Measuring Color

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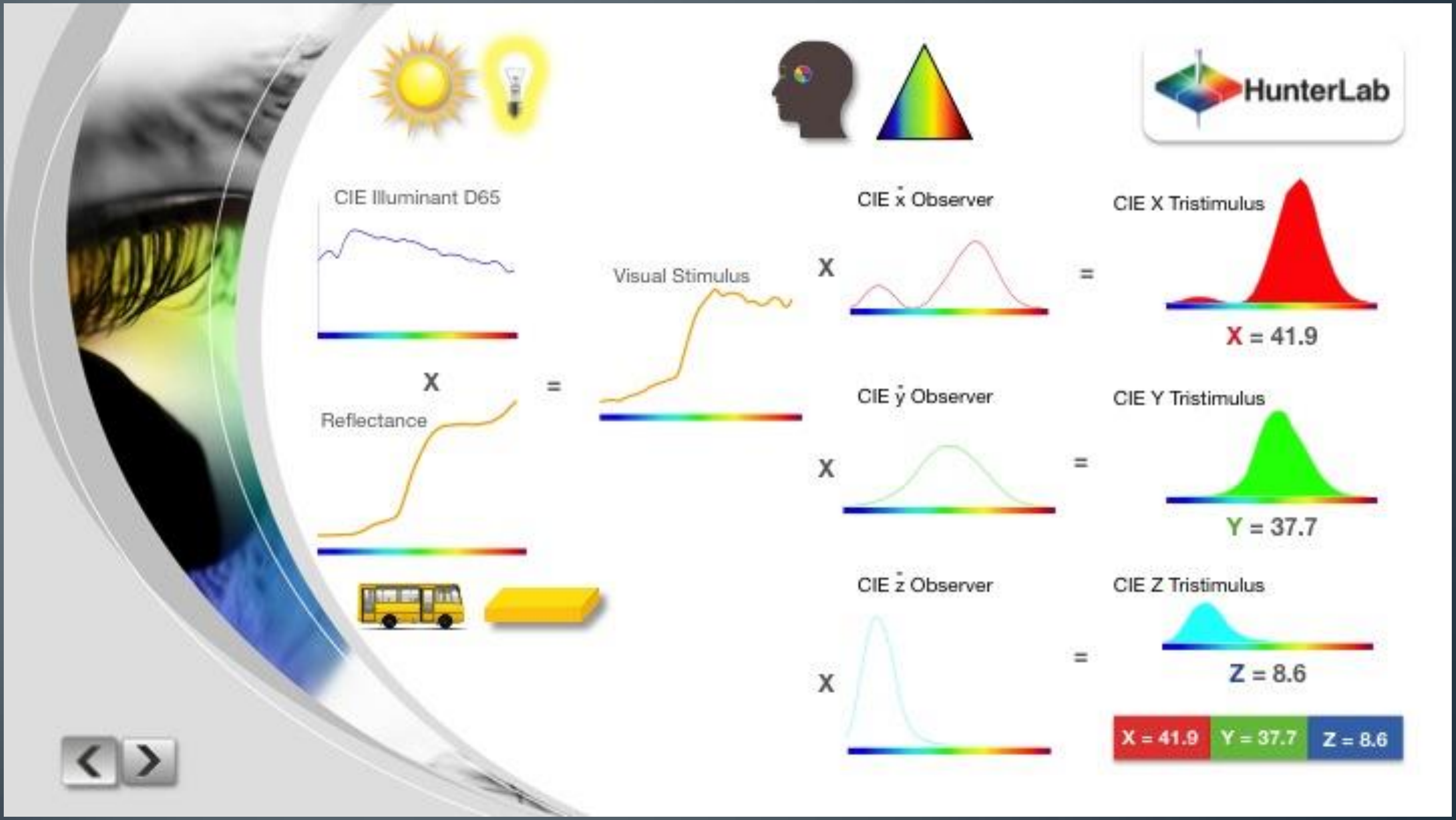
Recap



HunterLab
CIE Illuminant D65
Visual Stimulus
X
=
Reflectance
CIE $\bar{x}$ Observer
CIE X Tristimulus
X = 41.9
CIE $\bar{y}$ Observer
CIE Y Tristimulus
Y = 37.7
CIE $\bar{z}$ Observer
CIE Z Tristimulus
Z = 8.6
X = 41.9
Y = 37.7
Z = 8.6

How we can measure color?

- Spectrophotometer
  - Response throughout the entire visible spectrum
  - Relatively small areas (few cm^2) – Resolution is 1 point
  - “Flat” surfaces
- RGB Camera
  - Response in 3 wavelengths (Red, Green, Blue)
  - Large areas – High Spatial Resolution (< 50MPixels)
  - Any kind of surfaces
- Hyperspectral Camera
  - Response throughout the entire visible spectrum (and more)
  - Large areas – Low Spatial Resolution (< 2MPixels)
  - Any kind of surfaces

Measuring Color: Contents

- When Not to Measure Color
- Measuring with Spectrophotometers
- Measuring with RGB Cameras
- Future Trends ?

When Not to Measure Color

When Not to Measure Color

- Using instruments to measure color and compute differences objectively is not always needed.

- For example:

A company has a corporate color (possible ™)

Pantone 123C

Pantone 137C

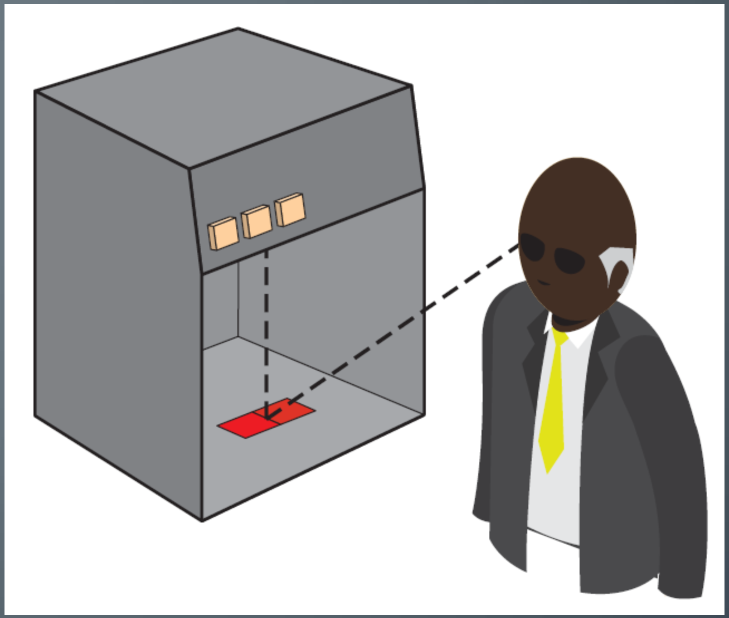
Pantone 18.1663TP

Products carrying the color are sold; however they are manufactured by different providers

Judging by Visual Assessment

- Need Consistent Lighting
- Need Consistent Viewing
- Need to Check for Metamers

→ Use a light booth (manufacturers use the same model)

