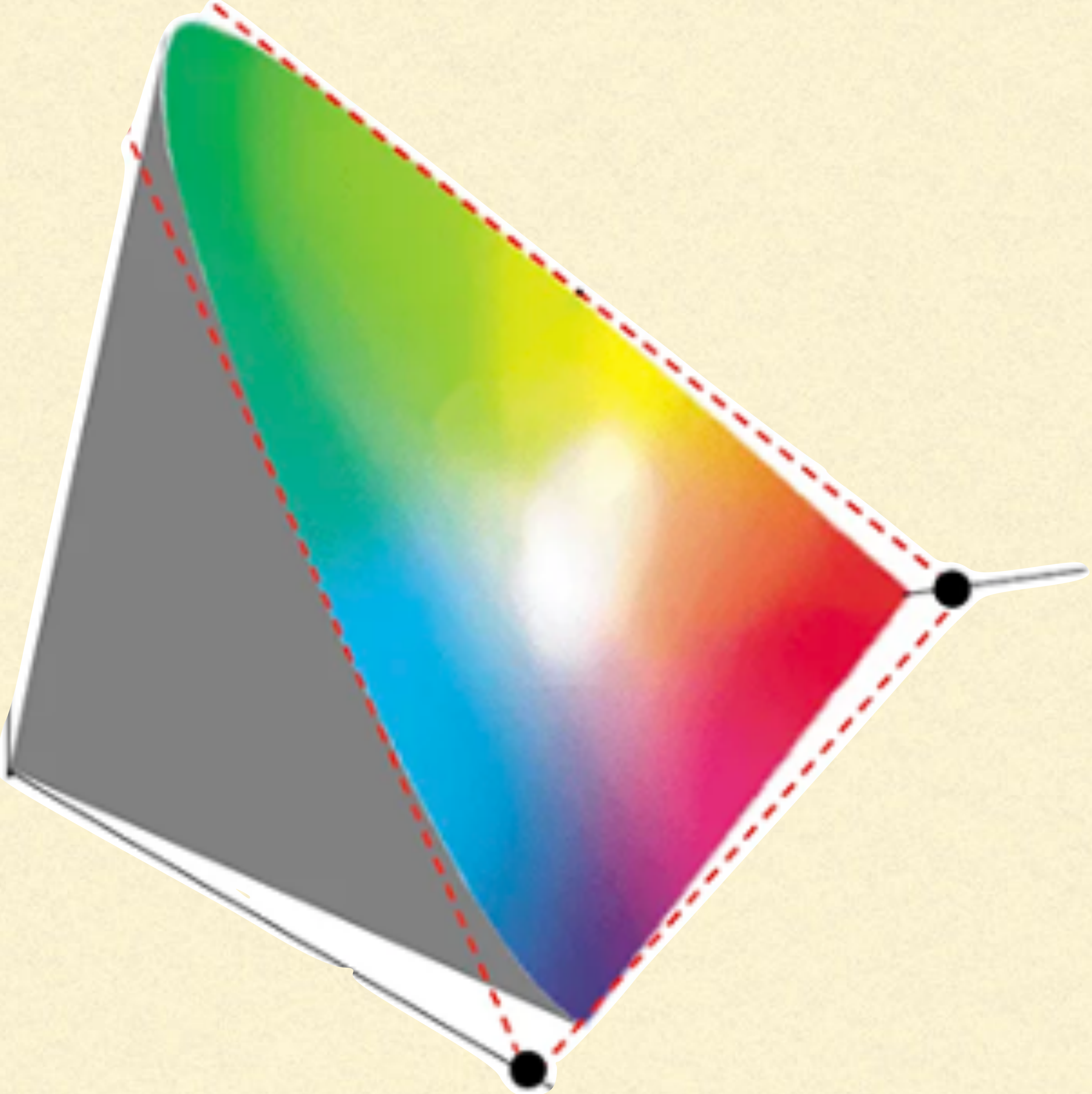

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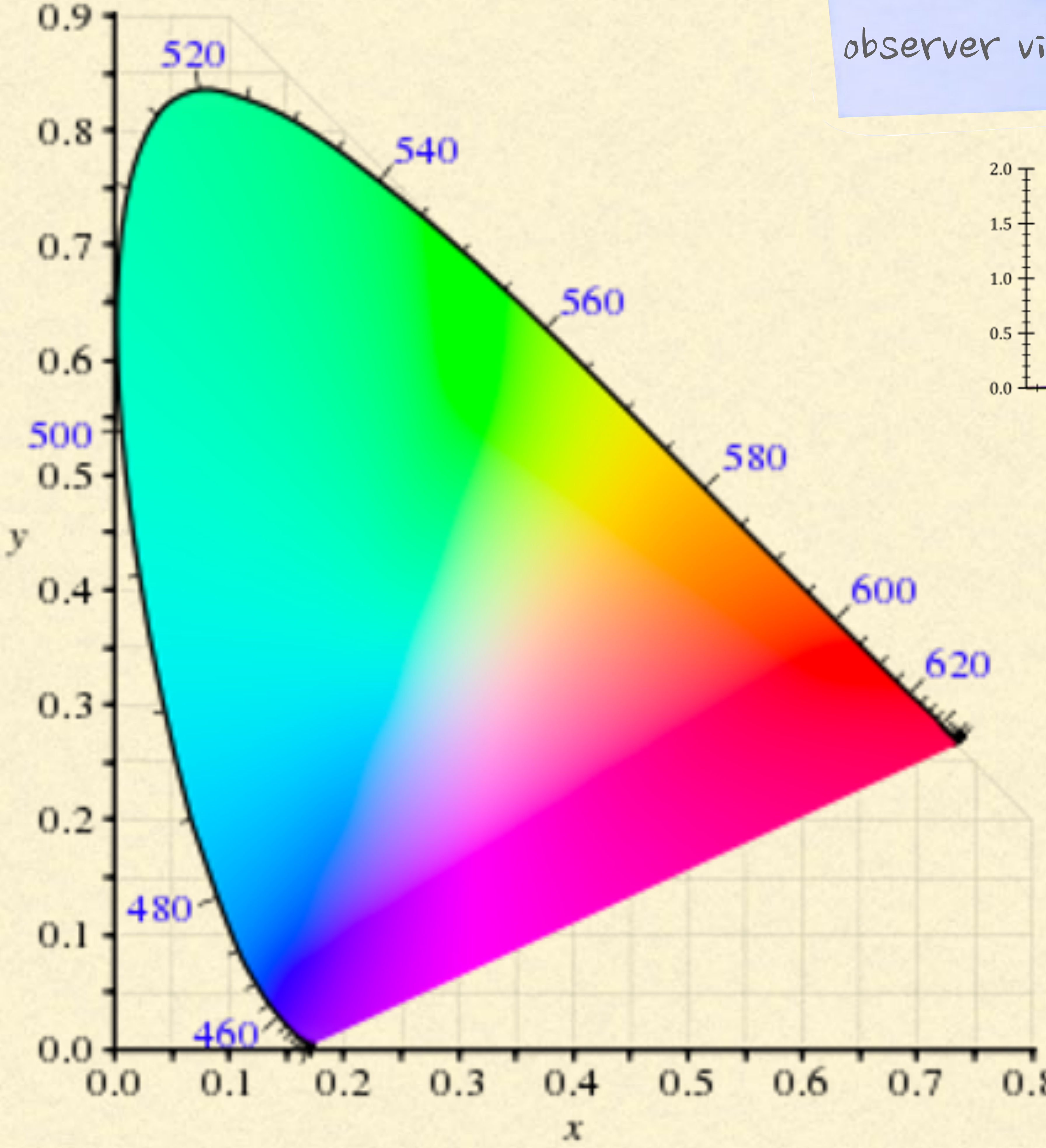
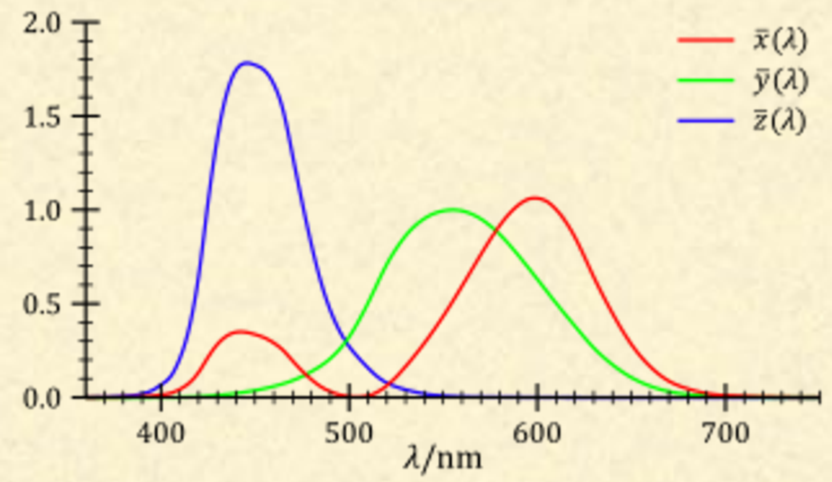
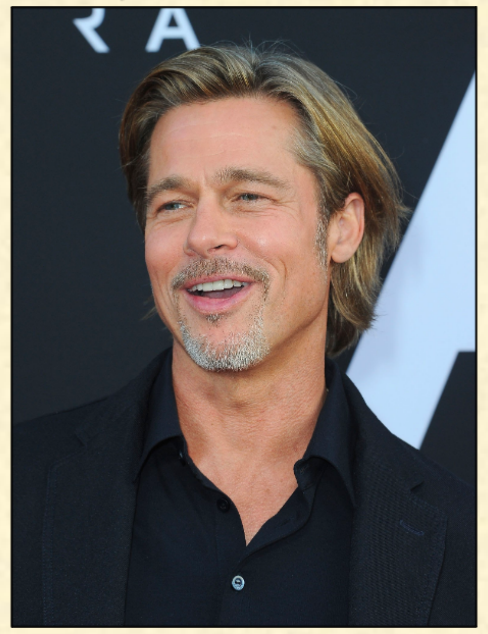


xy chromaticity diagram





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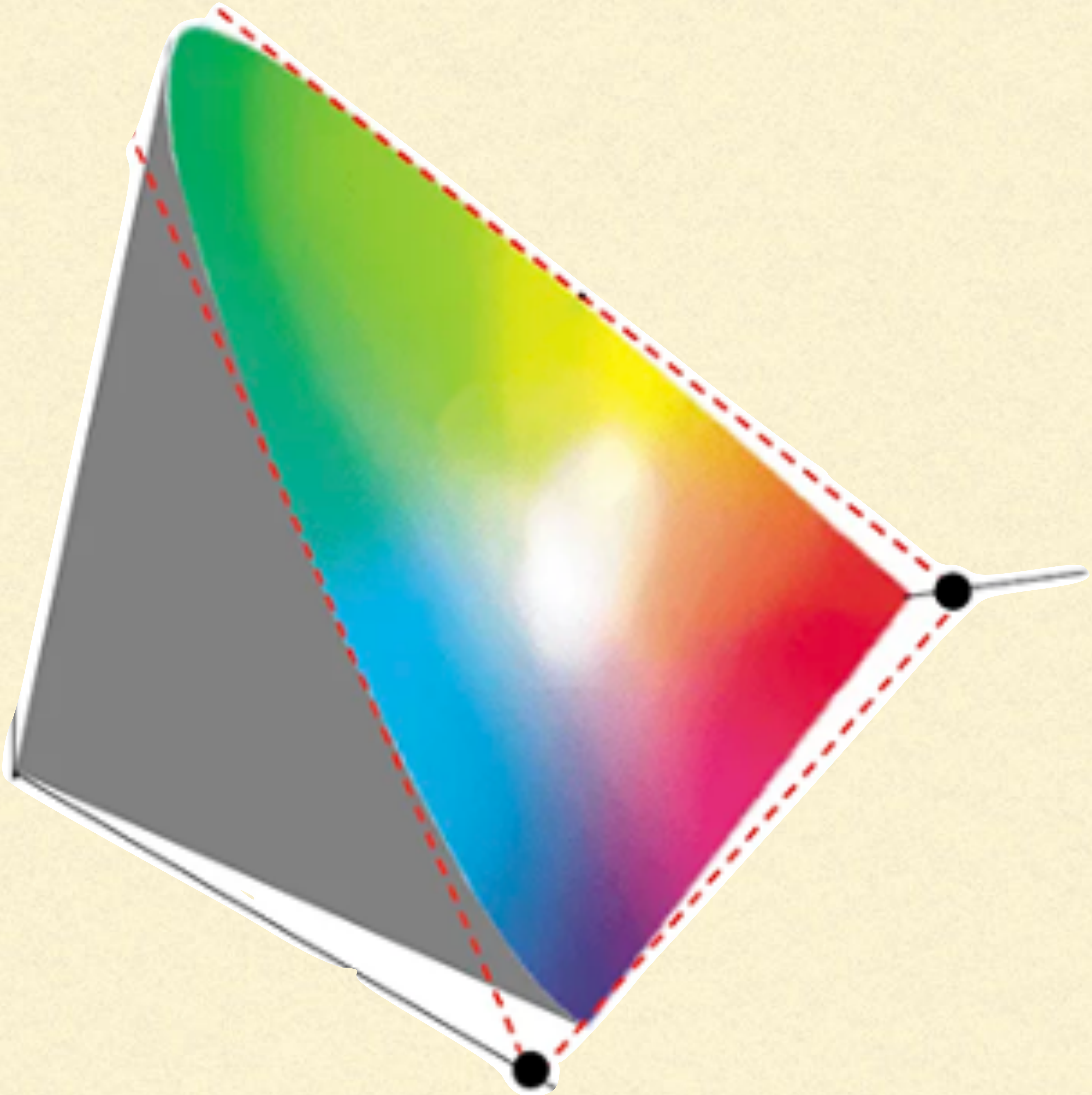

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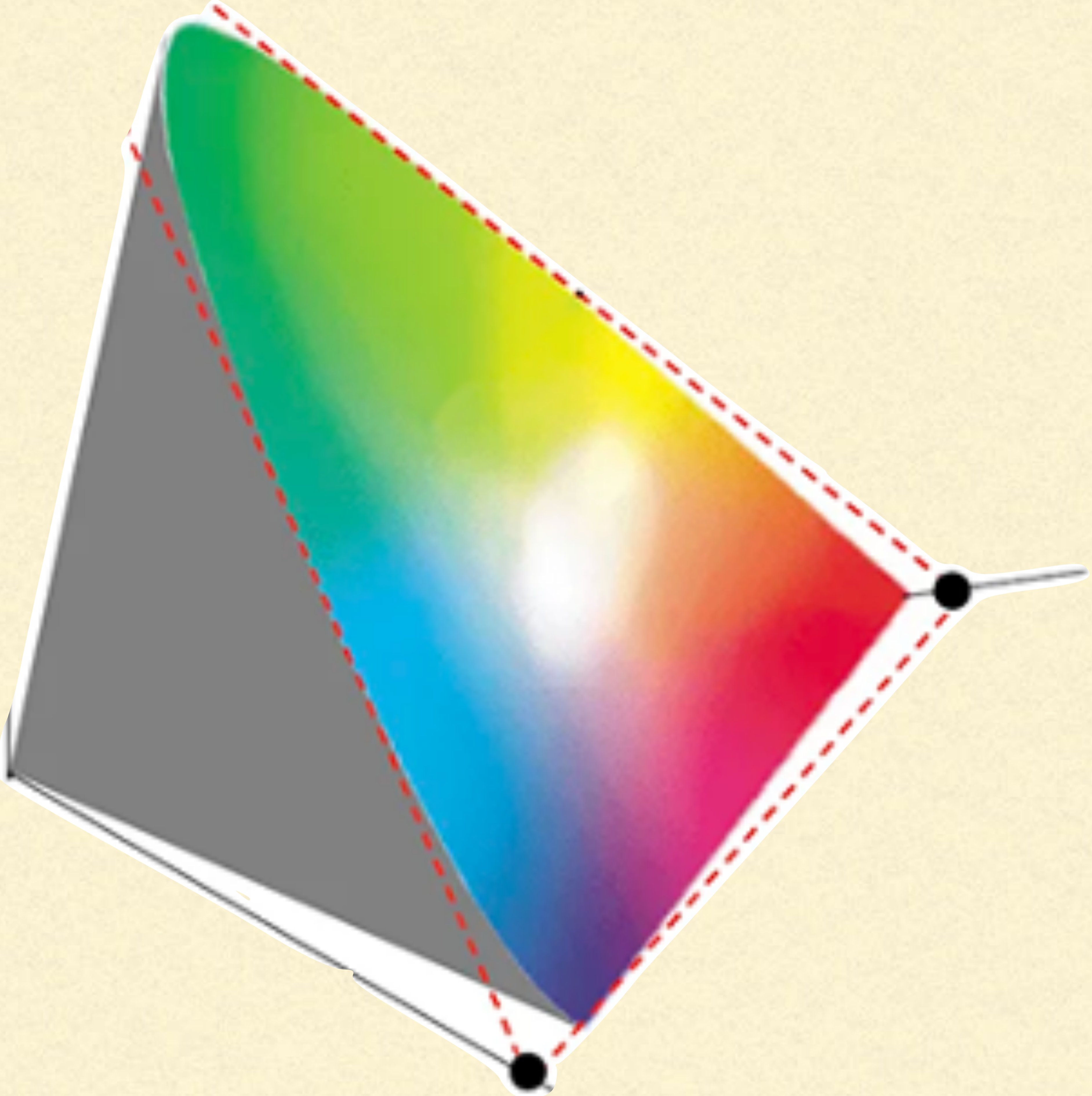

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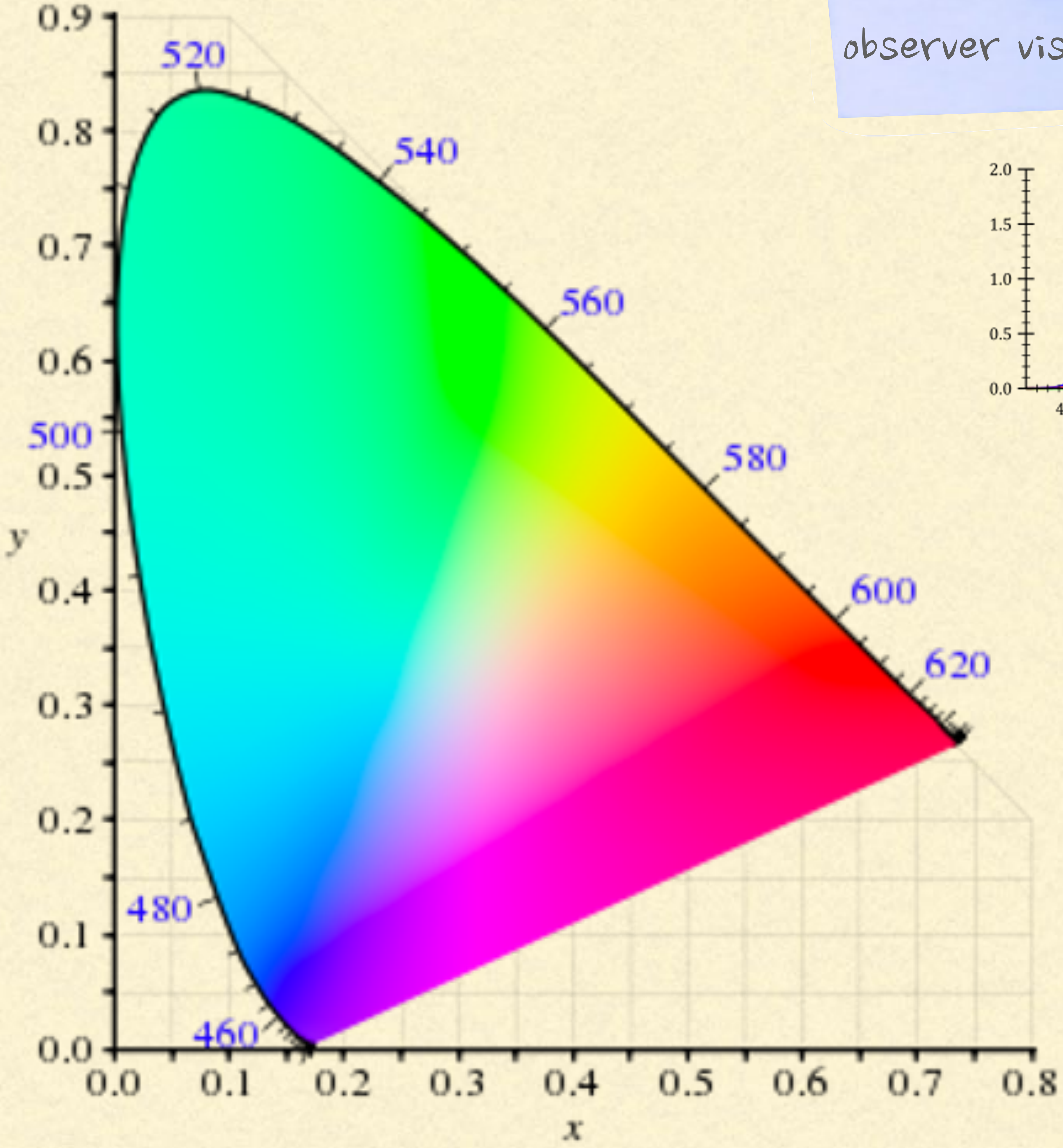

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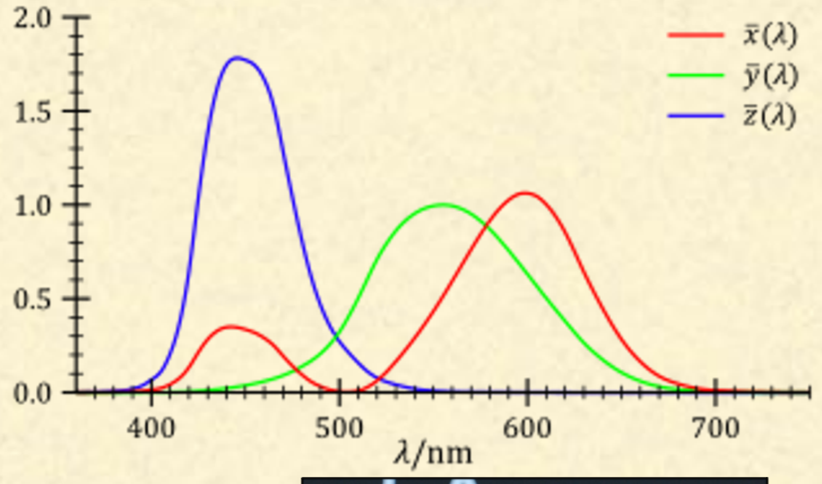

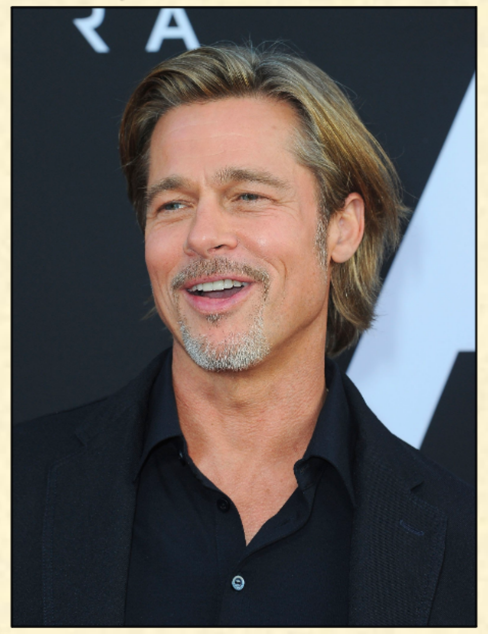

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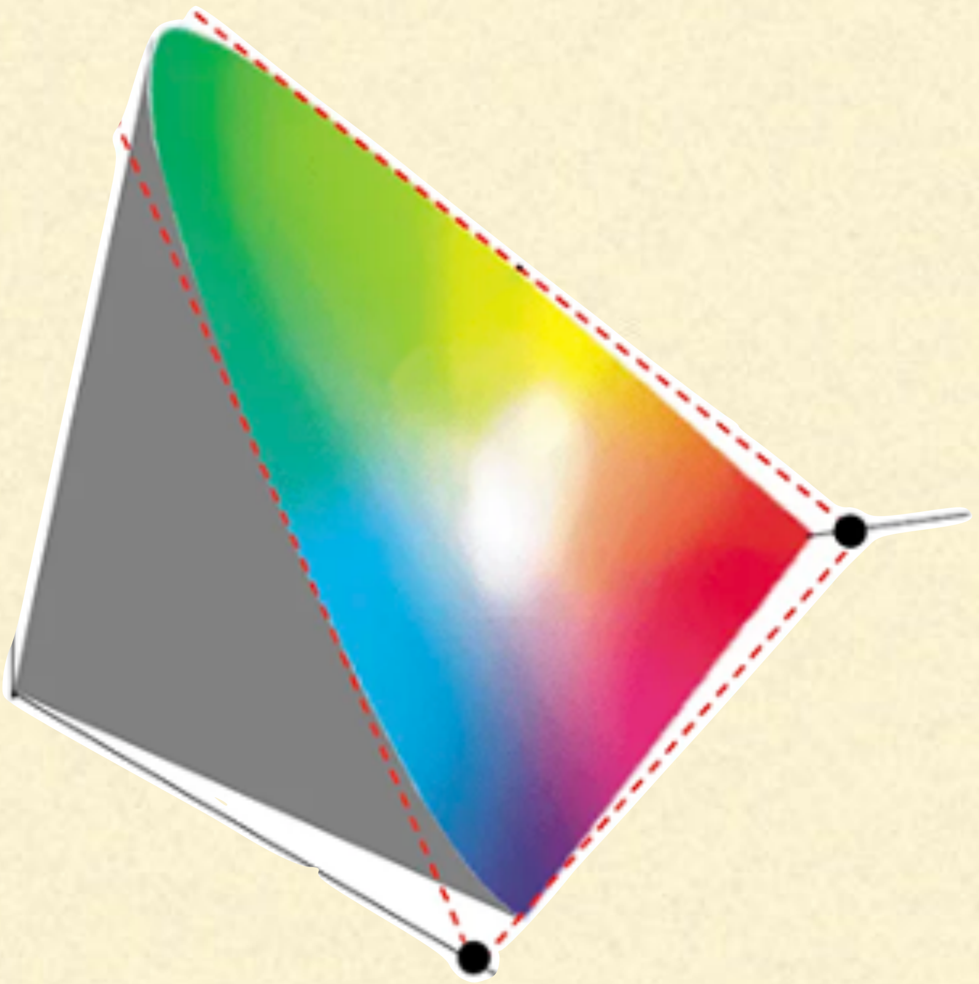

XYZ color solid

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

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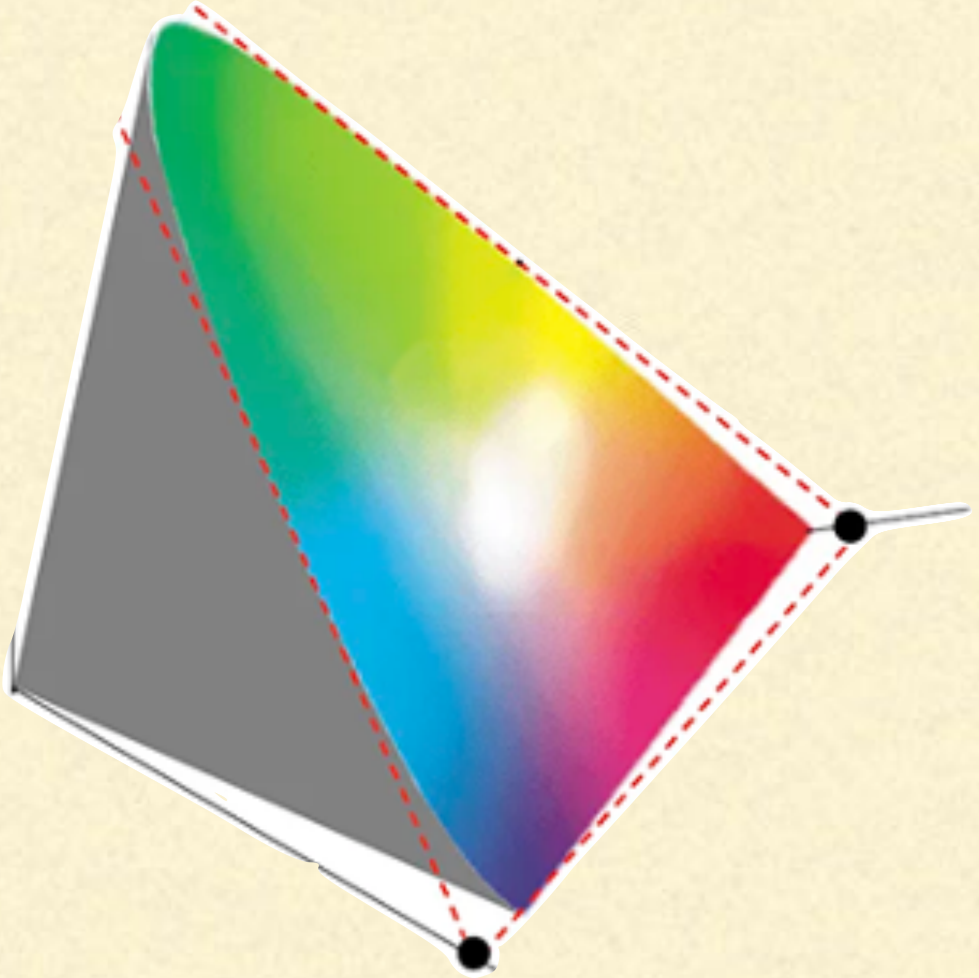

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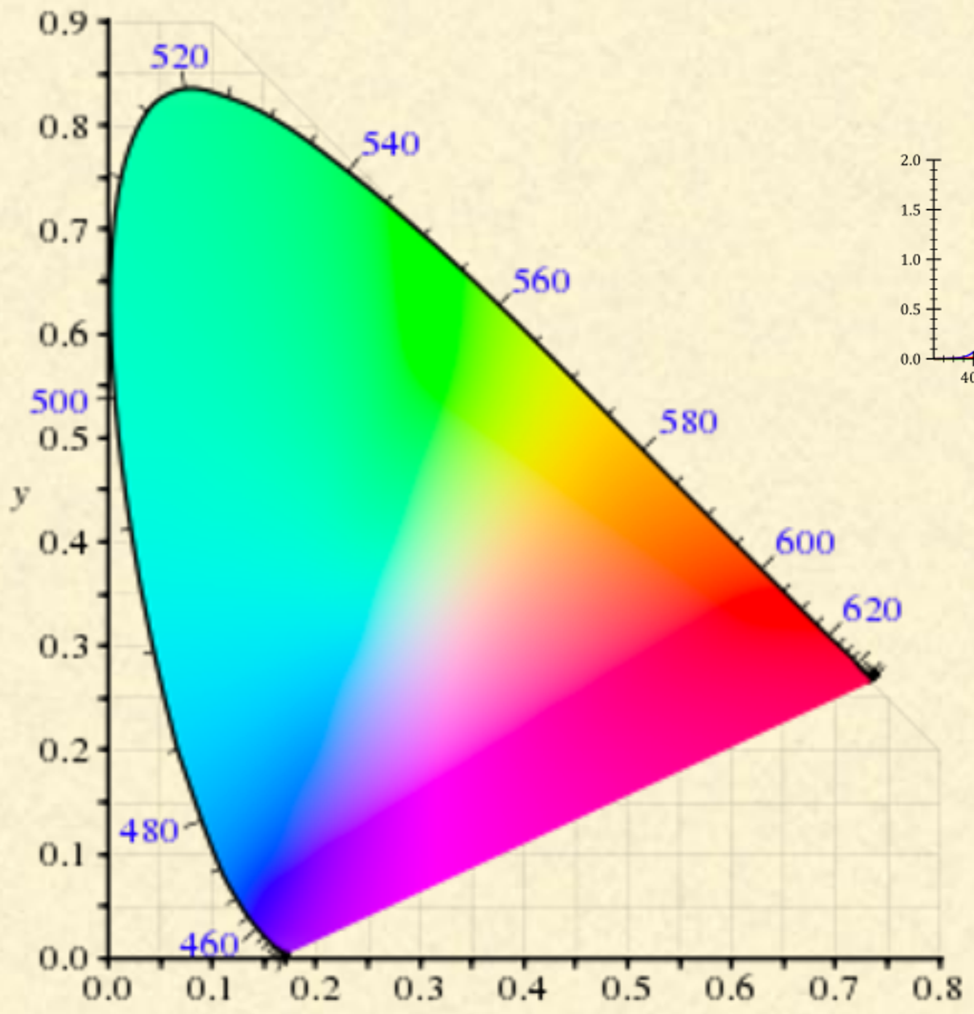
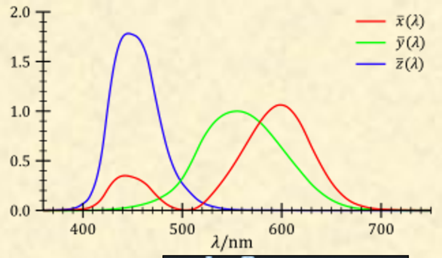
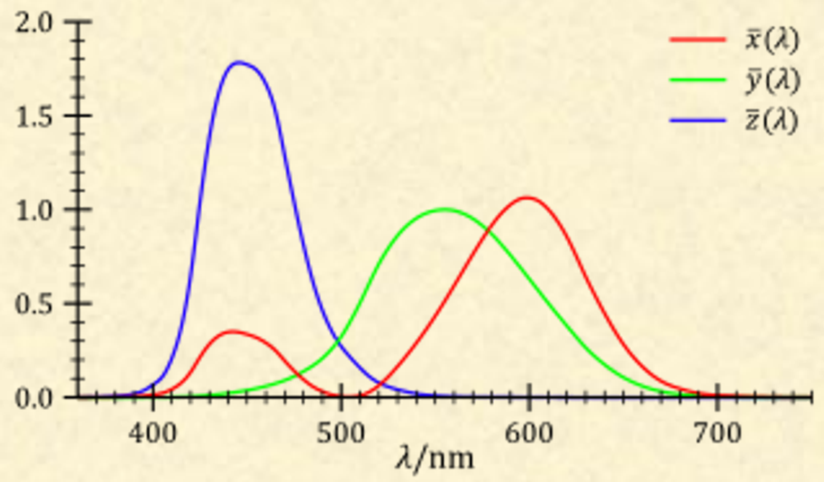
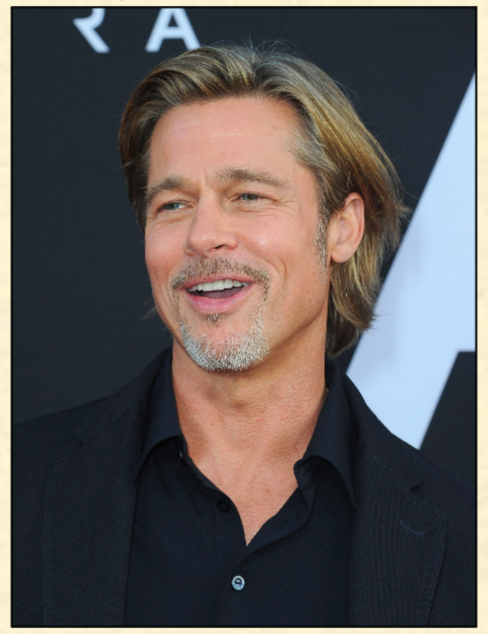




xy chromaticity diagram

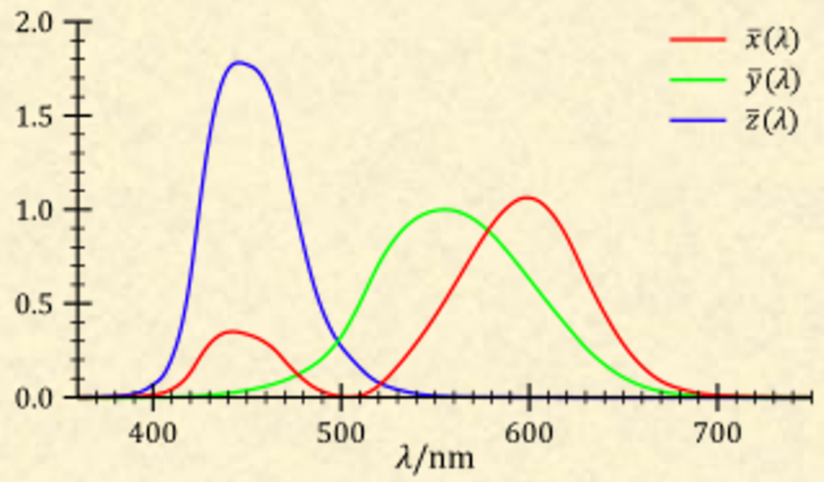
CIE 1931 XYZ Standard Observer

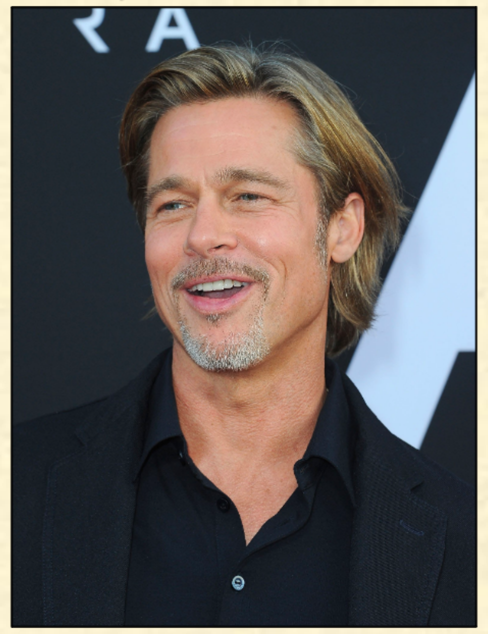




CIE 1931 XYZ Standard Observer

- "Spectral response of a human with normal color vision"





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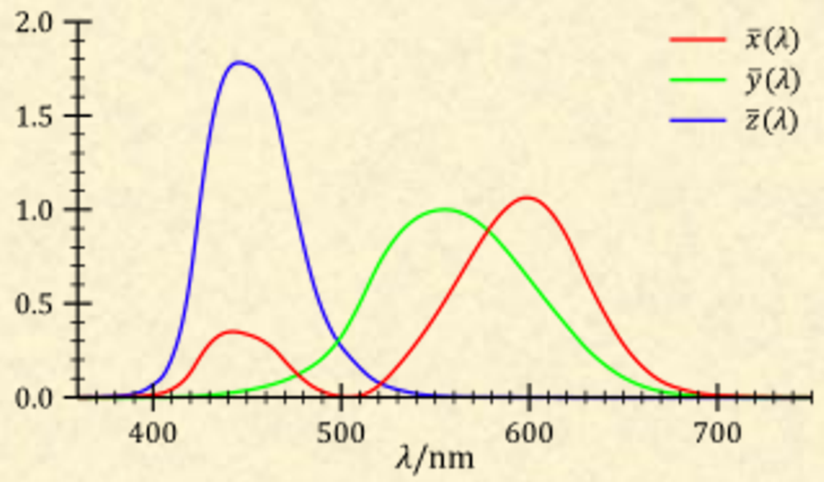

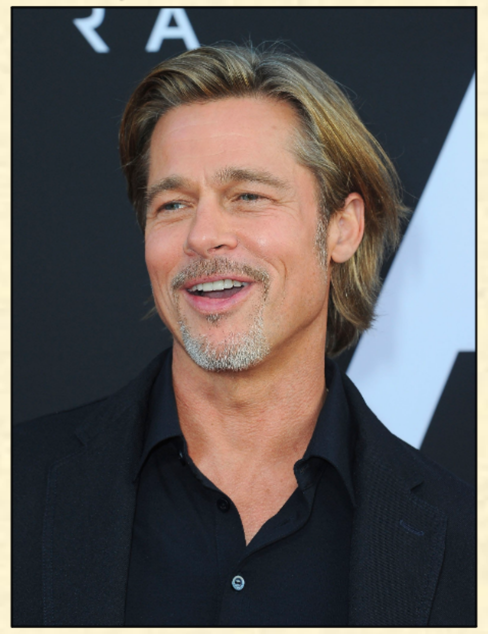

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- Curves come from <u>handful</u> of subjects tested in 1929 by John Guild, David Wright.