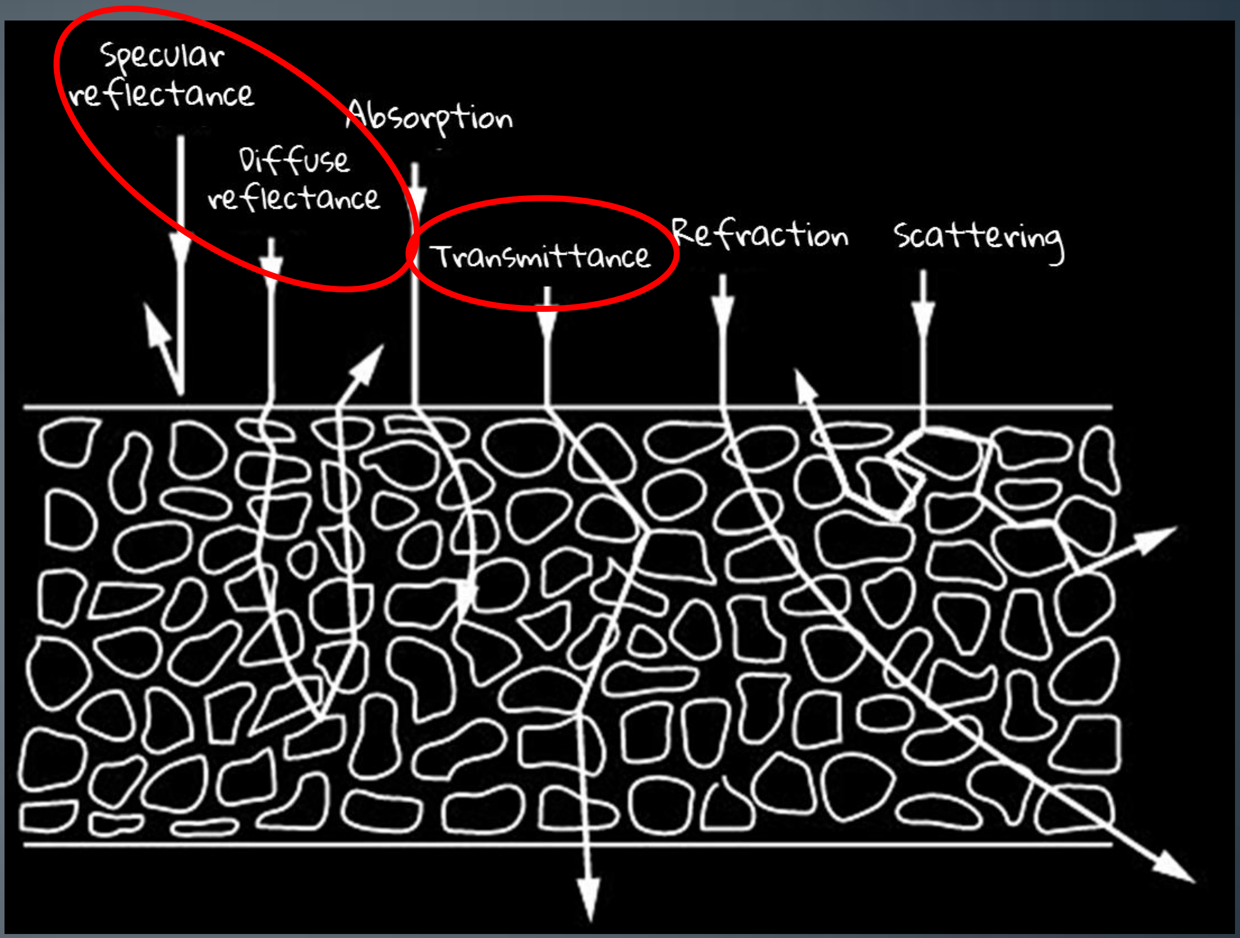


Judging by Visual Assessment

- Sufficient when there are few standard samples to be matched.
- Sufficient when tolerance is judged visually by color experts.
- Requires all manufacturers to have a physical copy of the standard, an to have the same hardware.
- Because there are no measurements, we don't know how to adjust our color workflow in case we need to match a color.

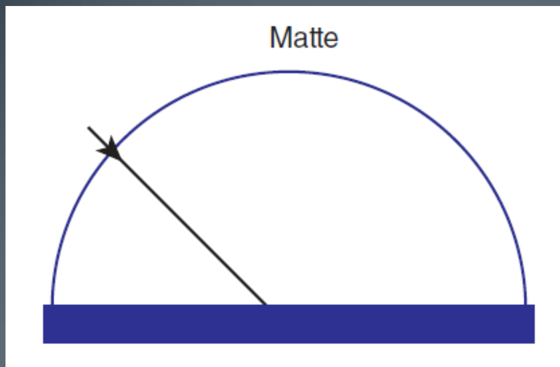
Measuring with Spectrophotometers

Remember Light Interaction

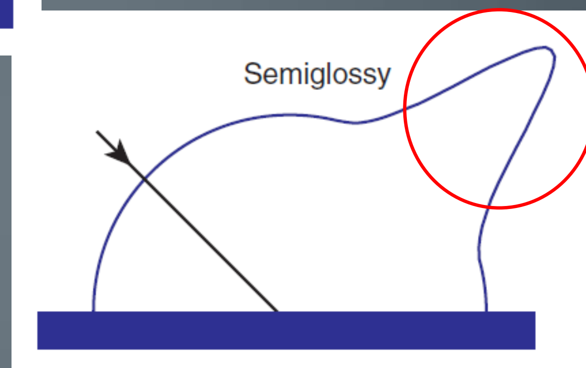


Spectrophotometers can measure Reflectance and Transmittance (specular and/or diffuse)

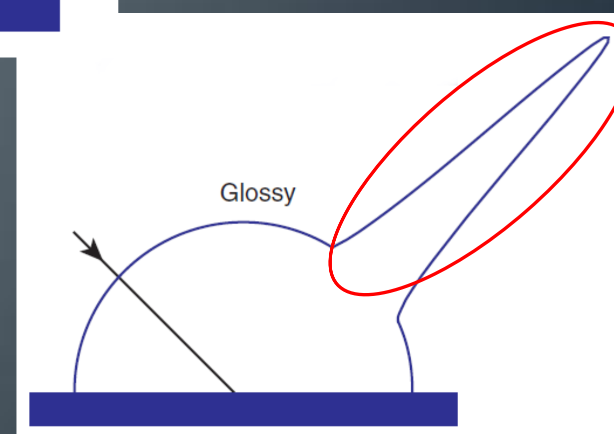
Light Reflection vs Material



Light is reflected in all directions equally



Light is reflected in all directions but a small part is reflected orthogonal to the incident angle



Light is reflected in all directions but a big part is reflected orthogonal to the incident angle

Spectrophotometers: In a Nutshell

- Spectral Reflectance:

  the ratio of reflected light (r) to the incident light (i) under specified geometric conditions.

$$R_\lambda = \frac{\phi_\lambda^r}{\phi_\lambda^i}$$

normally < 1
(except when
fluorescence)

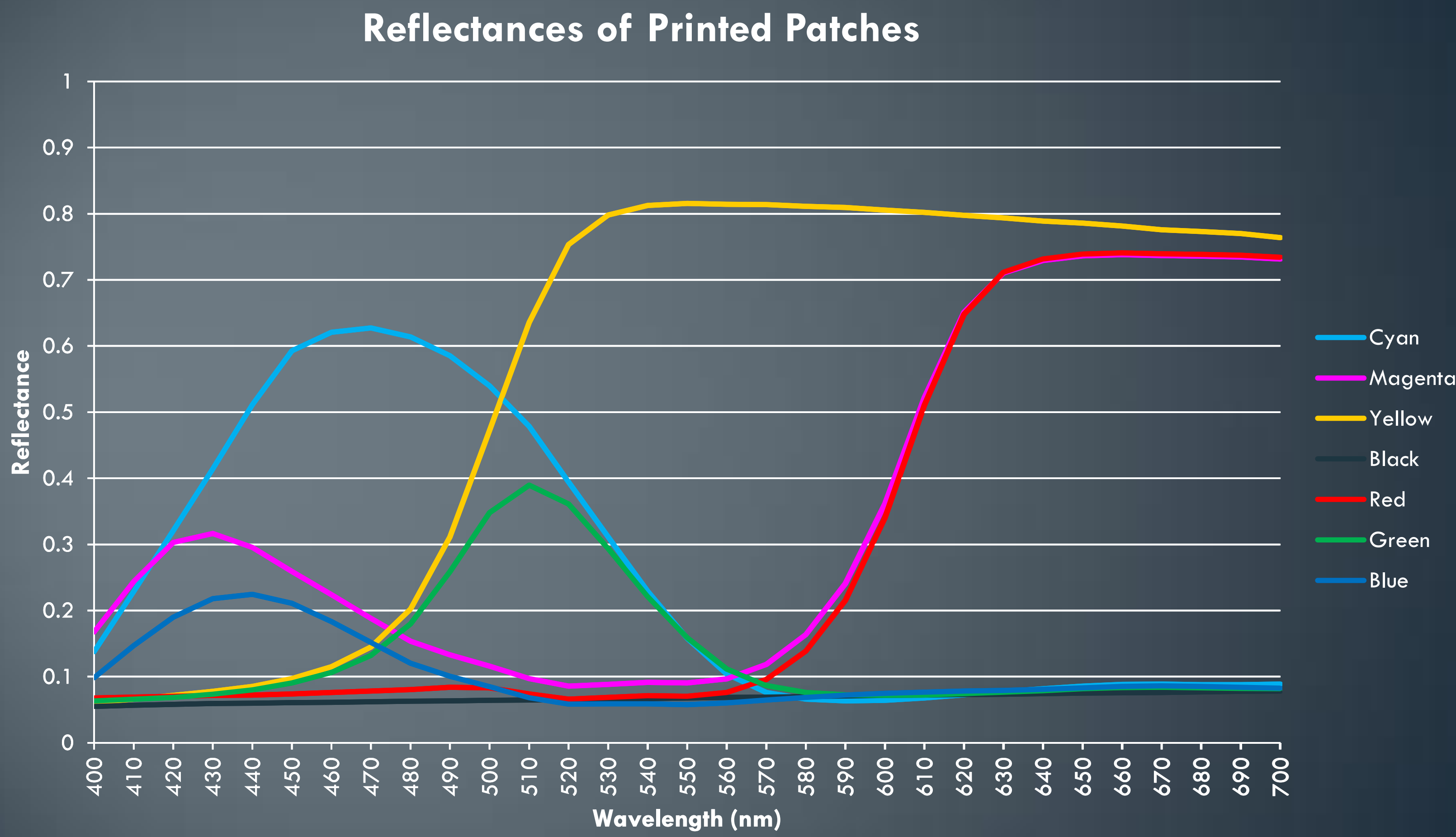
- Spectral Transmittance:

  the ratio of transmitted light (t) to the incident light (i) under specified geometric conditions.

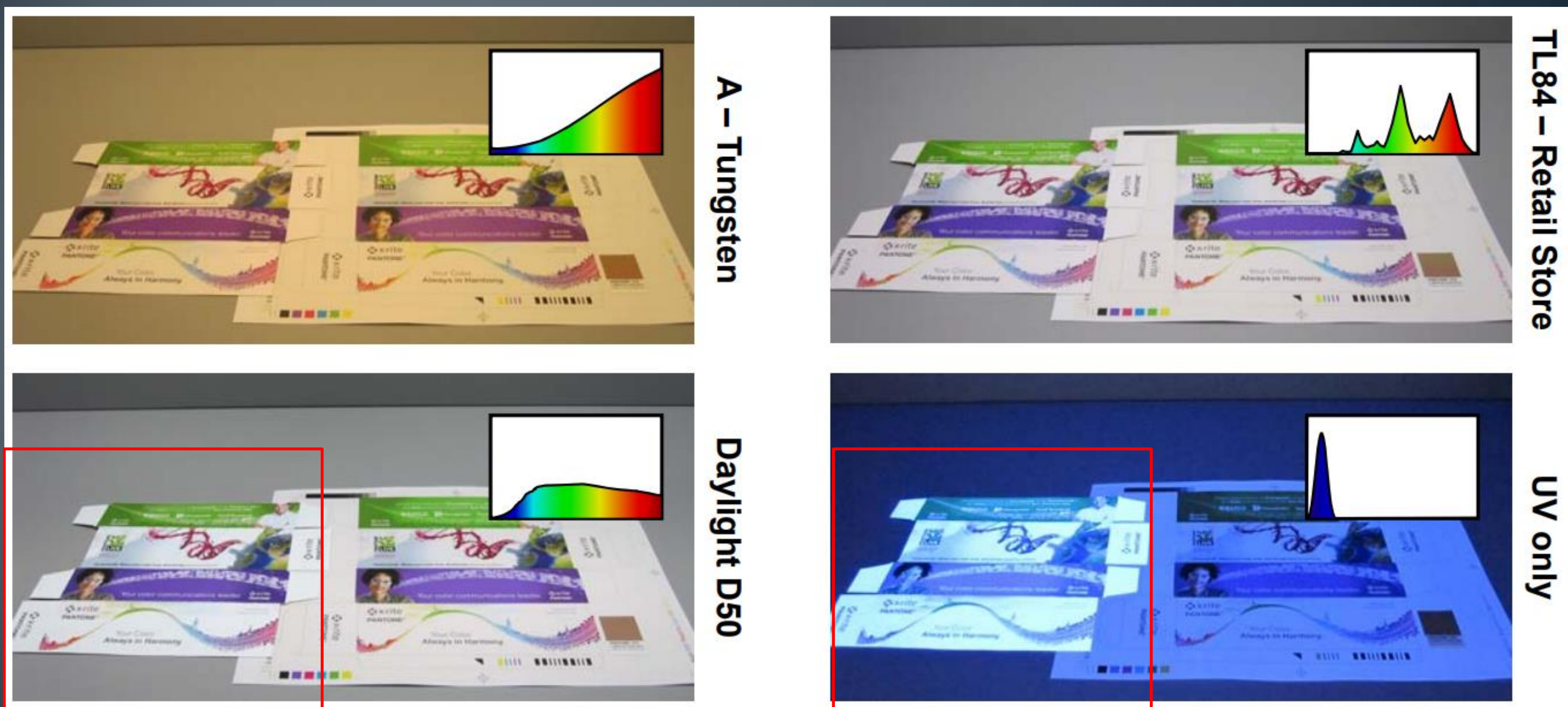
$$T_\lambda = \frac{\phi_\lambda^t}{\phi_\lambda^i}$$

- All measuring instruments need to be calibrated (e.g., using a White Tile made from Spectralon)

Spectrophotometers: Reflectances ?