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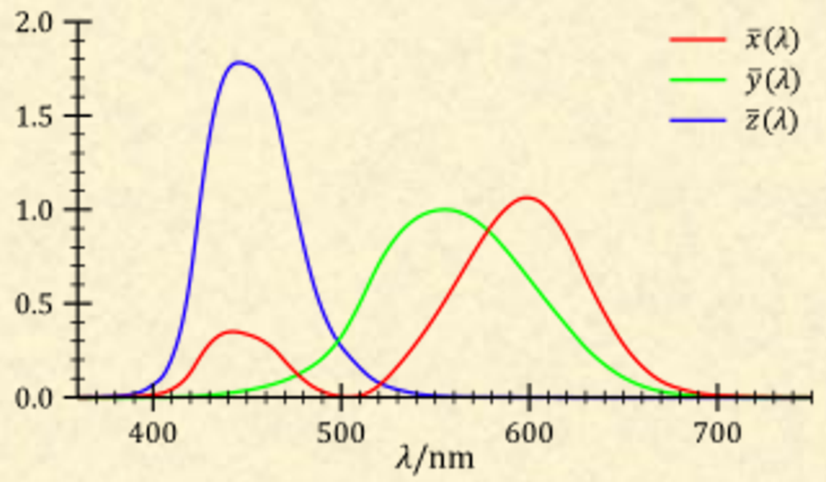

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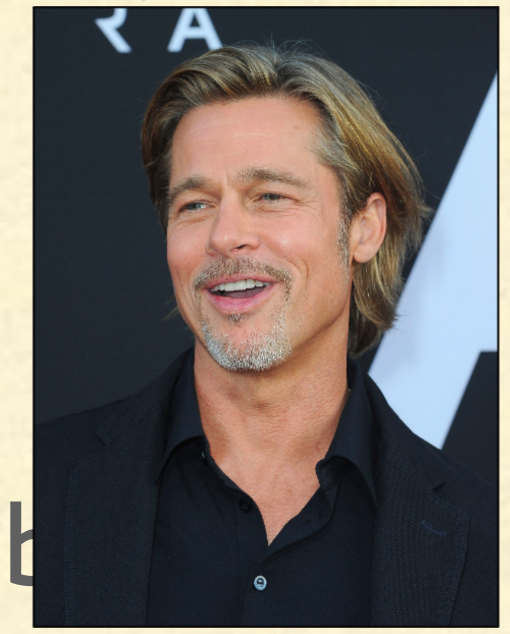
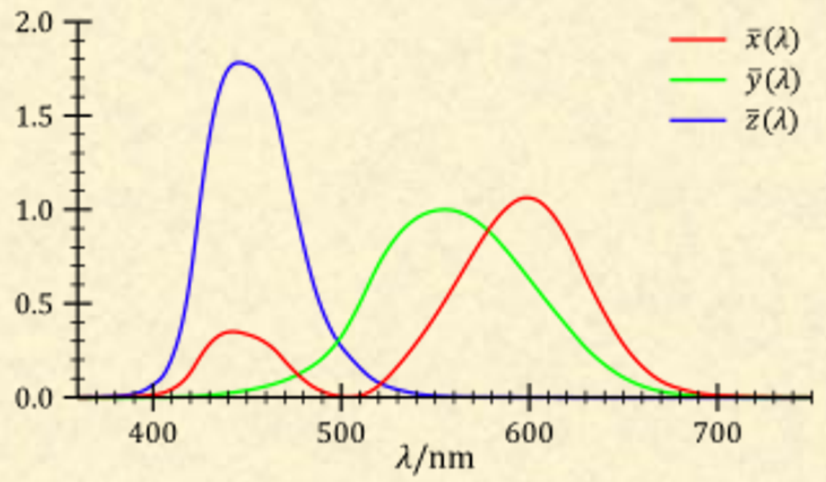
- Do ALL humans sense colors the same way ? (And is that the same as the CIE XYZ ob





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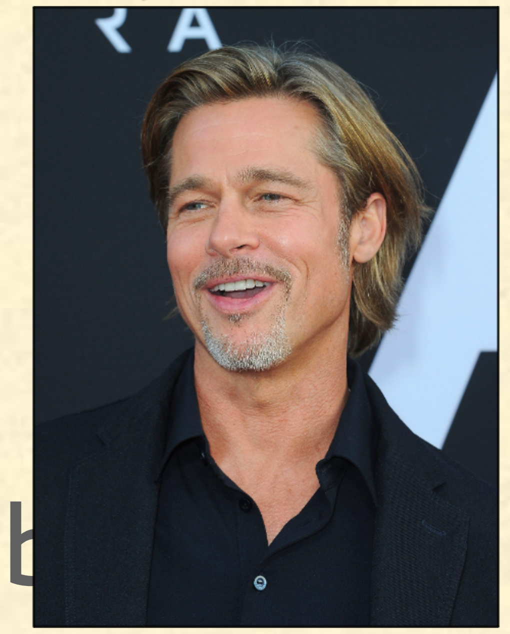

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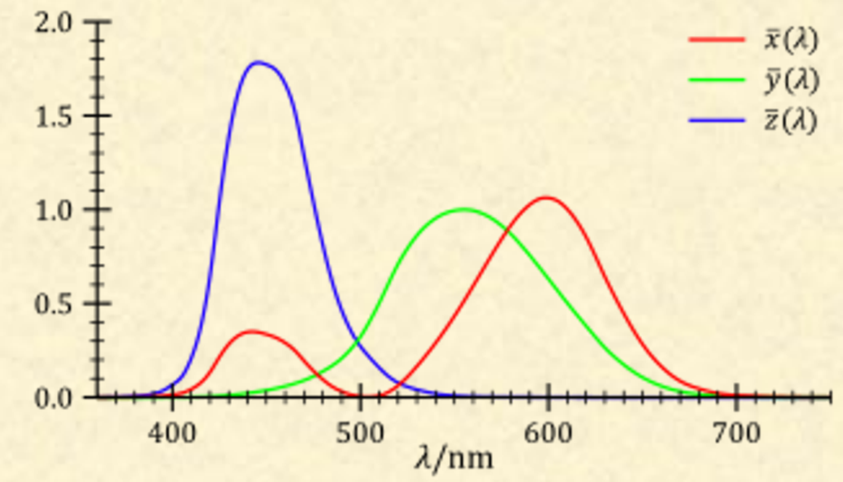

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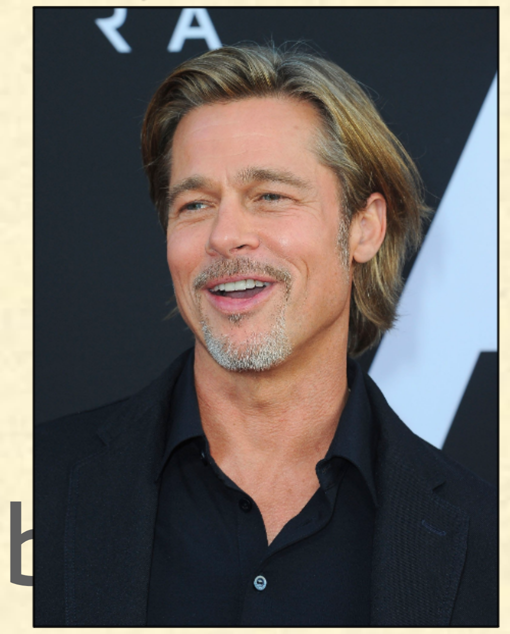

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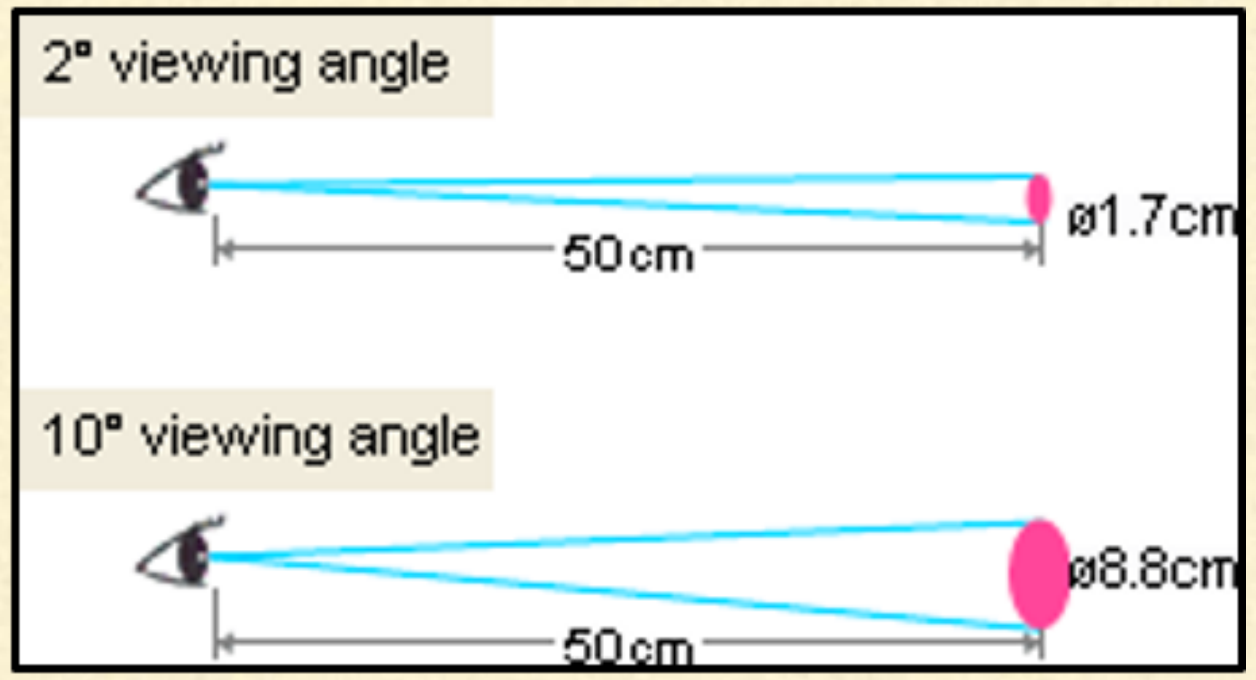
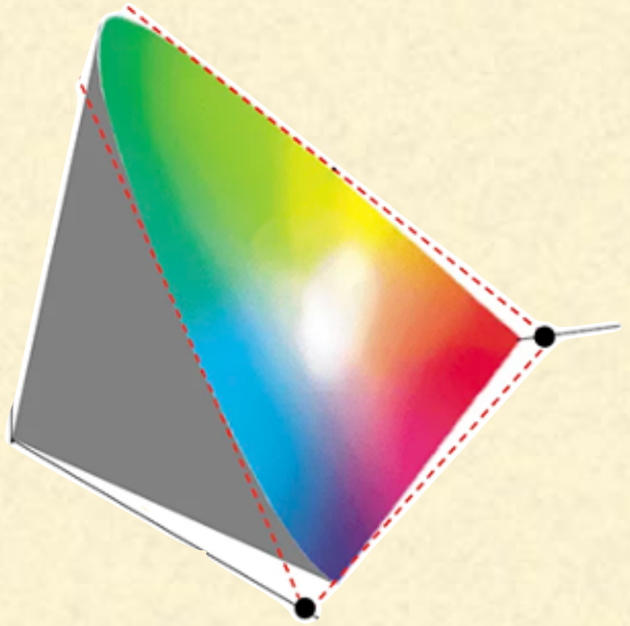
- There are slightly different curves for 2 degree vs 10 degree viewing angles.



Brief Summary of Key Concepts



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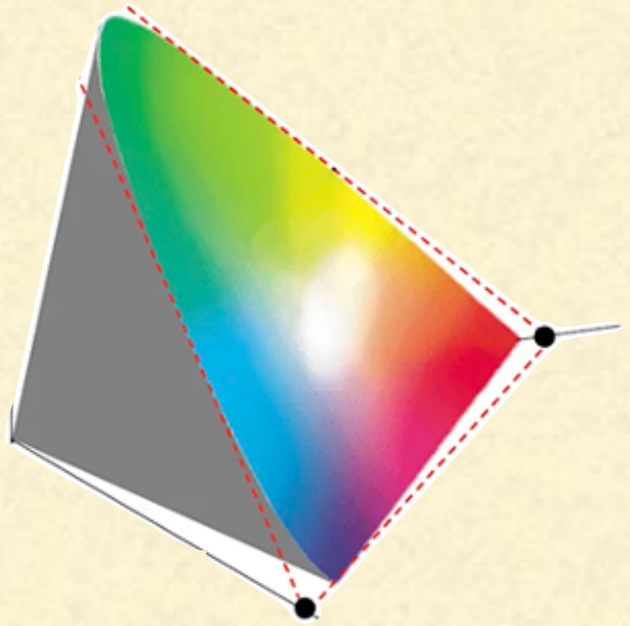

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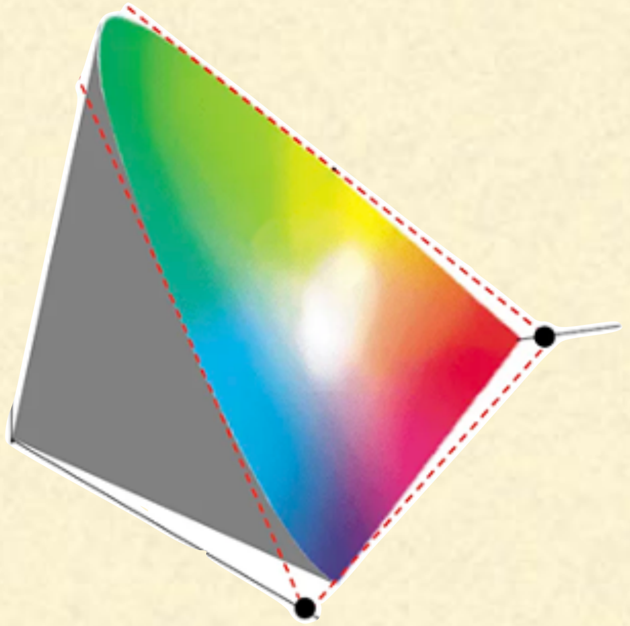

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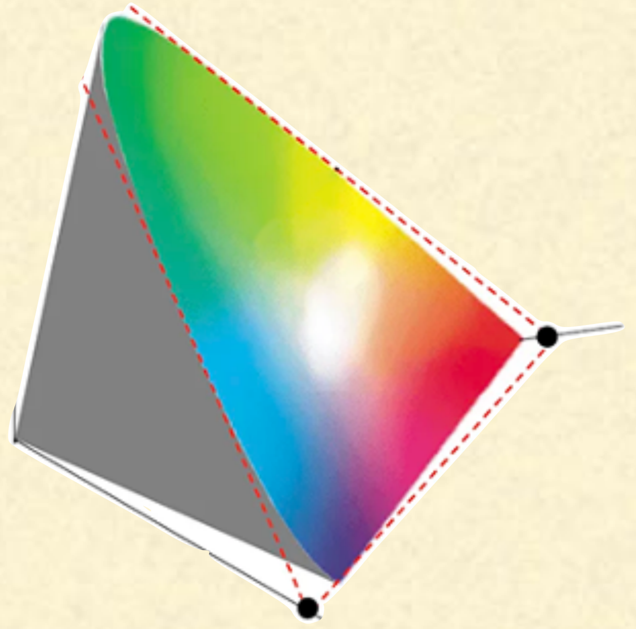

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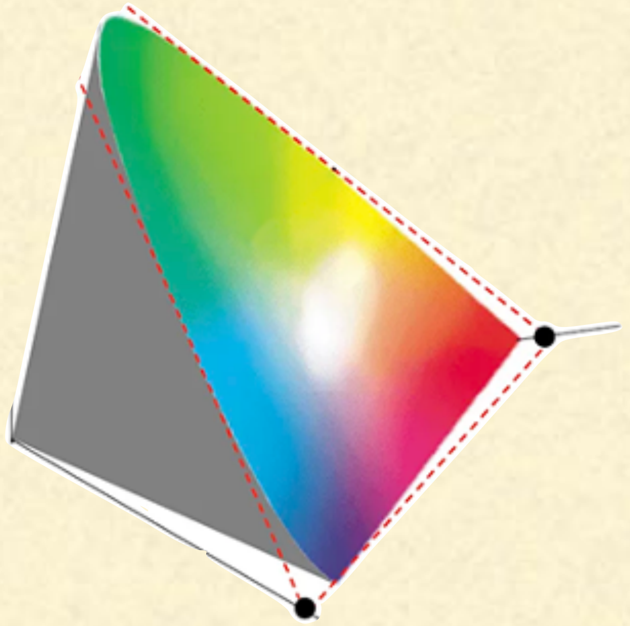

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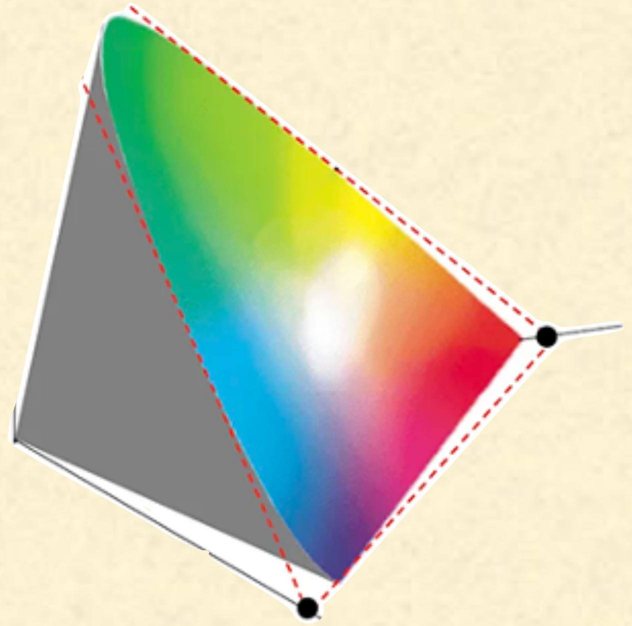