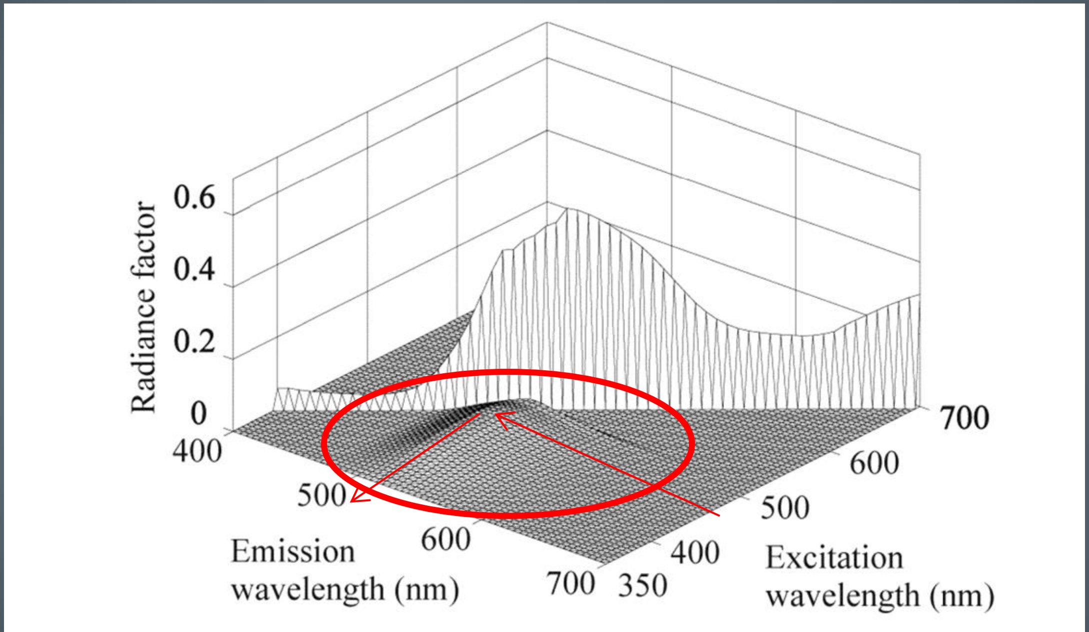
Interlude: Fluorescence



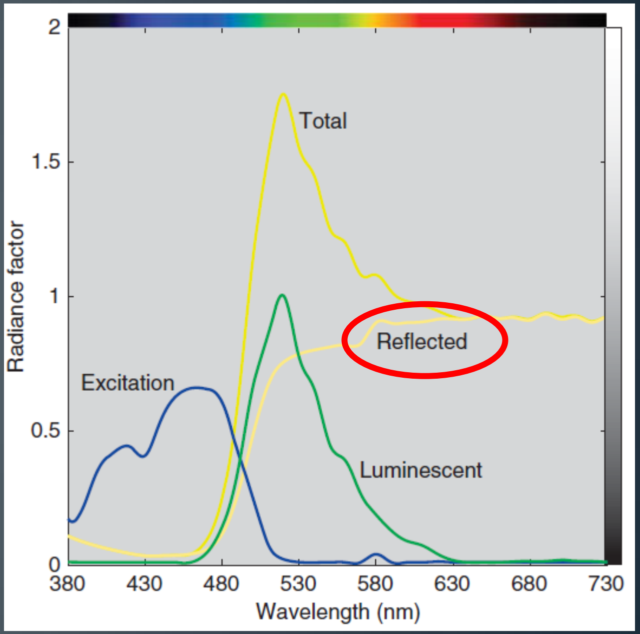
Fluorescence makes an object look more colorful in certain wavelengths (e.g., paper looks more white)

Interlude: Fluorescence

- Use an instrument called a Bispectrometer to measure it



Donaldson matrix obtained from a green sample emitting a more saturated green light



Radiance of sample

S. Tominaga et al, "*Estimation of fluorescent Donaldson matrices using a spectral imaging system*" (2018)

Colorimeters vs Spectrophotometers

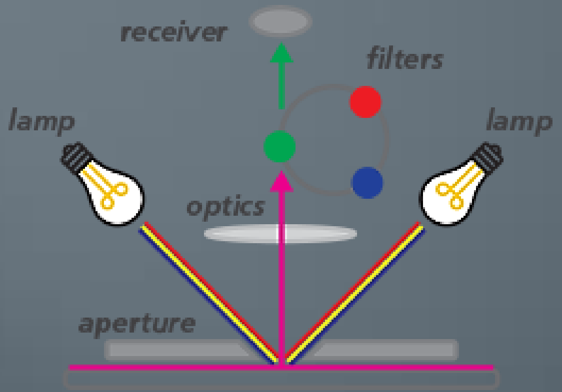
- Colorimeters are used generally to calibrate screens.

- They mimic the way our eyes perceive color

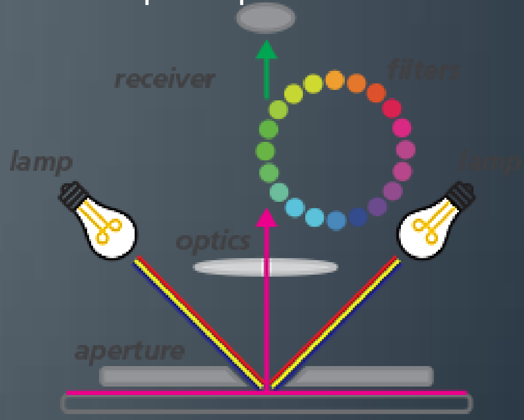
    They measure reflectance in 3 wavelengths (R, G, B)

    They do not provide a spectral response.

Colorimeter

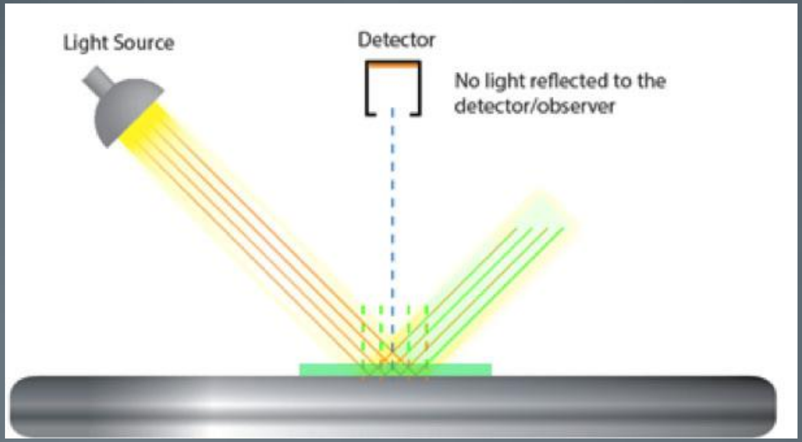


Spectrophotometer

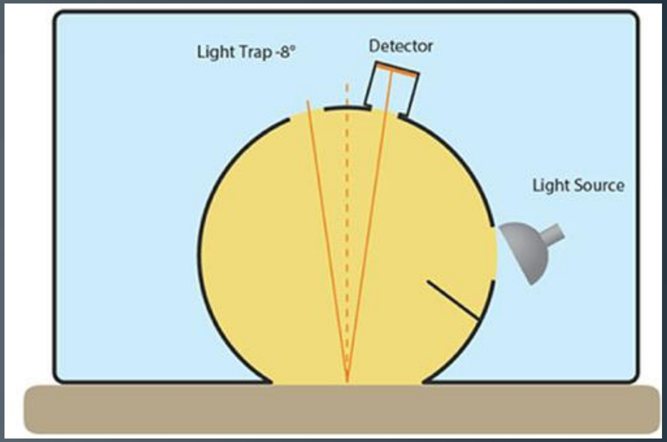


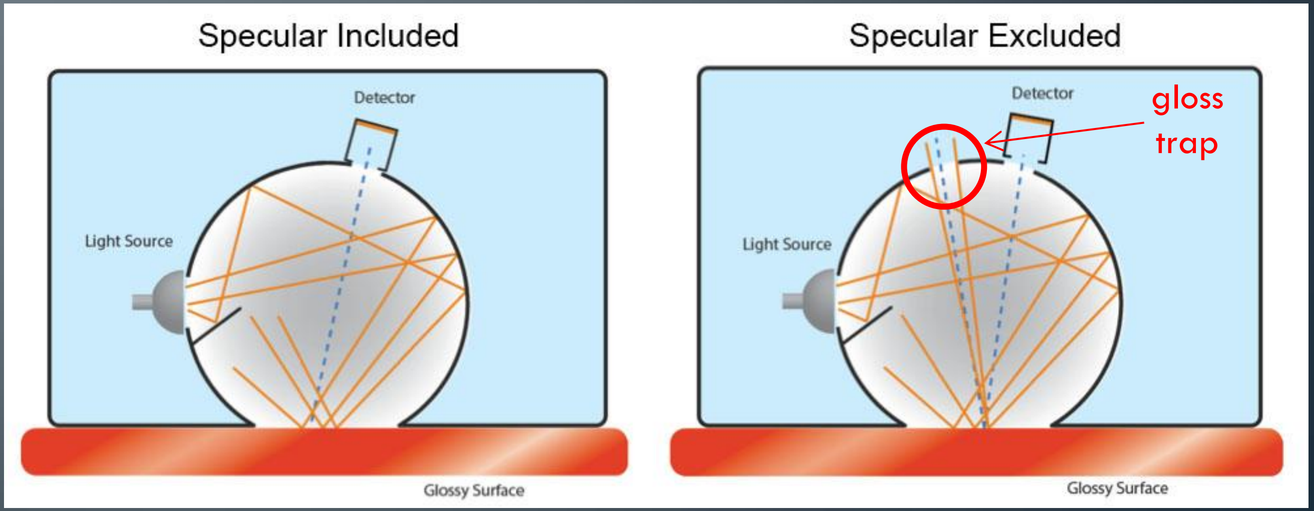
Spectrophotometers: Types

Bidirectional geometry



Integrating sphere



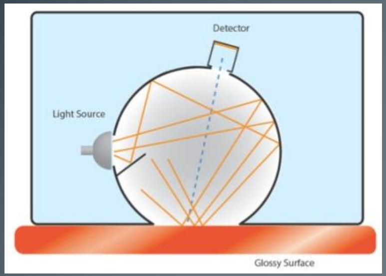


Bidirectional
Non-structured and Flat surfaces (Paper, Plastics)

Sphere
Structured and Glossy surfaces (Textiles, Metallic)

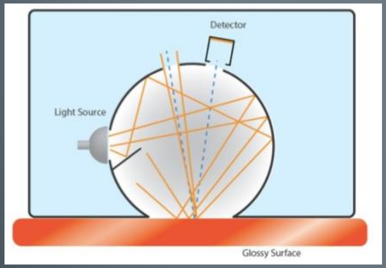
Spectrophotometers: SPIN vs SPEX

- SPIN Specular Included (Gloss is accounted for)



→ Color is measured independent of the sample's gloss or surface texture

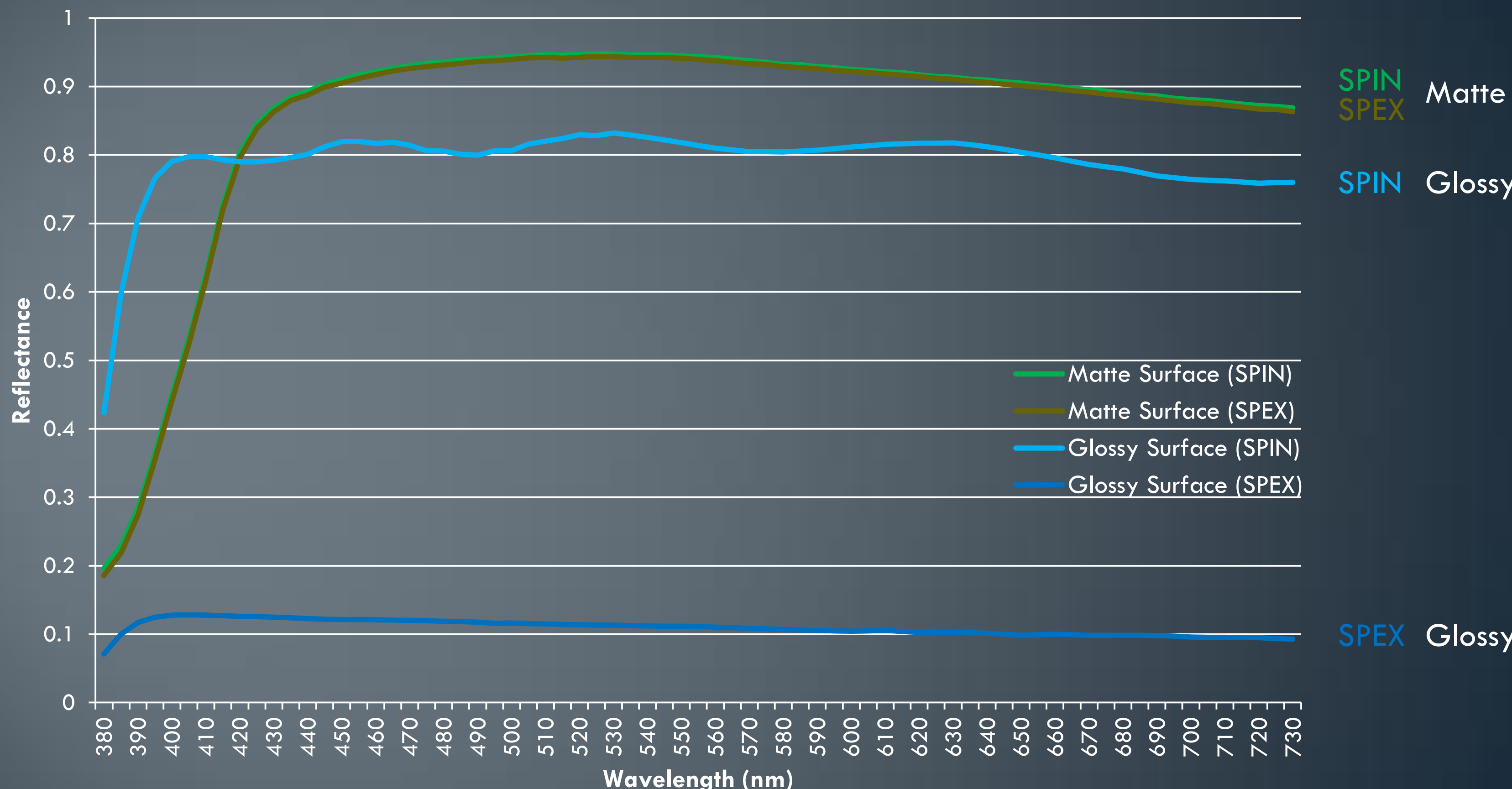
- SPEX Specular Excluded (Gloss is ignored)