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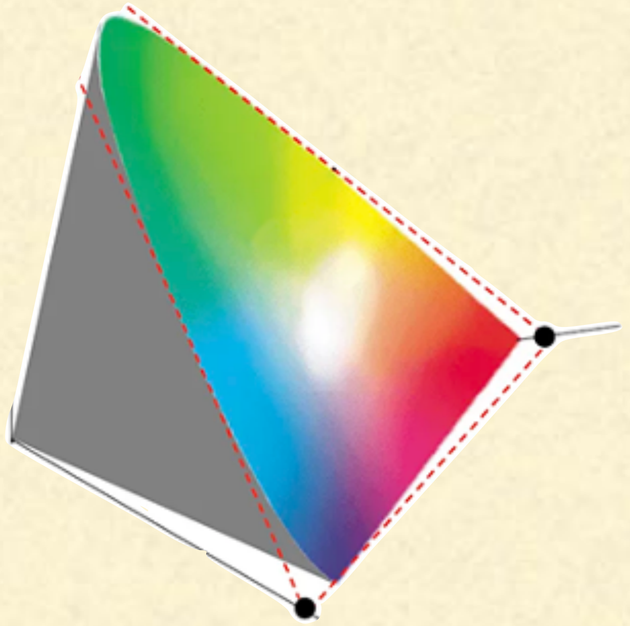

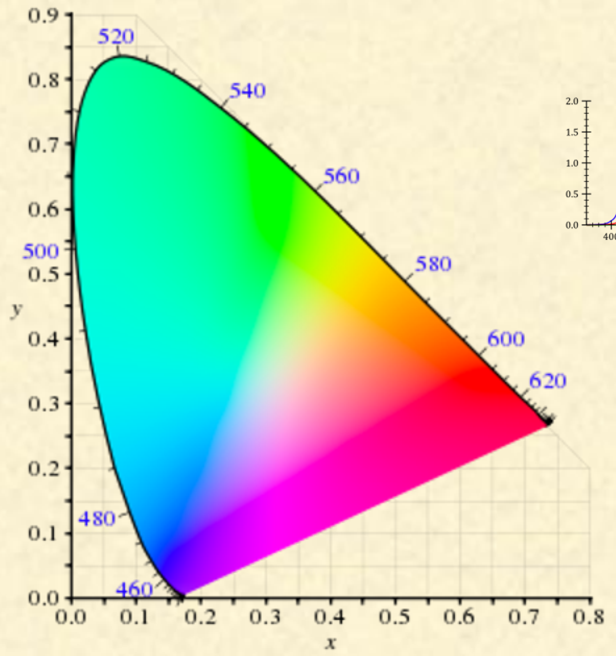

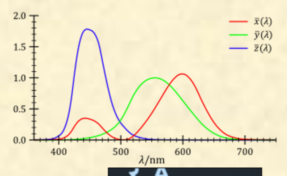

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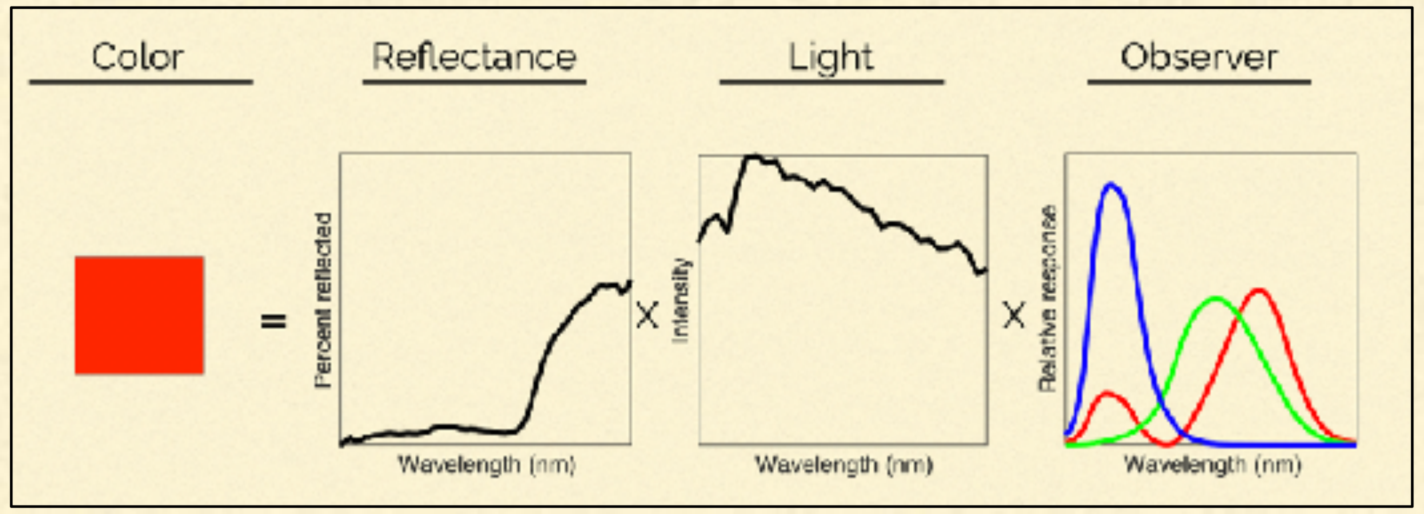

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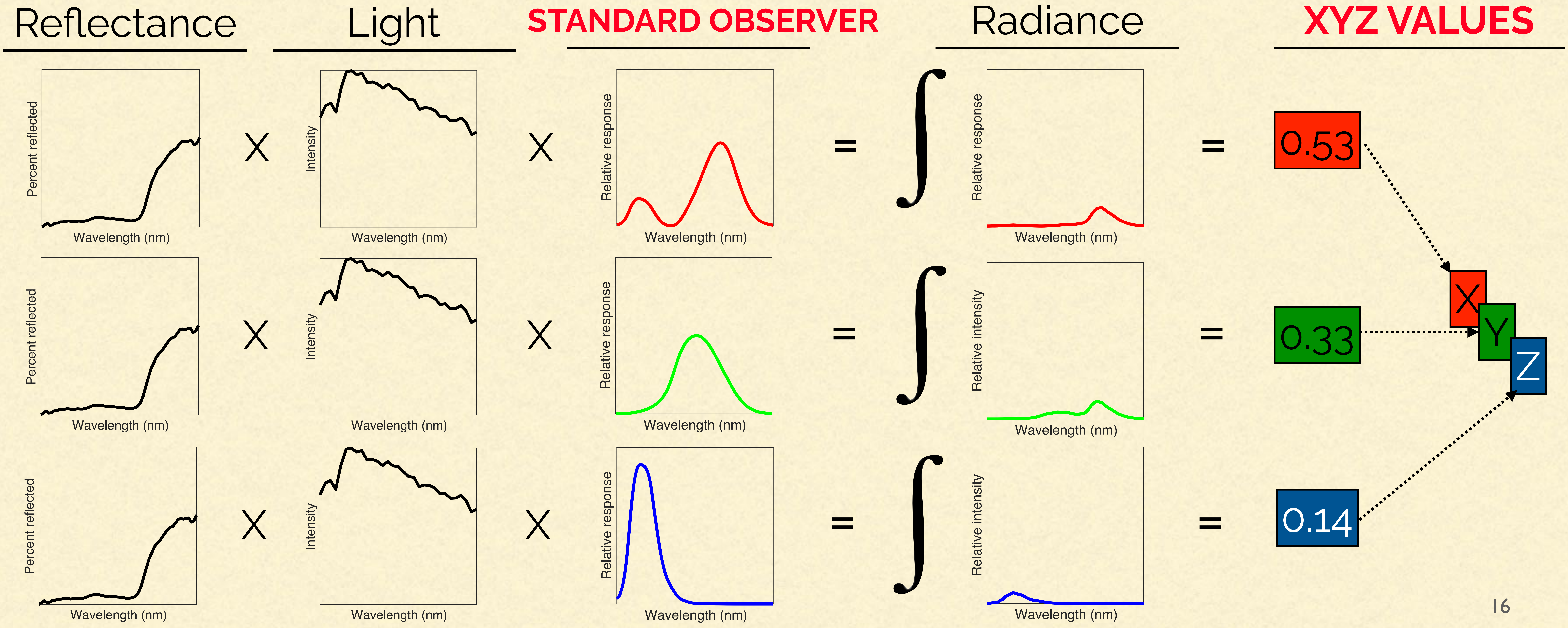

Camera RGB to XYZ transformation

But before that...

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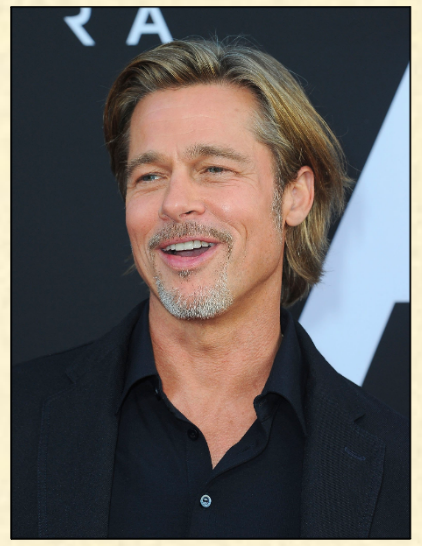
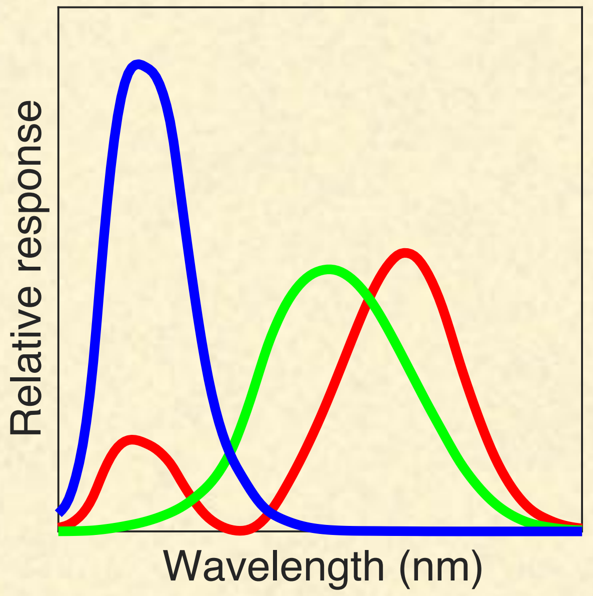
Think about which objects you need to include in the frame to calibrate.

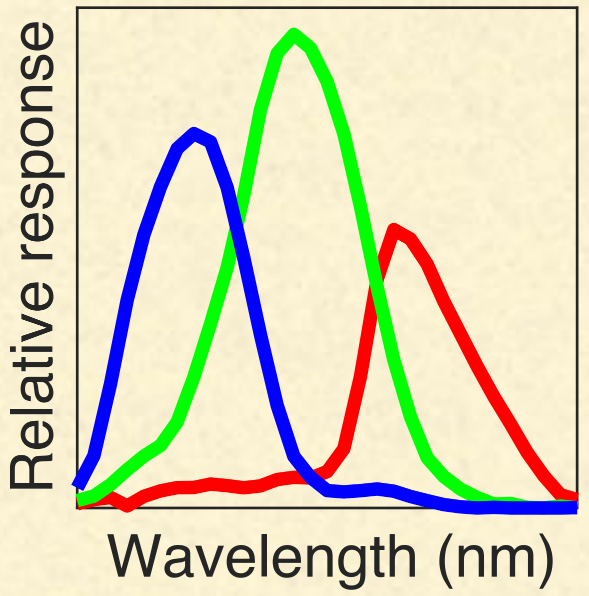
Camera RGB to XYZ transformation

Camera & illuminant specific !!!

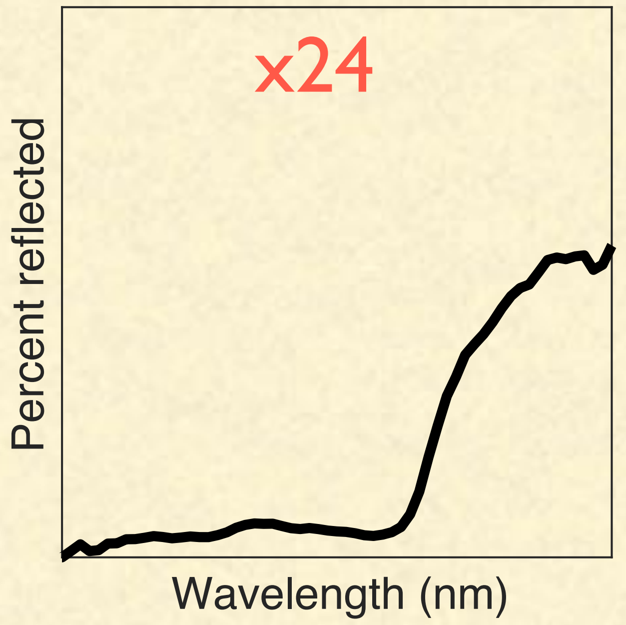
Spectral Response Curves



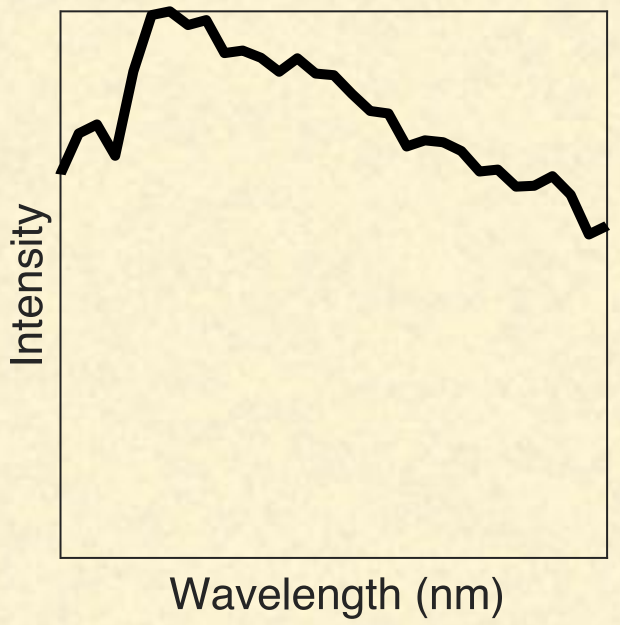




Reflectances of color chart patches



Illuminant Spectrum



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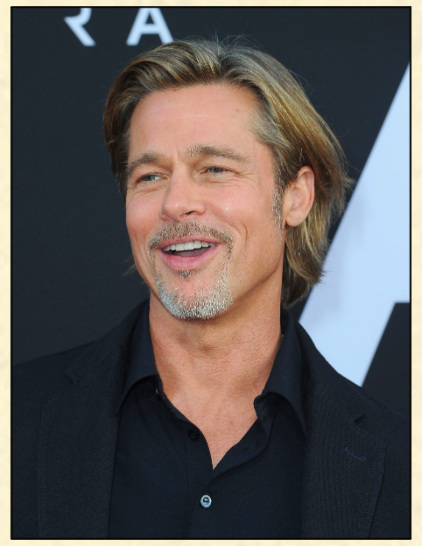

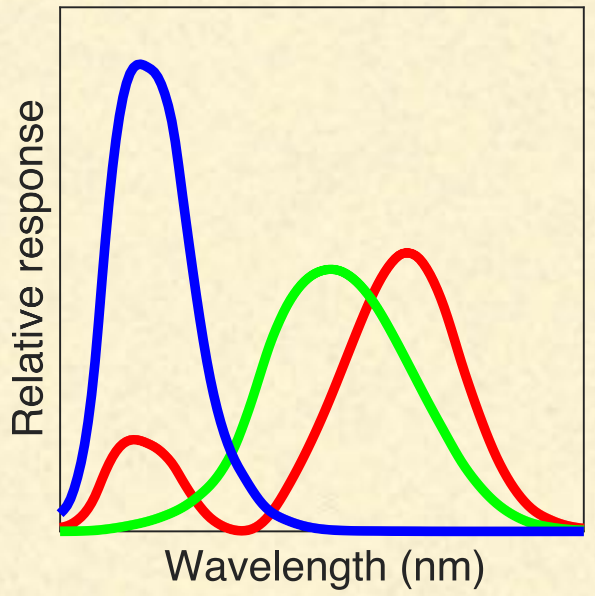

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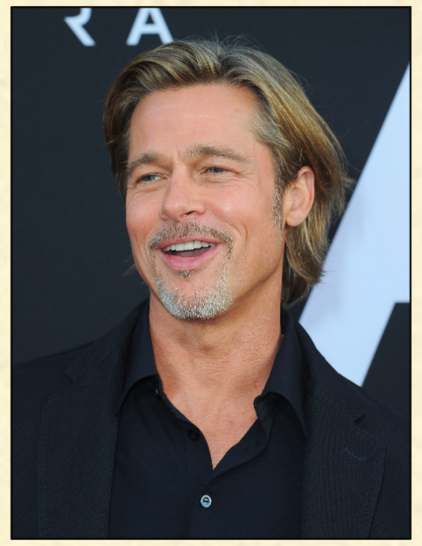
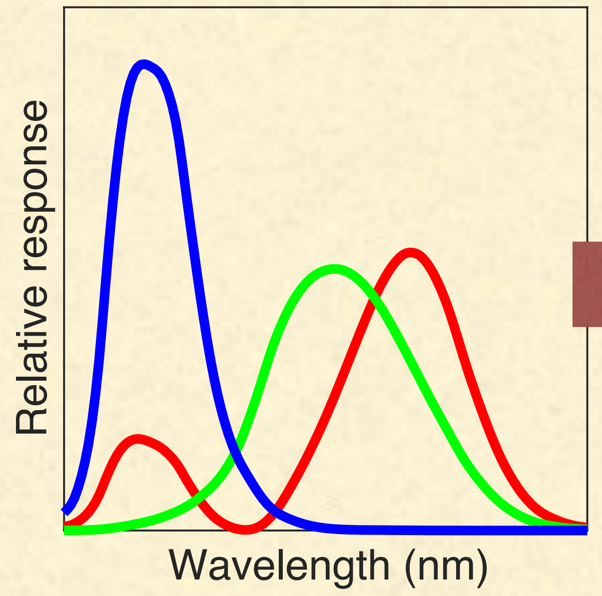
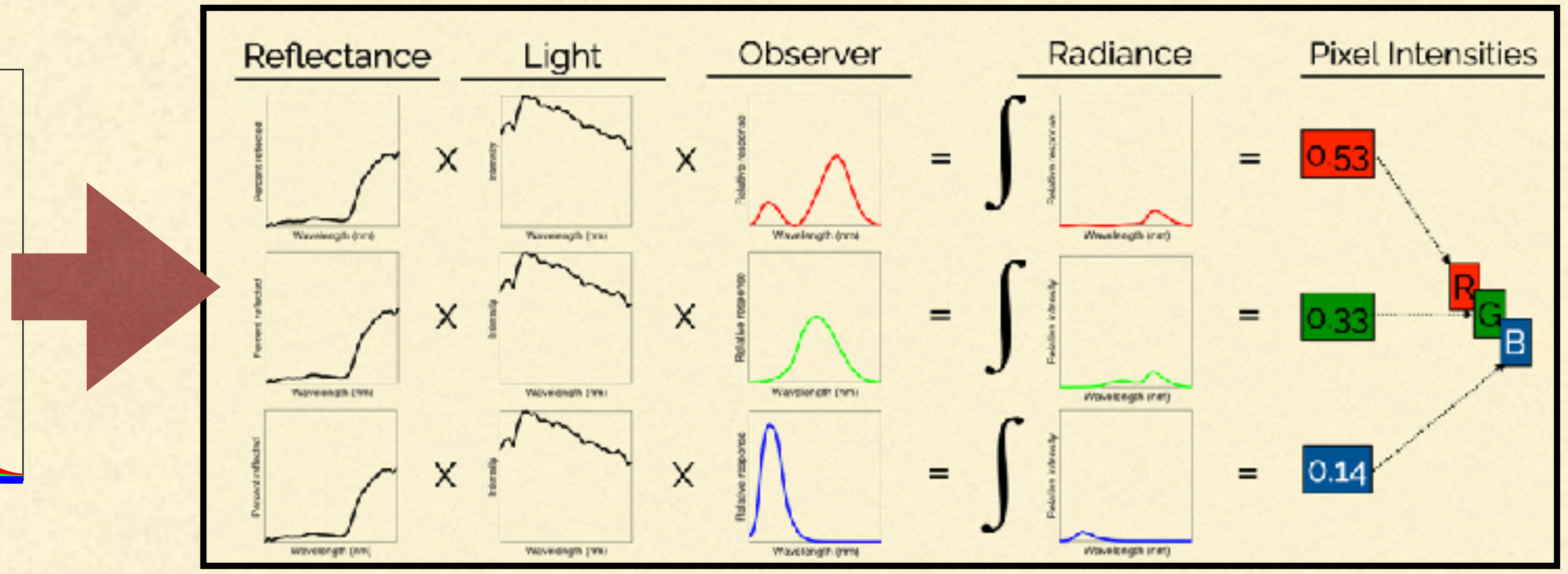
Camera & illuminant specific !!!