Which one to use?

Check with the customer. Some will require a SPIN tolerance, while others will require a SPEX.

Spectrophotometers: SPIN vs SPEX



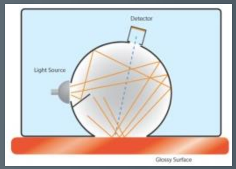
Specifications: SPIN vs SPEX

Example

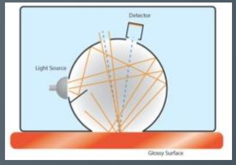
Automotive interior plaque

(items produced using different materials)

- SPIN → looks at the material independent of surface structure



- SPEX → values which depend gloss and surface conditions



SPEX $\Delta E =$ [illegible]
SPIN $\Delta E =$ [illegible]

If the texture and/or gloss of your samples can vary greatly

→ to truly evaluate the color <u>without</u> respect to how glossy or how textured the sample is, you need a SPIN reading.

https://www.byk.com/fileadmin/byk/support/instruments/theory/color/en/Intro_Solid_Color.pdf

Spectrophotometers: Specifications

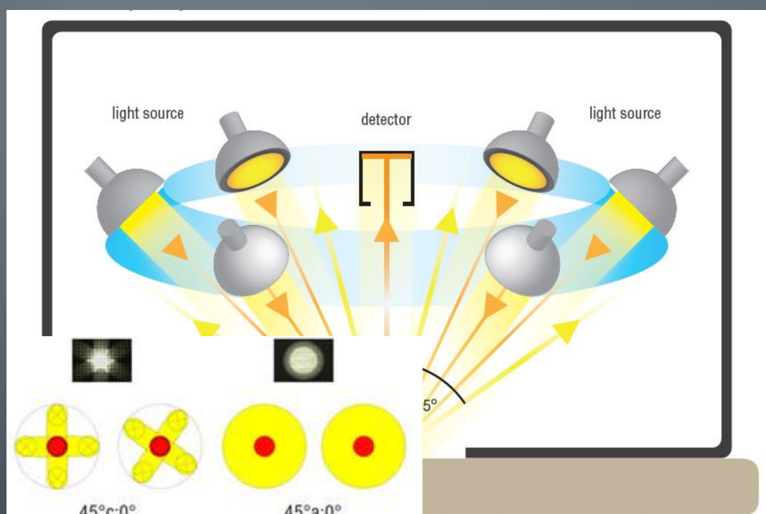
	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Measurement Geometry			
Light Source			
Measurement Aperture			
Measurement Conditions			
Spectral range			
Short term repeatability			
Inter-instrument agreement			

Choice of instrument depends on what you need to measure, at which accuracy

Specifications: Geometry

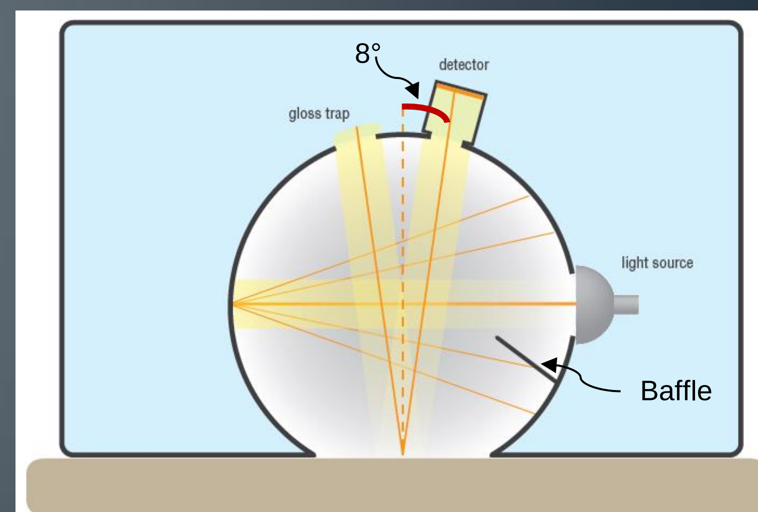


	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Measurement Geometry	45°a:0 (ring illumination)	d:8°	45°c:0 (circumferential)
Light Source	Gas filled tungsten lamp and UV LED	Gas-filled tungsten lamp	3 point circle, 7-LED chip