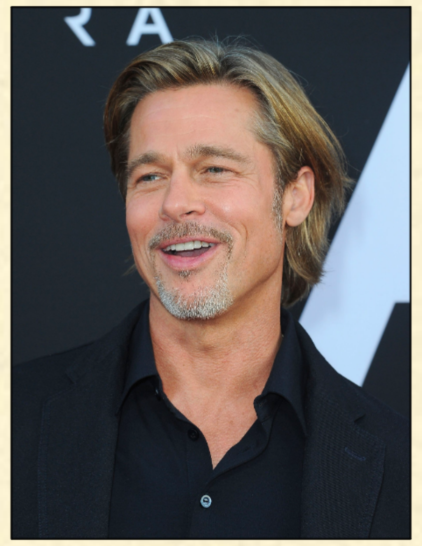


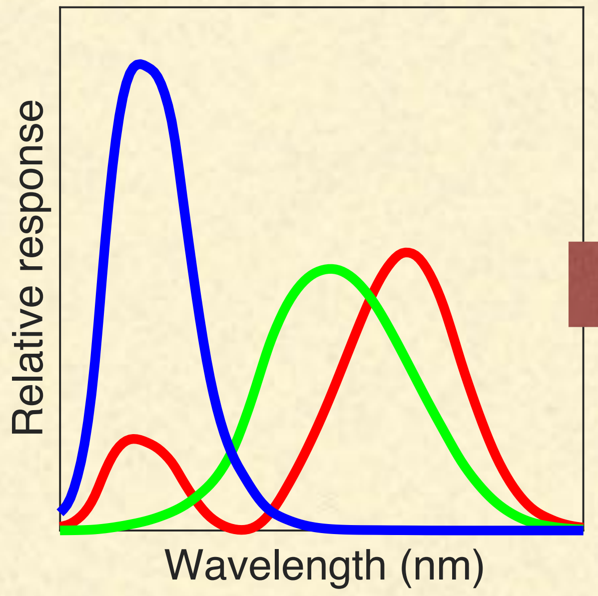


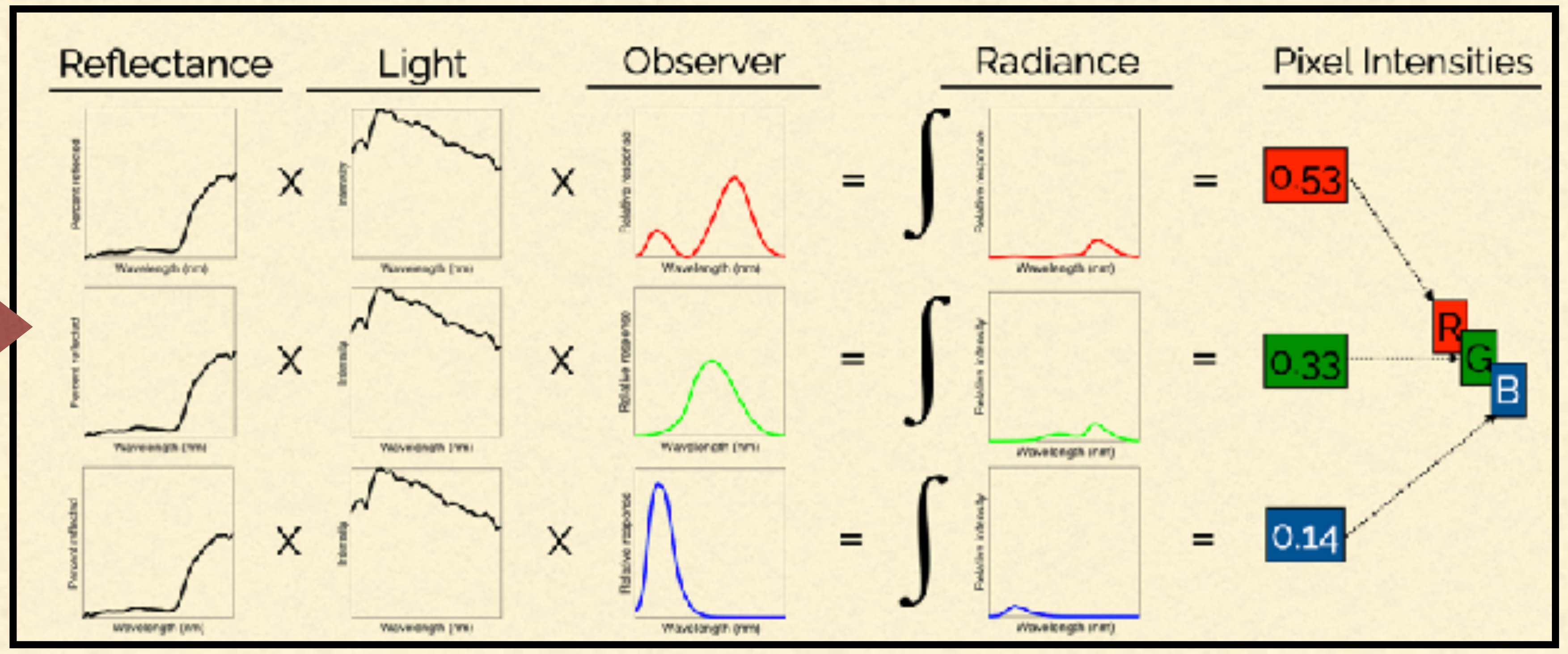


Camera RGB to XYZ transformation

Camera & illuminant specific !!!



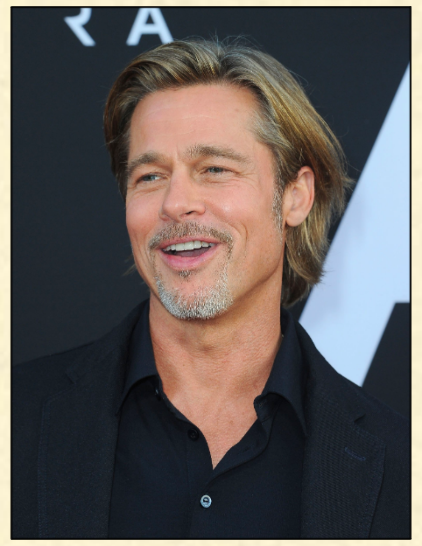


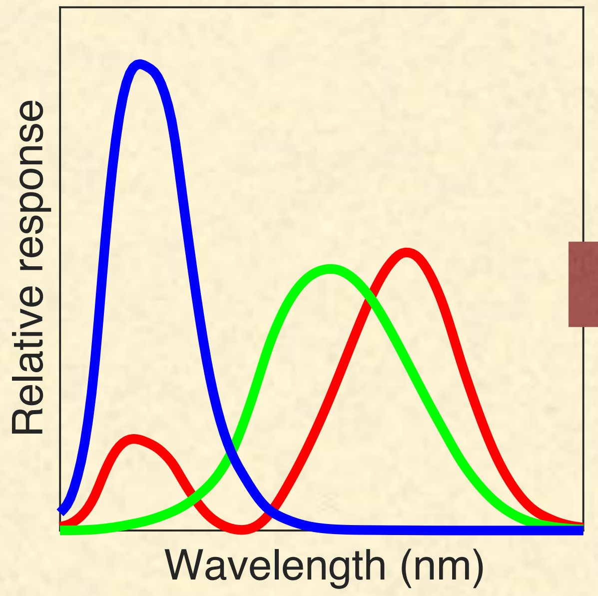


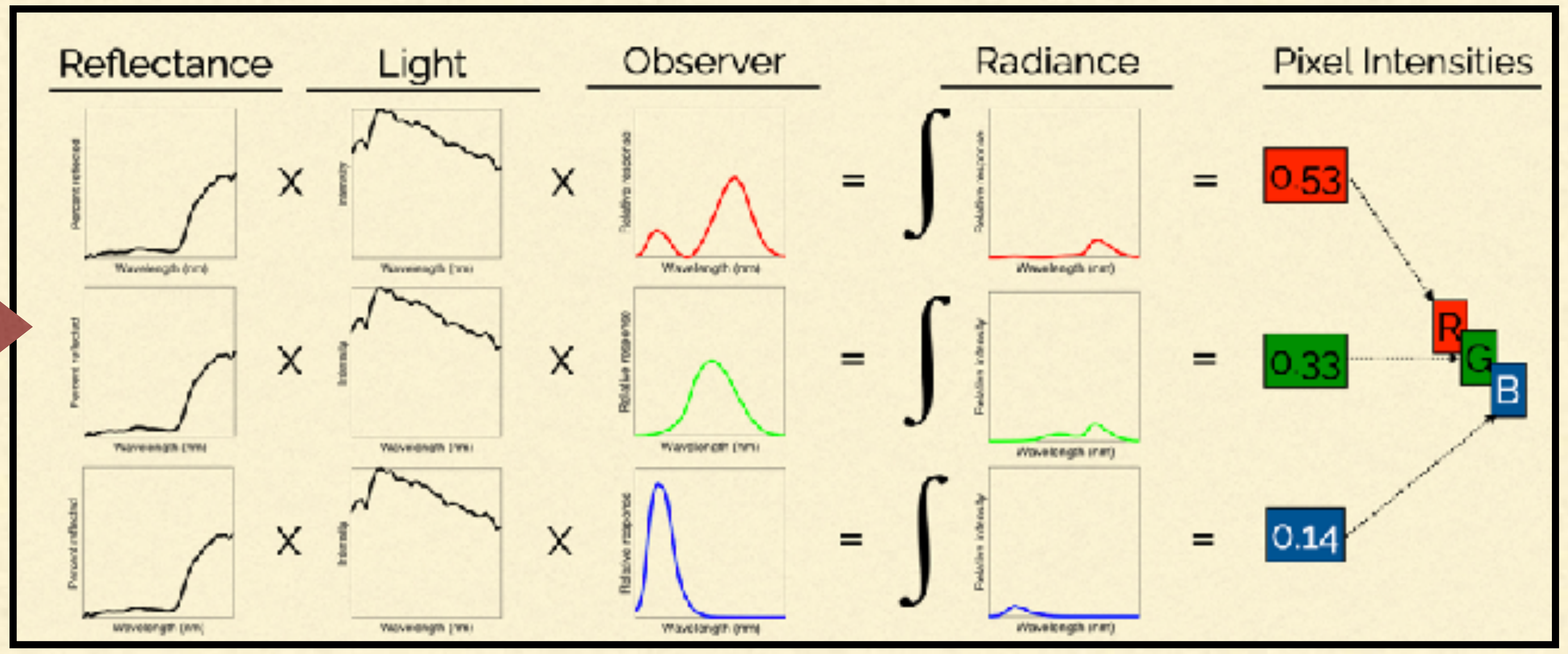
XYZ
[24 x 3]

Camera RGB to XYZ transformation

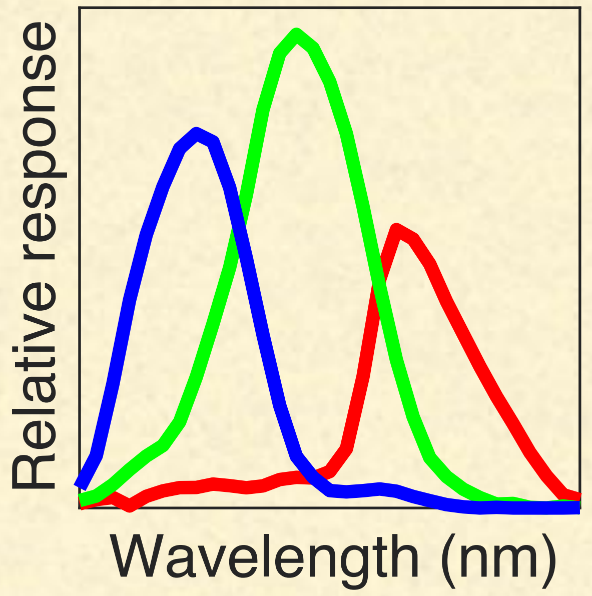
Camera & illuminant specific !!!





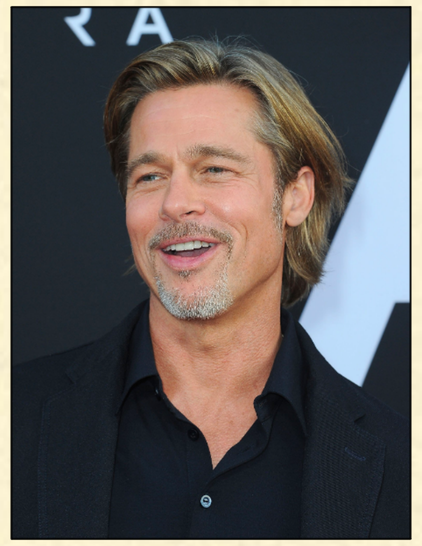


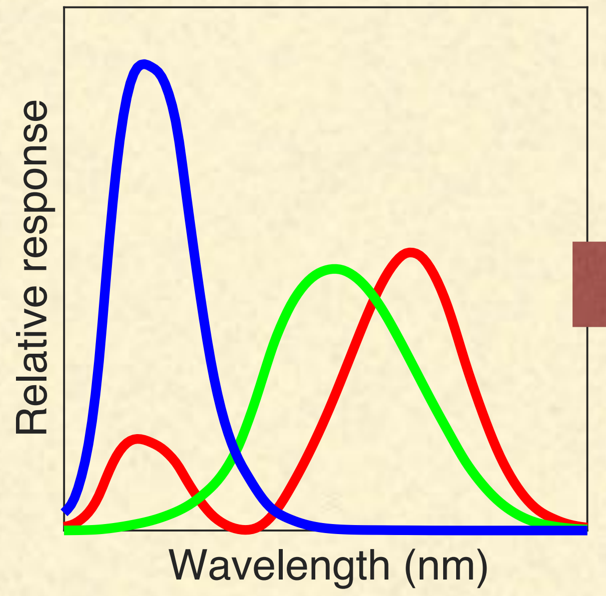
XYZ
[24 x 3]

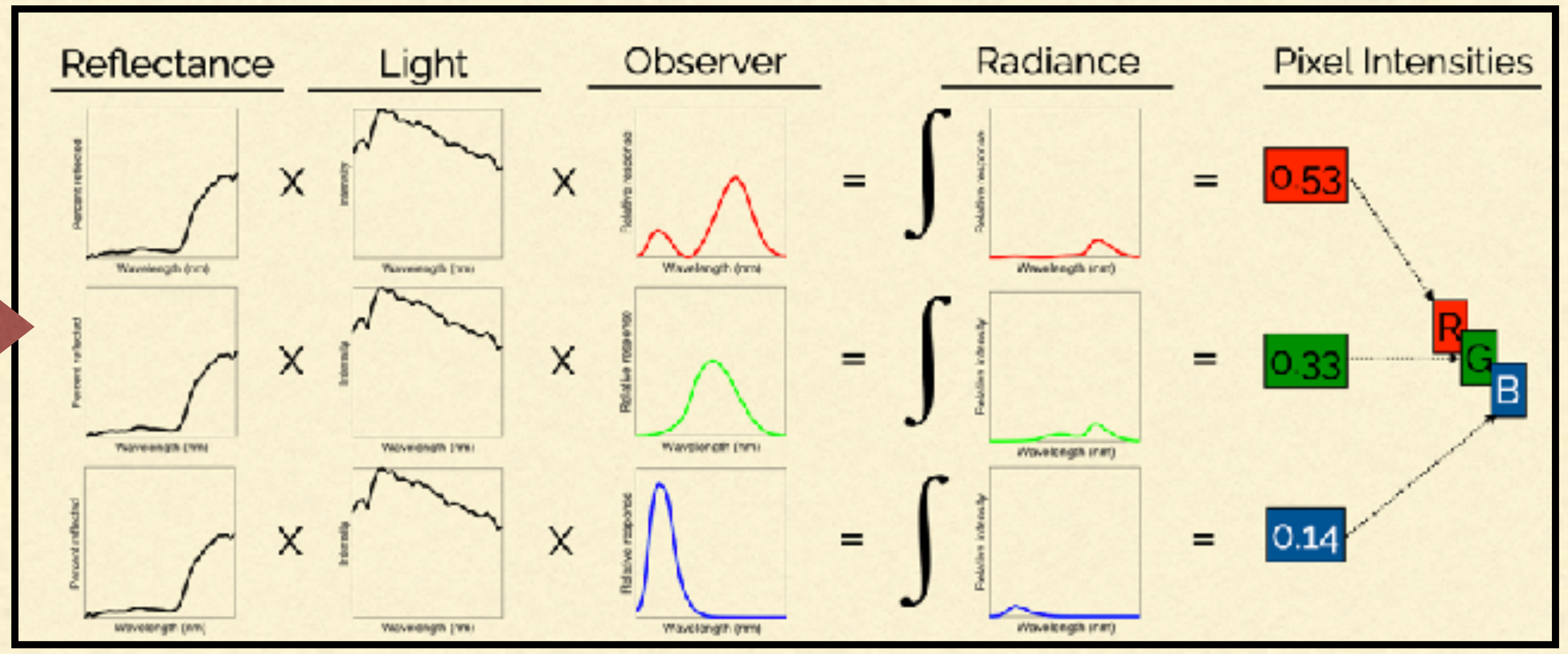


Camera RGB to XYZ transformation

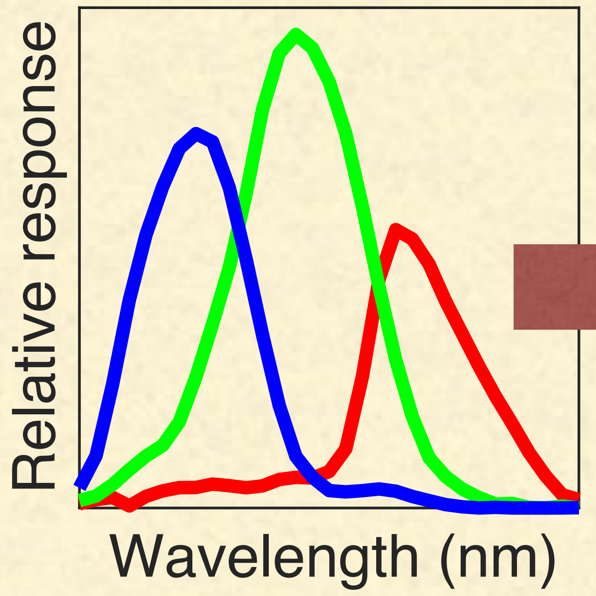
Camera & illuminant specific !!!

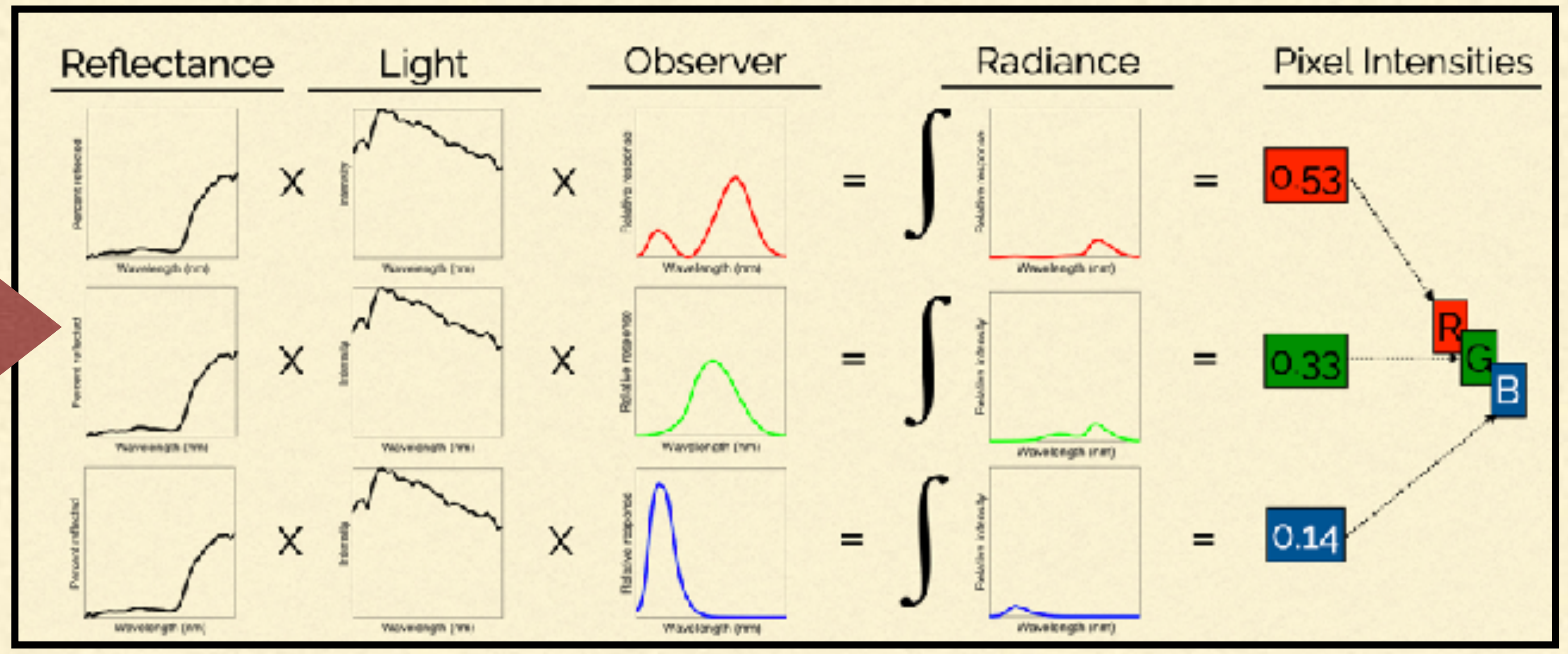






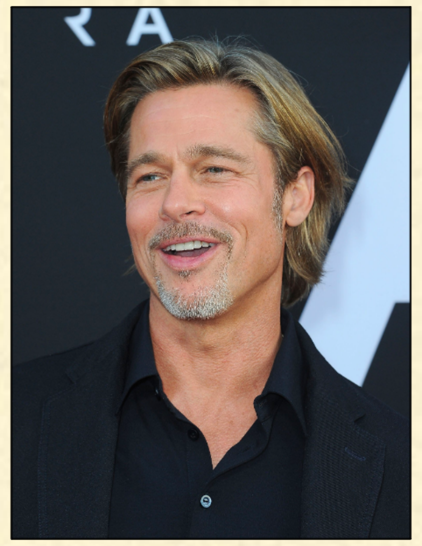
XYZ
[24 x 3]

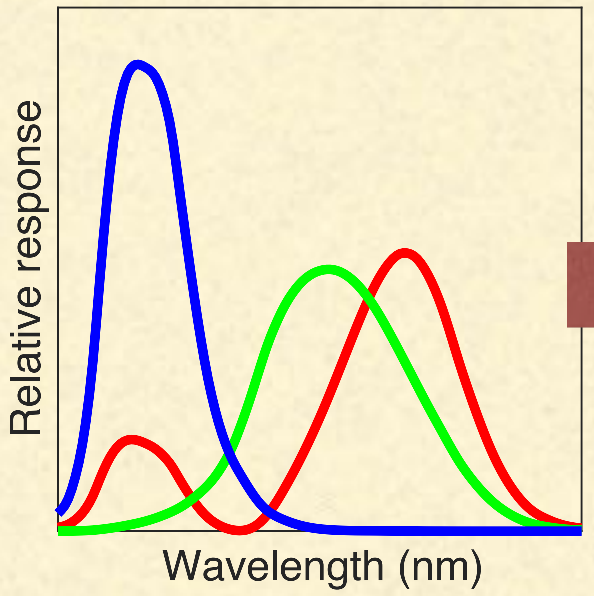


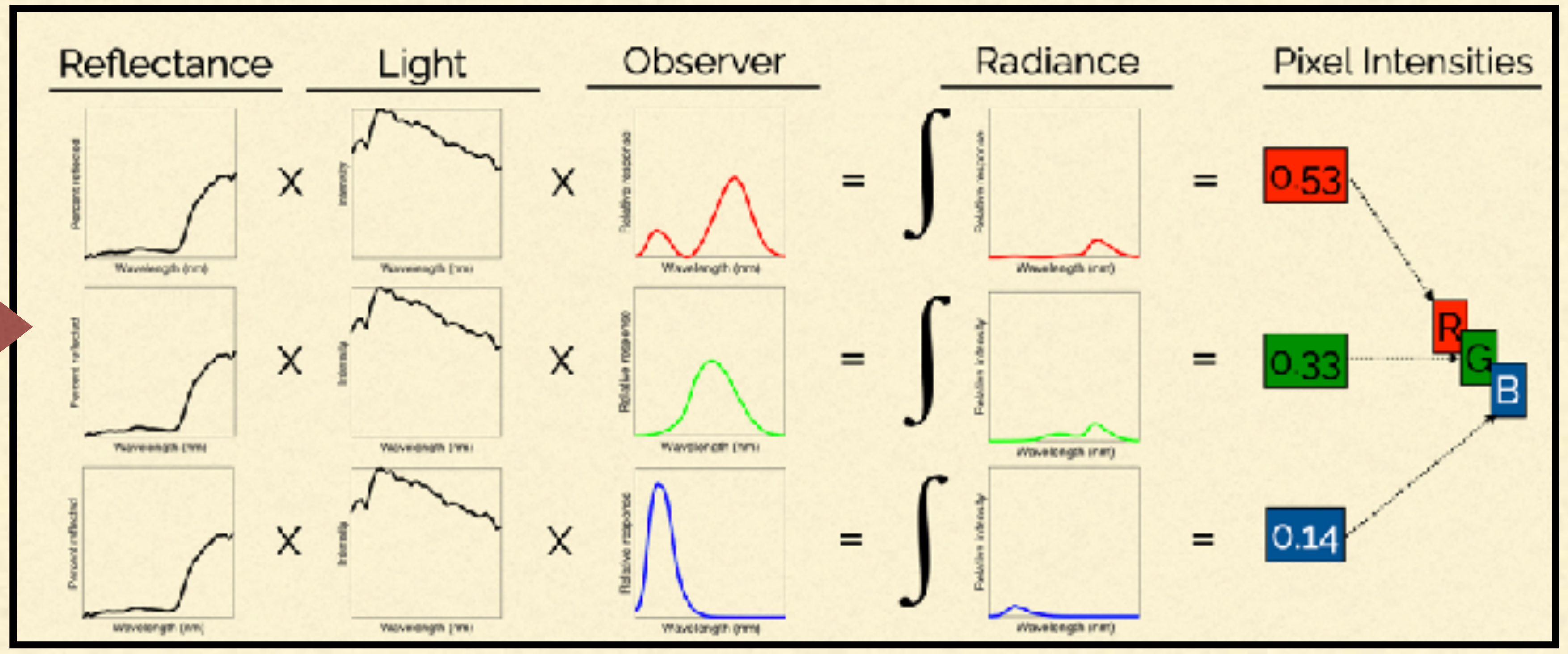


Camera RGB to XYZ transformation

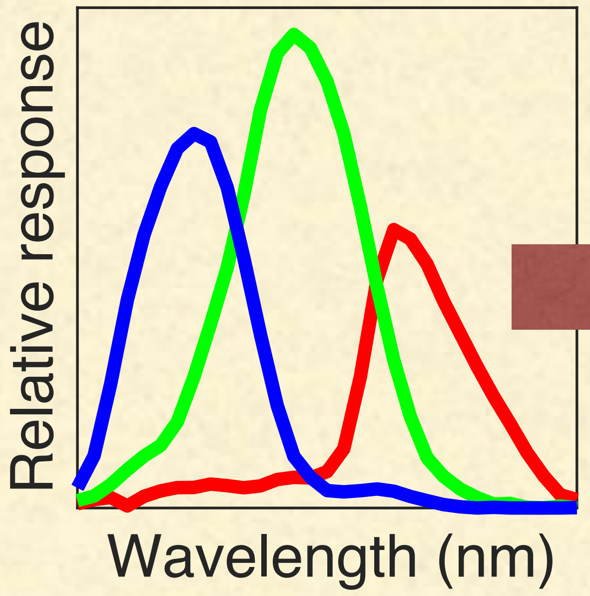
Camera & illuminant specific !!!

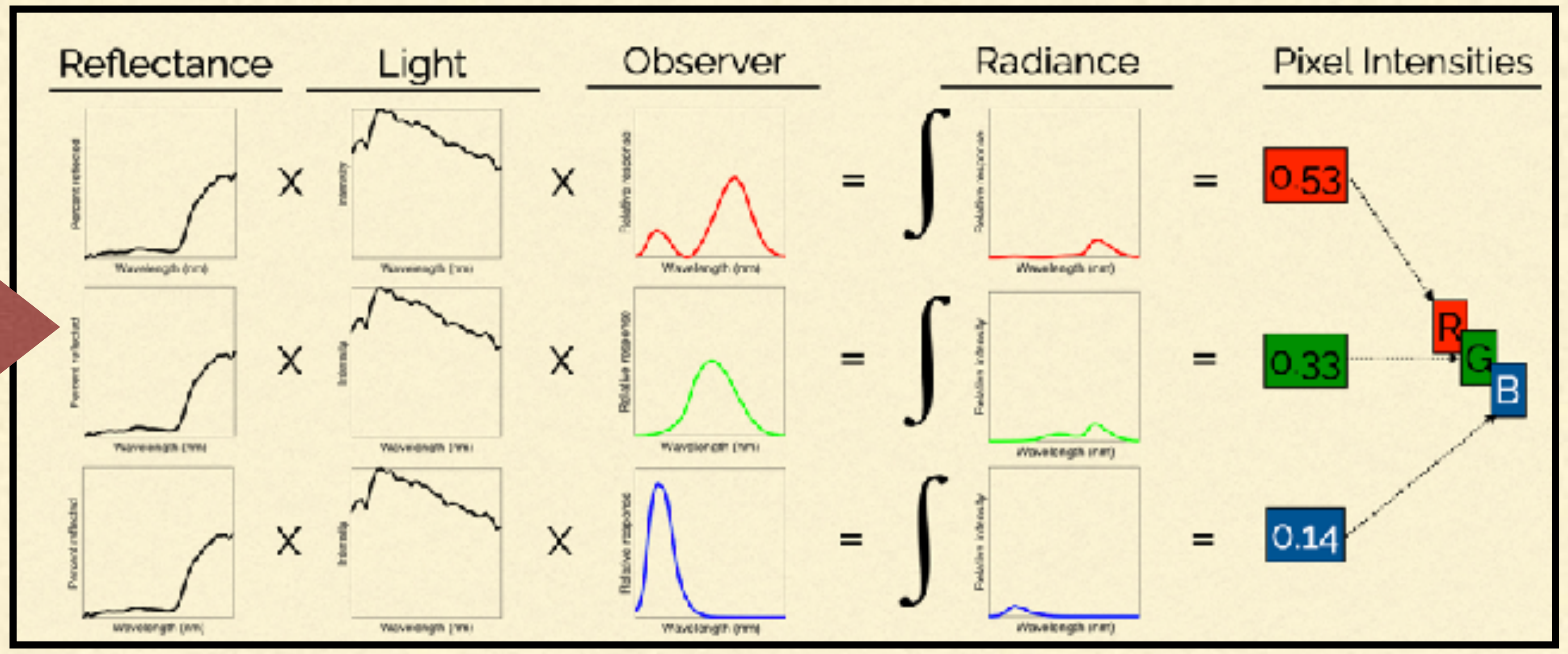






XYZ
[24 x 3]

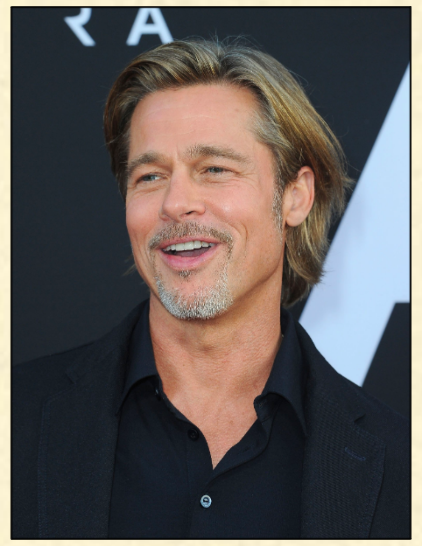


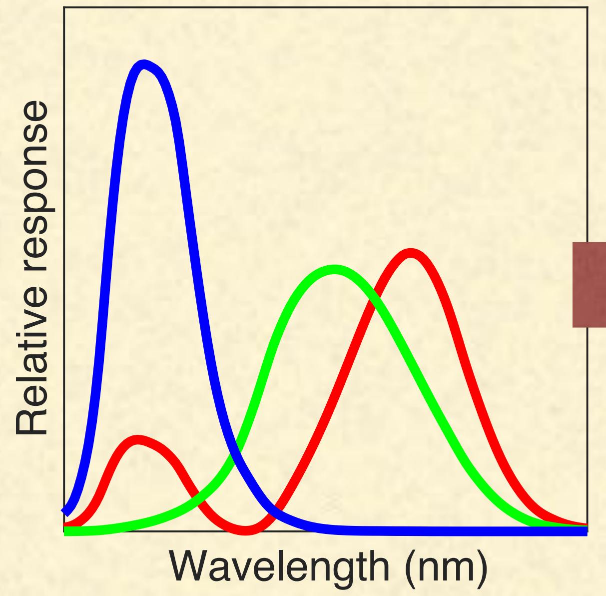


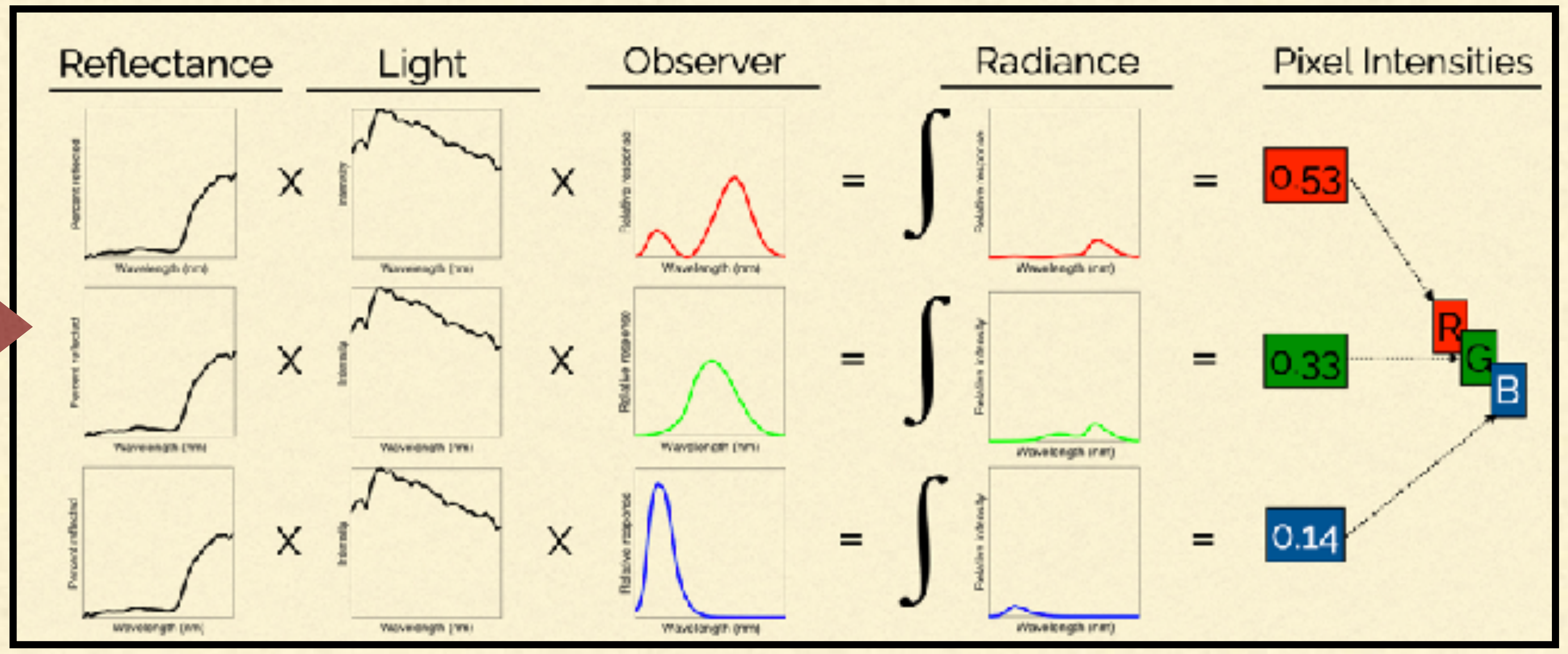
RGB
[24 x 3]

Camera RGB to XYZ transformation

Camera & illuminant specific !!!