45°a:0

45°c:0 → approximation of 45°a:0



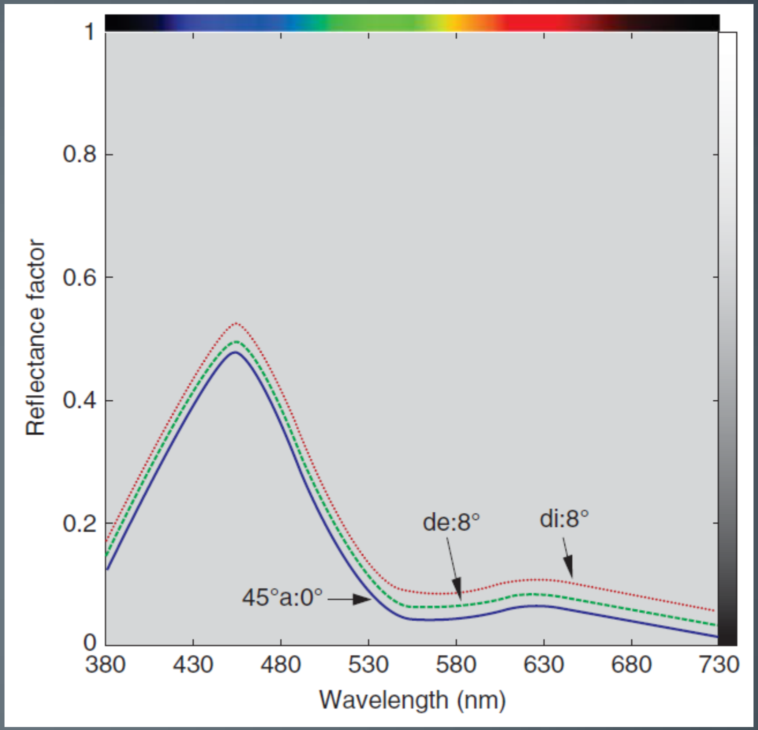
d:8°

XX:YY

XX → angle of incident light

YY → angle of detector w.r.t. sample

Specifications: Geometry



Reflectances of a semi-glossy object

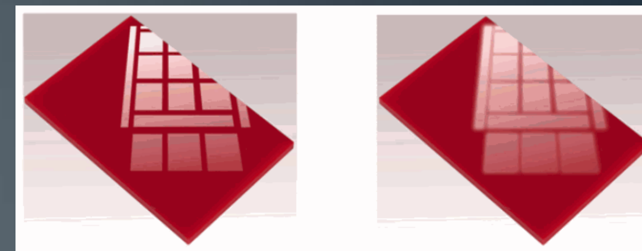
di:8° → SPIN Specular (gloss) included

de:8° → SPEX Specular (gloss) excluded

45°a:0° → Directional ring illumination (gloss excluded)

Specifications: Geometry

A high gloss sample with the same pigmentation is visually judged darker by the eye when compared to a matte sample.



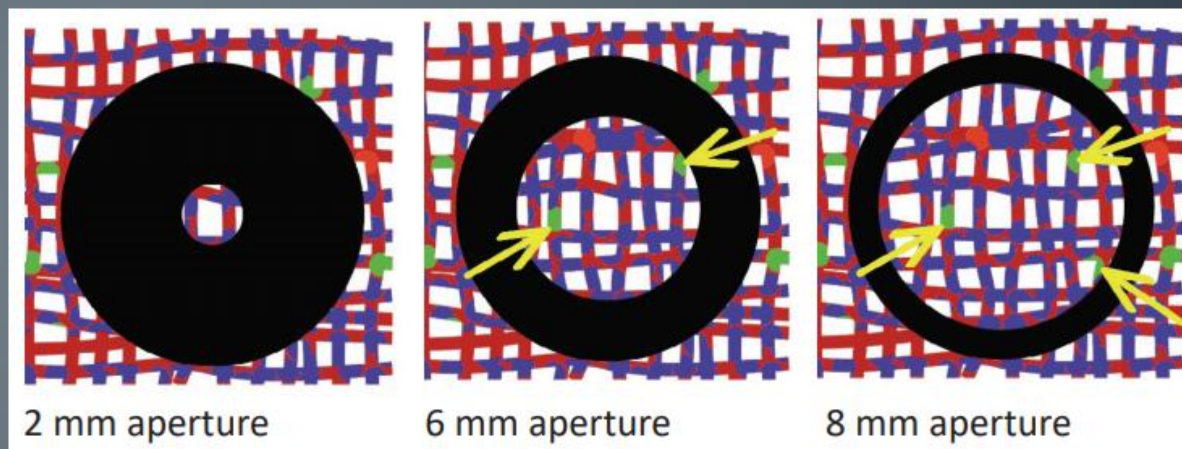
45°:0 measures that color difference.
di:8° measures the same color in both cases.

- 45°:0° simulates normal behavior
  e.g., when we read a glossy magazine we position it to avoid the gloss from coming into our eye.

45°:0° is ideal for flat surfaces; di:8° best for highly reflective and structured surfaces (cans, textiles, cars).

Specifications: Aperture

	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Measurement Aperture	4.5 mm	4 or 8mm	2, 6 and 8 mm

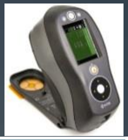


Small aperture:
- ✓ measures quickly
- ✗ may miss relevant information

Large aperture:
- ✓ more accurate
- ✗ measurement takes longer
- ✗ need larger sample

Barbieri, "*Why larger Measuring Aperture counts*", White Paper (2018)

Specifications: Conditions



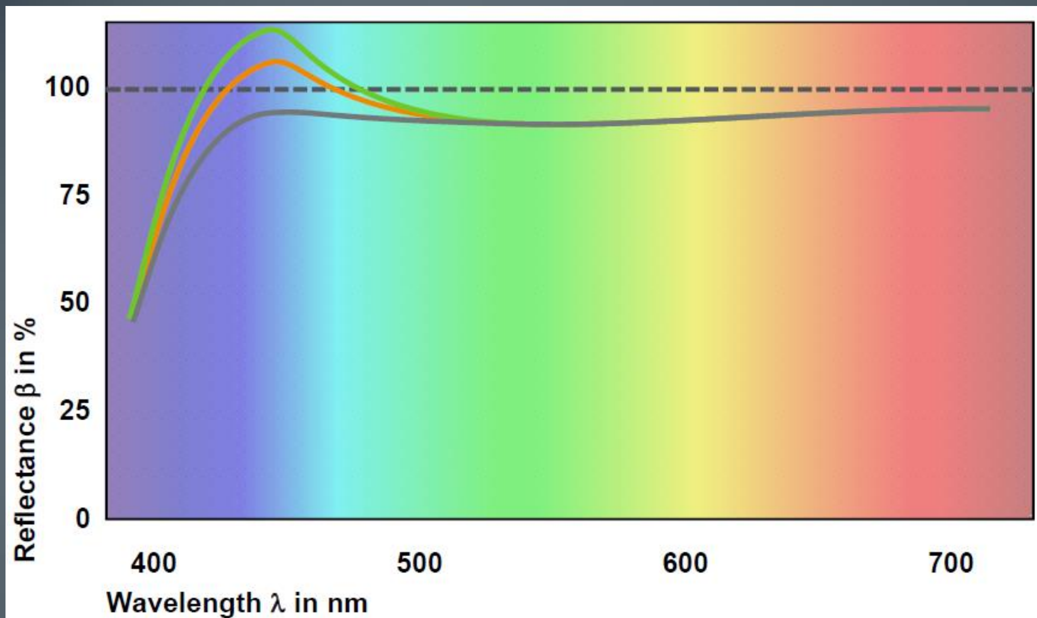
	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Measurement Conditions	M0, M1, M2	n/a	M0, M1, M2, M3

Defined by ISO13655 – valid only for 45°:0 geometries

- M0 legacy measurements (tungsten lamp, no standardization of UV content in illuminant, UV strength changes through time) obsolete, avoid when possible
- M1 spectral distribution of illuminant should match CIE D50 (takes optical brightener agents (OBAs) into account → includes fluorescence)
- M2 UV is excluded from measurements (no fluorescence due to OBAs)
- M3 Polarized light (based on M2) [90% of light (and gloss) is cut]