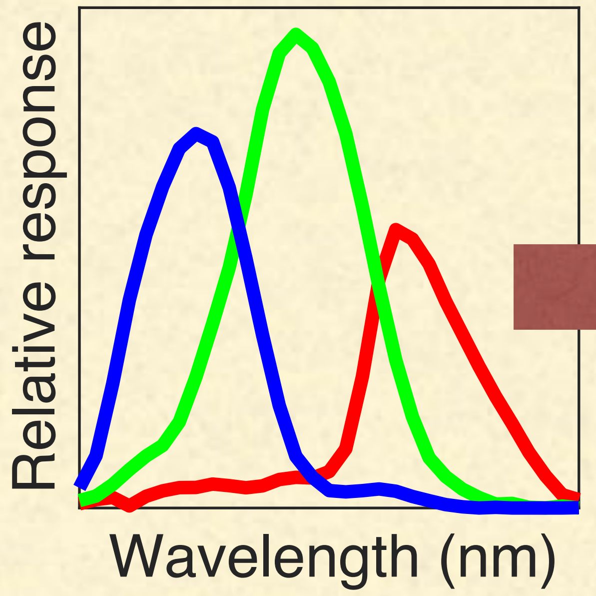


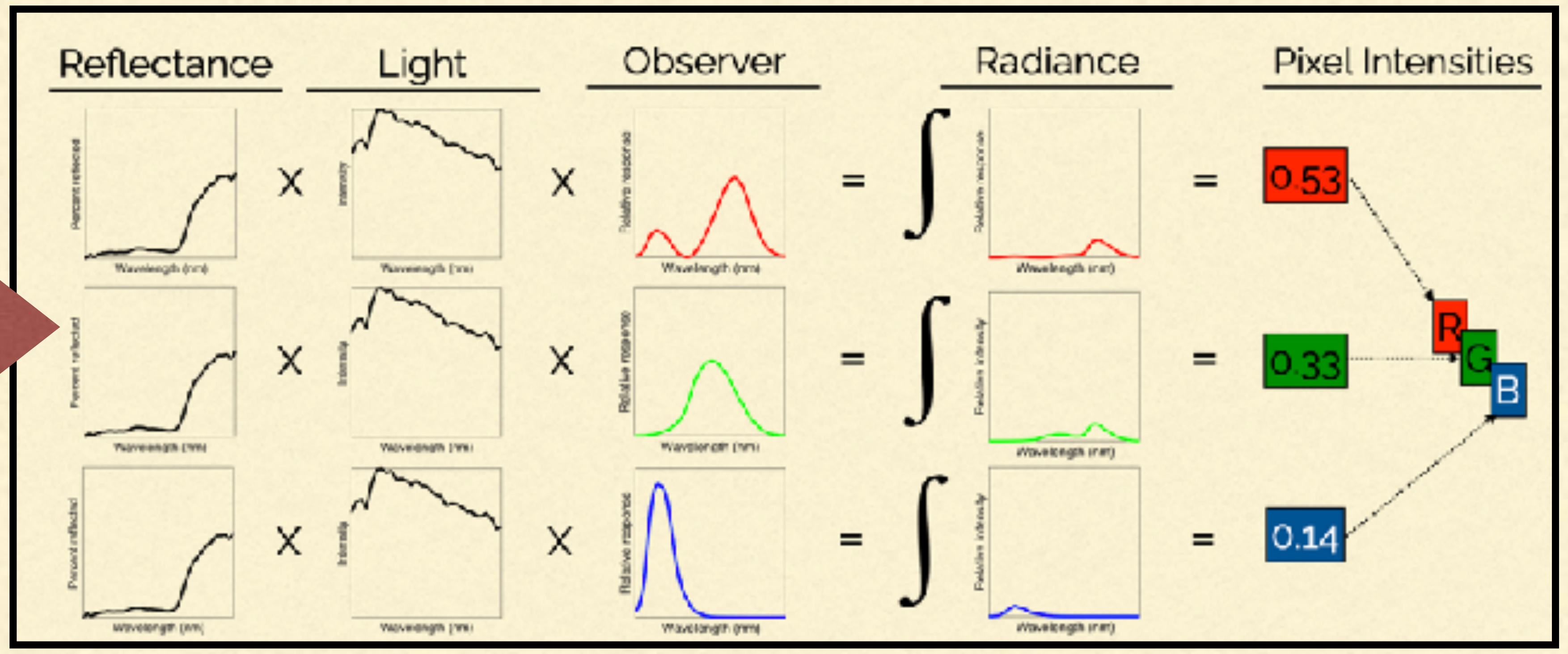


XYZ
[24 x 3]

M
[3 x 3]

$$[XYZ] = M[RGB]'$$





RGB
[24 x 3]

Camera RGB to XYZ transformation

Camera & illuminant specific !!!

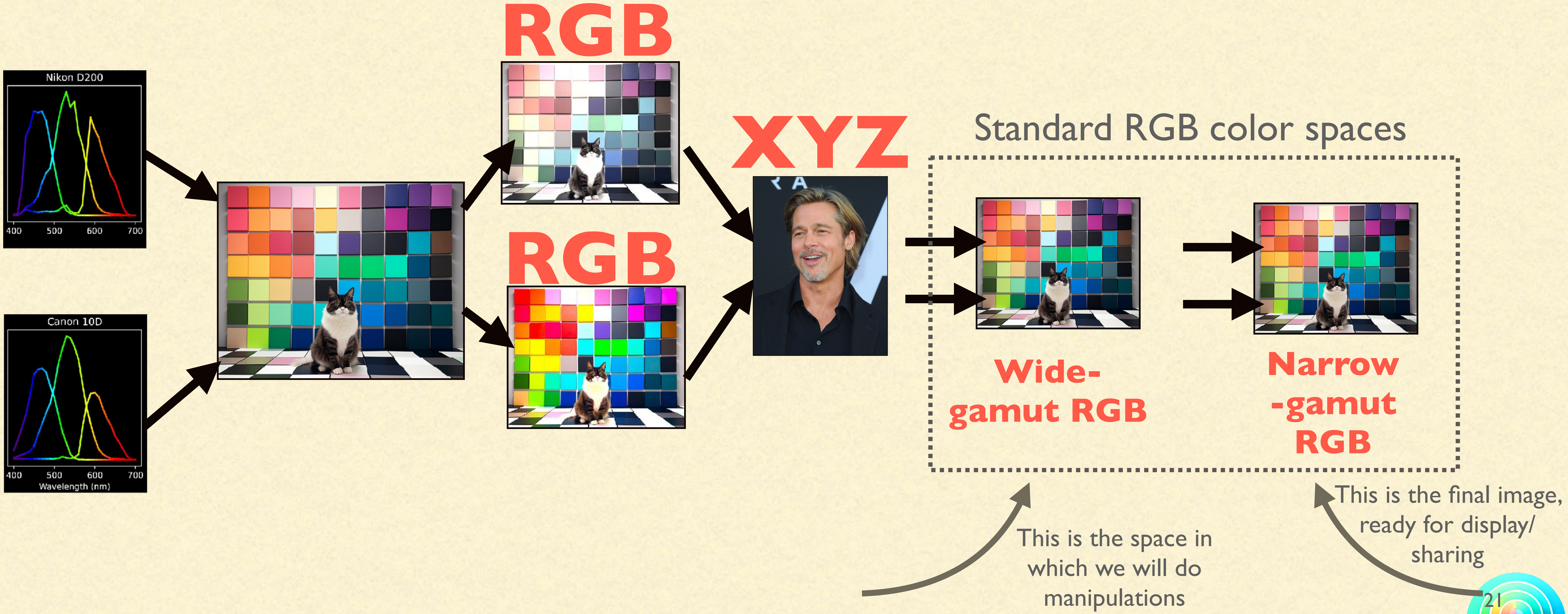
$$\underbrace{[XYZ]}_{24 \times 3} = \overbrace{M}^{3 \times 3}\underbrace{[RGB]'}_{(24 \times 3)'}$$

M is a 3 x 3 linear transformation matrix that maps camera-dependent RGB —> camera-independent XYZ under a given illuminant.

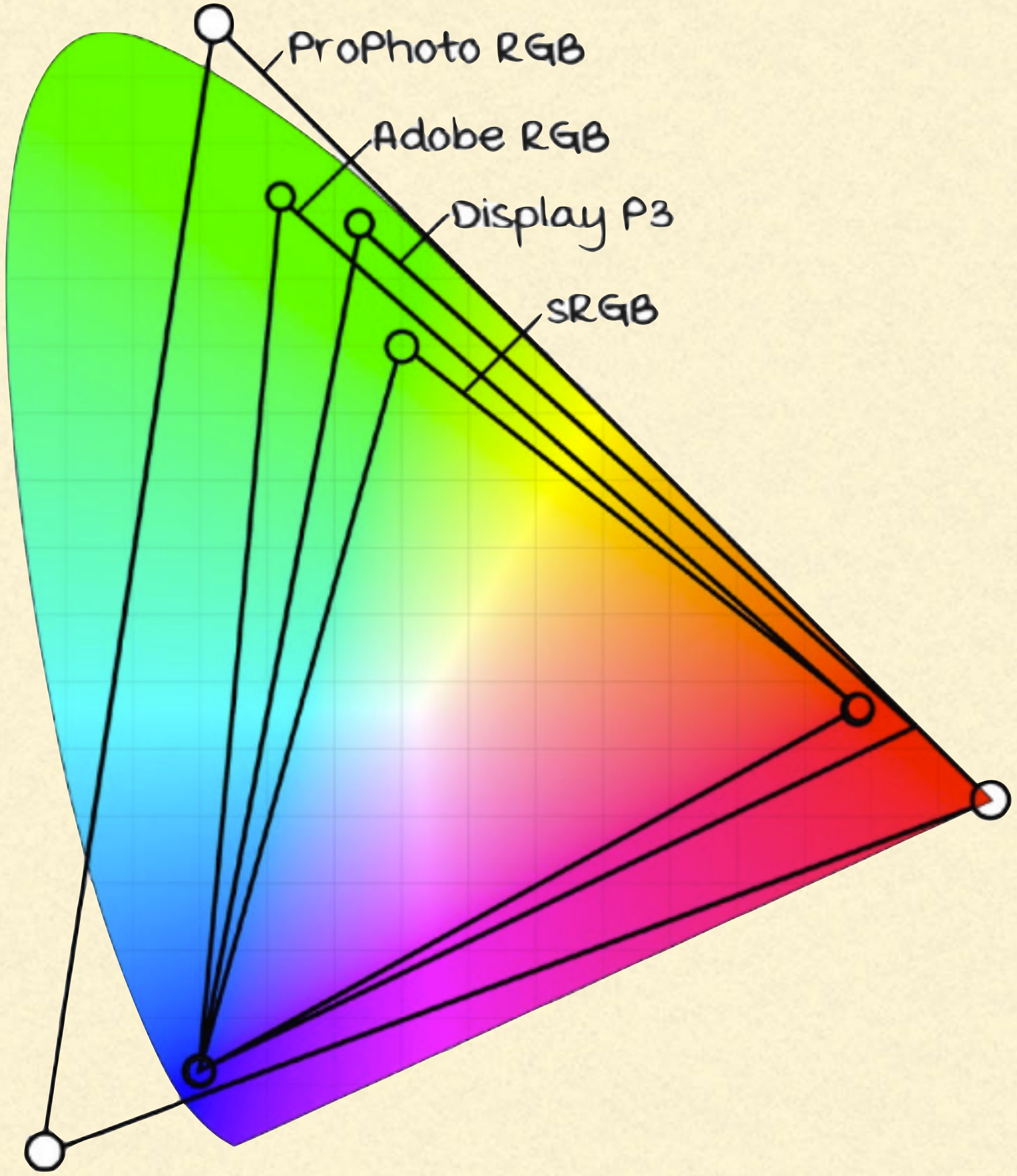
M depends on:

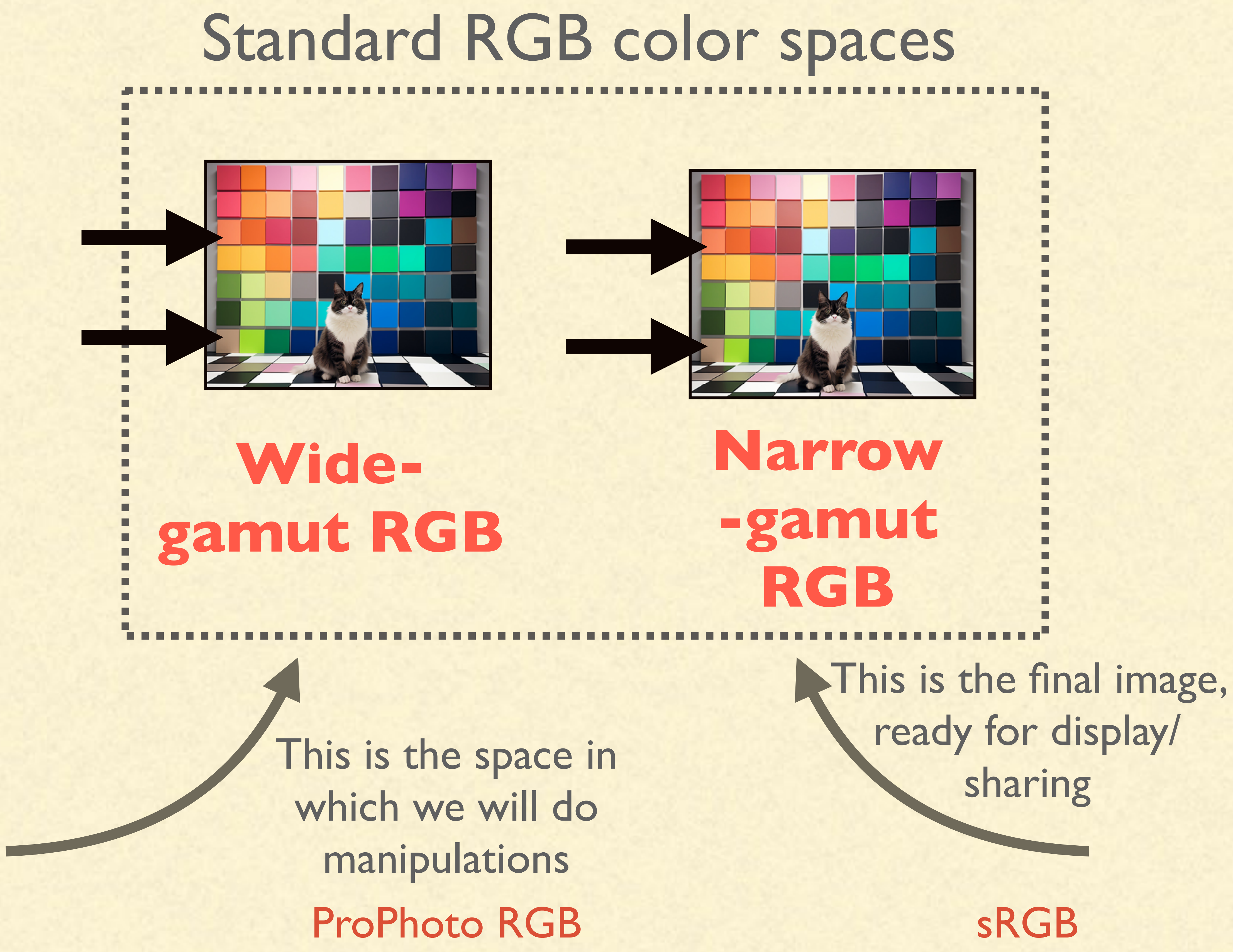
- The illuminant
- the number and type of patches used from the color chart
- The scaling of the RGB/XYZ matrices

WHAT HAPPENS AFTER XYZ?



STANDARD RGB COLOR SPACES





STANDARD RGB COLOR SPACES

RGB Working Space	Reference White	RGB to XYZ [M]	XYZ to RGB $[M]^{-1}$
Adobe RGB (1998)	D65	0.5767309 0.1855540 0.1881852 0.2973769 0.6273491 0.0752741 0.0270343 0.0706872 0.9911085	2.0413690 -0.5649464 -0.3446944 -0.9692660 1.8760108 0.0415560 0.0134474 -0.1183897 1.0154096
AppleRGB	D65	0.4497288 0.3162486 0.1844926 0.2446525 0.6720283 0.0833192 0.0251848 0.1411824 0.9224628	2.9515373 -1.2894116 -0.4730445 -1.0851093 1.9908566 0.0372026 0.0854934 -0.2694964 1.0912975
Best RGB	D50	0.6326696 0.2045558 0.1269946 0.2284569 0.7373523 0.0341908 0.0000000 0.0095142 0.8156958	1.7552599 -0.4836786 -0.2530000 -0.5441336 1.5068789 0.0215528 0.0063467 -0.0175761 1.2256959
Beta RGB	D50	0.6712537 0.1745834 0.1183829 0.3032726 0.6637861 0.0329413 0.0000000 0.0407010 0.7845090	1.6832270 -0.4282363 -0.2360185 -0.7710229 1.7065571 0.0446900 0.0400013 -0.0885376 1.2723640
Bruce RGB	D65	0.4674162 0.2944512 0.1886026 0.2410115 0.6835475 0.0754410 0.0219101 0.0736128 0.9933071	2.7454669 -1.1358136 -0.4350269 -0.9692660 1.8760108 0.0415560 0.0112723 -0.1139754 1.0132541
CIE RGB	E	0.4887180 0.3106803 0.2006017 0.1762044 0.8129847 0.0108109 0.0000000 0.0102048 0.9897952	2.3706743 -0.9000405 -0.4706338 -0.5138850 1.4253036 0.0885814 0.0052982 -0.0146949 1.0093968
ColorMatch RGB	D50	0.5093439 0.3209071 0.1339691 0.2748840 0.6581315 0.0669845 0.0242545 0.1087821 0.6921735	2.6422874 -1.2234270 -0.3930143 -1.1119763 2.0590183 0.0159614 0.0821699 -0.2807254 1.4559877
Don RGB 4	D50	0.6457711 0.1933511 0.1250978 0.2783496 0.6879702 0.0336802 0.0037113 0.0179861 0.8035125	1.7603902 -0.4881198 -0.2536126 -0.7126288 1.6527432 0.0416715 0.0078207 -0.0347411 1.2447743
ECI RGB	D50	0.6502043 0.1780774 0.1359384 0.3202499 0.6020711 0.0776791 0.0000000 0.0678390 0.7573710	1.7827618 -0.4969847 -0.2690101 -0.9593623 1.9477962 -0.0275807 0.0859317 -0.1744674 1.3228273
Ekta Space PS5	D50	0.5938914 0.2729801 0.0973485 0.2606286 0.7349465 0.0044249 0.0000000 0.0419969 0.7832131	2.0043819 -0.7304844 -0.2450052 -0.7110285 1.6202126 0.0792227 0.0381263 -0.0868780 1.2725438
NTSC RGB	C	0.6068909 0.1735011 0.2003480 0.2989164 0.5865990 0.1144845 0.0000000 0.0660957 1.1162243	1.9099961 -0.5324542 -0.2882091 -0.9846663 1.9991710 -0.0283082 0.0583056 -0.1183781 0.8975535
PAL/SECAM RGB	D65	0.4306190 0.3415419 0.1783091 0.2220379 0.7066384 0.0713236 0.0201853 0.1295504 0.9390944	3.0628971 -1.3931791 -0.4757517 -0.9692660 1.8760108 0.0415560 0.0678775 -0.2288548 1.0693490

RGB Working Space	Reference White	RGB to XYZ [M]	XYZ to RGB $[M]^{-1}$
ProPhoto RGB	D50	0.7976749 0.1351917 0.0313534 0.2880402 0.7118741 0.0000857 0.0000000 0.0000000 0.8252100	1.3459433 -0.2556075 -0.0511118 -0.5445989 1.5081673 0.0205351 0.0000000 0.0000000 1.2118128
SMPTE-C RGB	D65	0.3935891 0.3652497 0.1916313 0.2124132 0.7010437 0.0865432 0.0187423 0.1119313 0.9581563	3.5053960 -1.7394894 -0.5439640 -1.0690722 1.9778245 0.0351722 0.0563200 -0.1970226 1.0502026
sRGB	D65	0.4124564 0.3575761 0.1804375 0.2126729 0.7151522 0.0721750 0.0193339 0.1191920 0.9503041	3.2404542 -1.5371385 -0.4985314 -0.9692660 1.8760108 0.0415560 0.0556434 -0.2040259 1.0572252
Wide Gamut RGB	D50	0.7161046 0.1009296 0.1471858 0.2581874 0.7249378 0.0168748 0.0000000 0.0517813 0.7734287	1.4628067 -0.1840623 -0.2743606 -0.5217933 1.4472381 0.0677227 0.0349342 -0.0968930 1.2884099

All related to XYZ color space with a 3 x 3 linear transform!

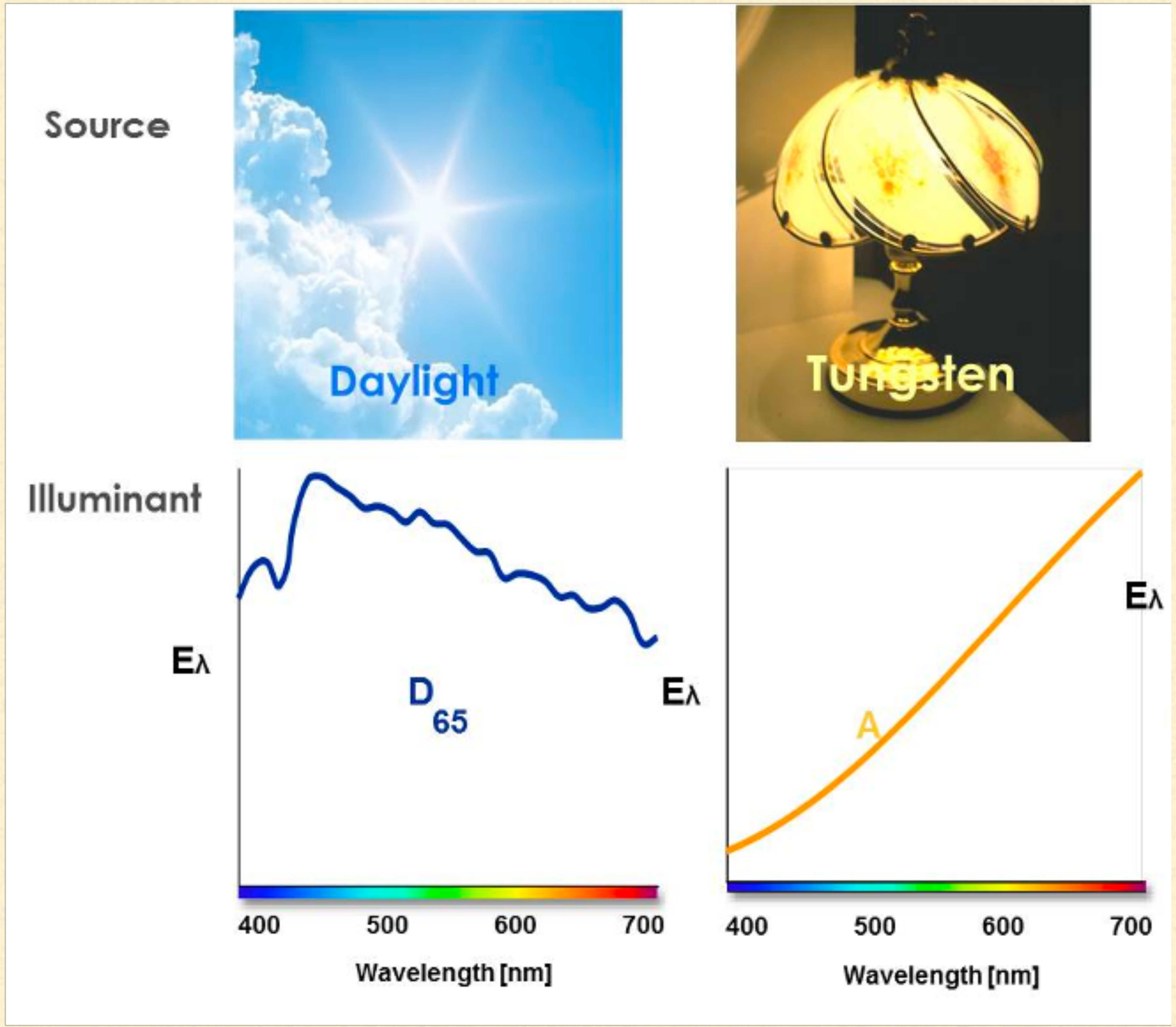
STANDARD RGB COLOR SPACES

$$\underbrace{[XYZ]}_{\text{Your image in XYZ color space}} = M\underbrace{[RGB]'}_{\text{Your image in camera color space}}$$

$$\underbrace{[RGB_{standard}]}_{\text{Your image in a standard RGB color space, eg ProPhoto}} = T\underbrace{[XYZ]}_{\text{Your image in XYZ color space}}$$

T is a 3x3 linear transformation matrix that maps colors from the XYZ space to a standard RGB space.

CIE STANDARD ILLUMINANTS : D65, A



From the ISO standards:

a) **CIE standard illuminant A**

This is intended to represent typical, domestic, tungsten-filament lighting. Its relative spectral power distribution is that of a Planckian radiator at a temperature of approximately 2856 K. CIE standard illuminant A should be used in all applications of colorimetry involving the use of incandescent lighting, unless there are specific reasons for using a different illuminant.

b) **CIE standard illuminant D65**

This is intended to represent average daylight and has a correlated colour temperature of approximately 6500 K. CIE standard illuminant D65 should be used in all colorimetric calculations requiring representative daylight, unless there are specific reasons for using a different illuminant. Variations in the relative spectral power distribution of daylight are known to occur, particularly in the ultraviolet spectral region, as a function of season, time of day, and geographic location.

Illuminant is a mathematical description of a light source. It has:

- a spectral distribution
- Correlated color temperature

CIE DAYLIGHT MODEL

T: correlated color temperature: a way to describe the "warmth" or "coolness" of light sources.

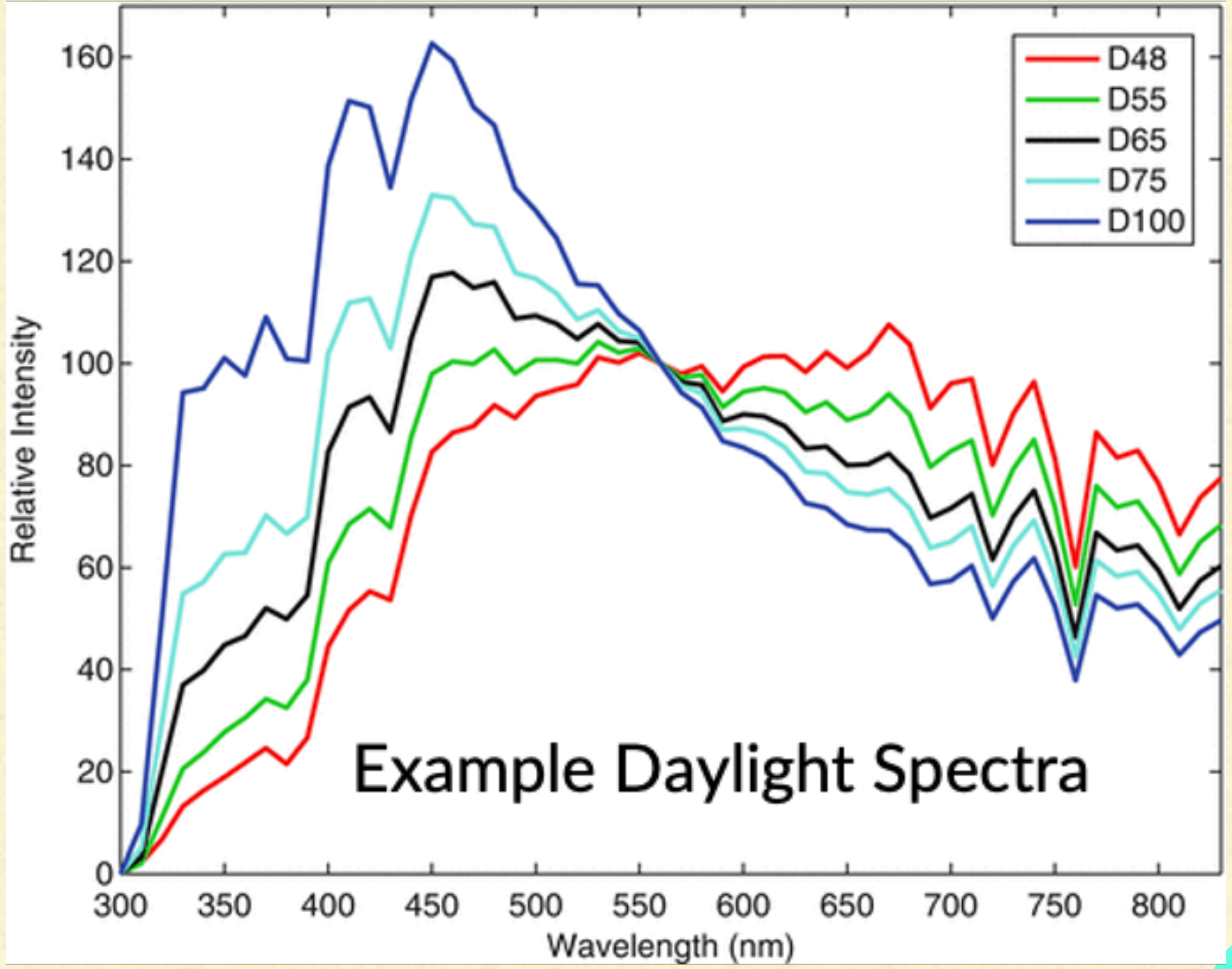
CCT is the temperature at which a theoretical blackbody radiator would emitted light of same color.

A blackbody is an "ideal" object that absorbs all electromagnetic radiation and re-emits radiation based on its temperature.

$$L_T(\lambda) = L_0(\lambda) + M_1(T)L_1(\lambda) + M_2(T)L_2(\lambda)$$

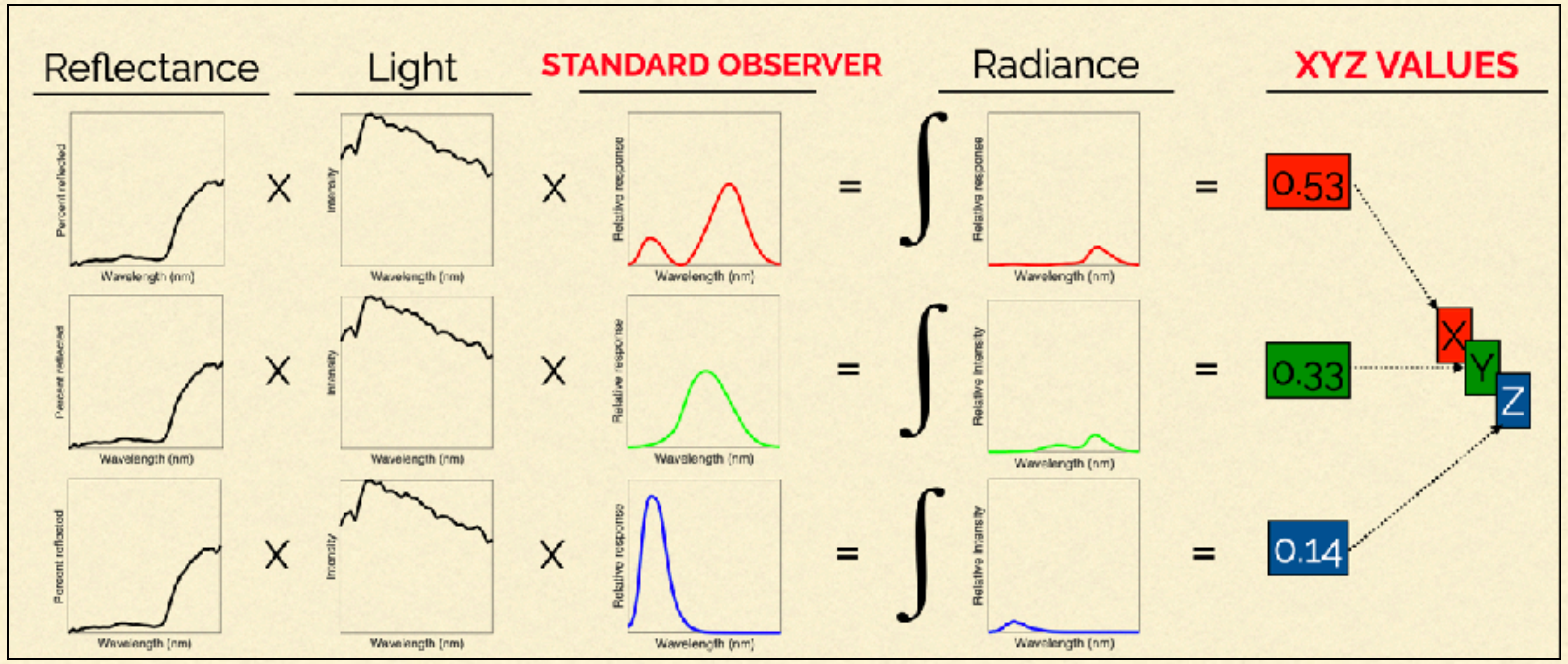
where

$$\begin{aligned}
M_1 &= (-1.3515 - 1.7703x_D(T) + 5.9114y_D(T))/M ,\\
M_2 &= (0.0300 - 31.4424x_D(T) + 30.0717y_D(T))/M ,\\
M &= 0.0241 + 0.2562x_D(T) - 0.7341y_D(T) ,\\
y_D(T) &= -3.000x_D(T)^2 + 2.879x_D(T) - 0.275,\\
x_D(T) &= \begin{cases} 0.244063 + 0.09911\frac{10^3}{T} + 2.9678\frac{10^6}{T^2} - 4.6070\frac{10^9}{T^3} & \text{if } 4000\text{K} \le T \le 7000\text{K} \\ 0.237040 + 0.24748\frac{10^3}{T} + 1.9018\frac{10^6}{T^2} - 2.0064\frac{10^9}{T^3} & \text{if } 7000\text{K} < T \le 25000\text{K} \end{cases}
\end{aligned}$$



WHITE POINT OF AN ILLUMINANT

RGB Working Space	Reference White	RGB to XYZ [M]	XYZ to RGB $[M]^{-1}$
ProPhoto RGB	D50	0.7976749 0.1351917 0.0313534 0.2880402 0.7118741 0.0000857 0.0000000 0.0000000 0.8252100	1.3459433 -0.2556075 -0.0511118 -0.5445989 1.5081673 0.0205351 0.0000000 0.0000000 1.2118128
SMPTE-C RGB	D65	0.3935891 0.3652497 0.1916313 0.2124132 0.7010437 0.0865432 0.0187423 0.1119313 0.9581563	3.5053960 -1.7394894 -0.5439640 -1.0690722 1.9778245 0.0351722 0.0563200 -0.1970226 1.0502026
sRGB	D65	0.4124564 0.3575761 0.1804375 0.2126729 0.7151522 0.0721750 0.0193339 0.1191920 0.9503041	3.2404542 -1.5371385 -0.4985314 -0.9692660 1.8760108 0.0415560 0.0556434 -0.2040259 1.0572252
Wide Gamut RGB	D50	0.7161046 0.1009296 0.1471858 0.2581874 0.7249378 0.0168748 0.0000000 0.0517813 0.7734287	1.4628067 -0.1840623 -0.2743606 -0.5217933 1.4472381 0.0677227 0.0349342 -0.0968930 1.2884099



Calculate the XYZ values just the same way you would, but assume reflectance is 100% uniform (i.e., a perfect white surface).

CHROMATIC ADAPTATION TRANSFORM (CAT)

- Converting from the white point of one illuminant to another (source→ destination)
- A kind of white-balancing but more elaborate as it relates to color constancy
- Once again, a sequence of simple 3 x 3 linear transforms

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = [M] \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

XYZ white point of your destination color space (eg, D50 for prophoto)

XYZ white point of your source illuminant

$$[M] = [M_A]^{-1} \begin{bmatrix} \rho_D/\rho_S & 0 & 0 \\ 0 & \gamma_D/\gamma_S & 0 \\ 0 & 0 & \beta_D/\beta_S \end{bmatrix} [M_A]$$

$$\begin{bmatrix} \rho_S \\ \gamma_S \\ \beta_S \end{bmatrix} = [M_A] \begin{bmatrix} X_{WS} \\ Y_{WS} \\ Z_{WS} \end{bmatrix}$$

$$\begin{bmatrix} \rho_D \\ \gamma_D \\ \beta_D \end{bmatrix} = [M_A] \begin{bmatrix} X_{WD} \\ Y_{WD} \\ Z_{WD} \end{bmatrix}$$

Method	$[M_A]$	$[M_A]^{-1}$
XYZ Scaling	1.0000000 0.0000000 0.0000000 0.0000000 1.0000000 0.0000000 0.0000000 0.0000000 1.0000000	1.0000000 0.0000000 0.0000000 0.0000000 1.0000000 0.0000000 0.0000000 0.0000000 1.0000000
Bradford	0.8951000 0.2664000 -0.1614000 -0.7502000 1.7135000 0.0367000 0.0389000 -0.0685000 1.0296000	0.9869929 -0.1470543 0.1599627 0.4323053 0.5183603 0.0492912 -0.0085287 0.0400428 0.9684867
Von Kries	0.4002400 0.7076000 -0.0808100 -0.2263000 1.1653200 0.0457000 0.0000000 0.0000000 0.9182200	1.8599364 -1.1293816 0.2198974 0.3611914 0.6388125 -0.0000064 0.0000000 0.0000000 1.0890636

CHROMATIC ADAPTATION TRANSFORM (CAT)

- Converting from the white point of one illuminant to another (source → destination)
- A kind of white-balancing but more elaborate as it relates to color constancy
- Once again, a sequence of simple 3 x 3 linear transforms

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = [M] \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

XYZ white point of your destination color space (eg, D50 for prophoto)

XYZ white point of your source illuminant

$$[M] = [M_A]^{-1} \begin{bmatrix} \rho_D/\rho_S & 0 & 0 \\ 0 & \gamma_D/\gamma_S & 0 \\ 0 & 0 & \beta_D/\beta_S \end{bmatrix} [M_A]$$

$$\begin{bmatrix} \rho_S \\ \gamma_S \\ \beta_S \end{bmatrix} = [M_A] \begin{bmatrix} X_{WS} \\ Y_{WS} \\ Z_{WS} \end{bmatrix}$$

$$\begin{bmatrix} \rho_D \\ \gamma_D \\ \beta_D \end{bmatrix} = [M_A] \begin{bmatrix} X_{WD} \\ Y_{WD} \\ Z_{WD} \end{bmatrix}$$

Method	$[M_A]$			$[M_A]^{-1}$		
XYZ Scaling	1.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000
	0.0000000	1.0000000	0.0000000	0.0000000	1.0000000	0.0000000
	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	1.0000000
Bradford	0.8951000	0.2664000	-0.1614000	0.9869929	-0.1470543	0.1599627
	-0.7502000	1.7135000	0.0367000	0.4323053	0.5183603	0.0492912
	0.0389000	-0.0685000	1.0296000	-0.0085287	0.0400428	0.9684867
Von Kries	0.4002400	0.7076000	-0.0808100	1.8599364	-1.1293816	0.2198974
	-0.2263000	1.1653200	0.0457000	0.3611914	0.6388125	-0.0000064
	0.0000000	0.0000000	0.9182200	0.0000000	0.0000000	1.0890636

SUMMARY

- If using "colors" as data, you must specify in which color space your data are in.
- Values in your camera's color space will not be reproducible by anyone else (that might be ok depending on your question/application)
- You always need a calibrated color chart, ideally in every frame
- You must have proper grays (ie with uniform reflectance) to capture the color of light
- Wait till you hear how all of this gets harder underwater!

Break

- Thank you for not using your cell phones during the lectures.

- Brain rot: A condition of mental fogginess, lethargy, reduced attention span, and cognitive decline that results from an overabundance of screen time.

"It keeps me from looking at my phone every two seconds."

Liam Walsh/The New Yorker