Typically used in printing, to measure color when paper is still wet

Specifications: Conditions



	M0	M1	M2
L*	94	94	94
a*	2,5	3	0,5
b*	-9	-12	-4

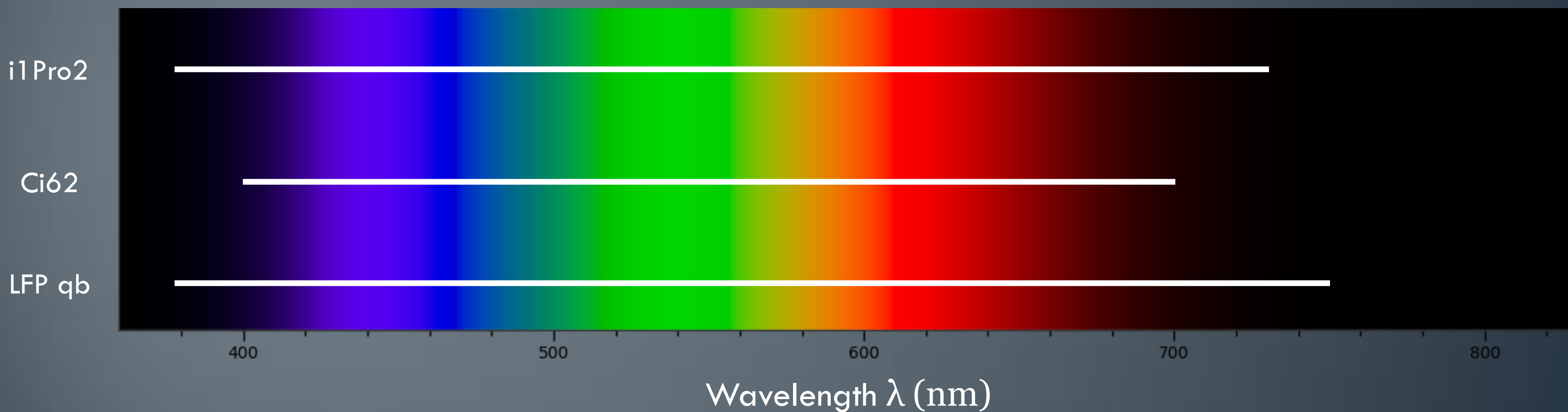
Measurement condition has an impact on the color

(note how Reflectance goes beyond 100% if UV is not filtered!)

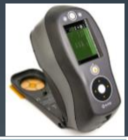
X-Rite, “*How to use the new ISO 13655 measurement conditions M0-M3*”, ICC Graphic Arts Experts’ Day (2017)

Specifications: Spectral Range

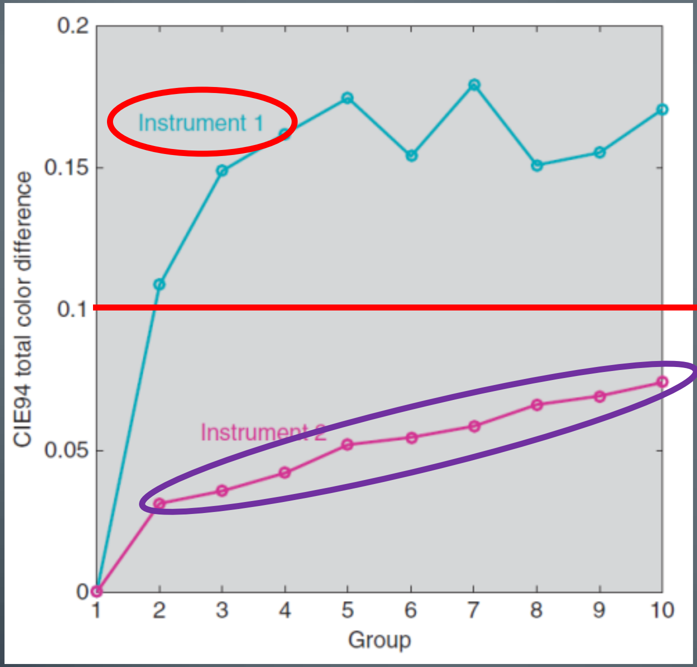
	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Spectral range	380-730 nm	400-700nm	380-750nm



Specifications: Repeatability


	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Short term repeatability	0.1 ΔE_{94}	0.05 ΔE_{ab}	0.05 ΔE_{00}



Two different *i1Pro 2* spectrophotometers

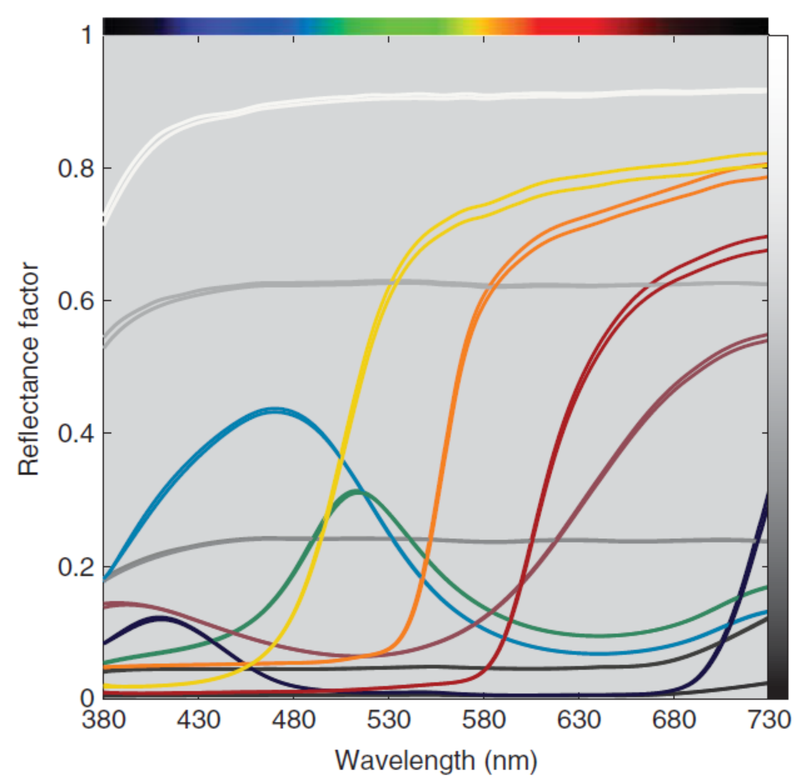
- 10 measurements of the same object were taken for each instrument
- ΔE between first and other measurements were computed for each instrument

Is any of them out of specification?

Specifications: Inter-instrument agreem.



	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Inter-instrument agreement	Average 0.4 ΔE_{94} Max. 1.0 ΔE_{94}	Average 0.2 ΔE_{ab} Max. 0.4 ΔE_{ab}	Average 0.5 ΔE_{00} Max. 1.0 ΔE_{00}



The same two i1Pro spectrophotometers from the repeatability test

- Measure 12 color tiles object with each of them

How different the measurements are?

Average ΔE_{94}: 0.40

Maximum ΔE_{94}: 0.87

Are they within specification?

R. Berns, "*Billmeyer and Saltzman's Principles of Color Technology*" (2017)

Specifications: Recap

	X-Rite i1Pro 2	X-Rite Ci62	Barbieri LFP qb
Measurement Geometry	45°a:0 (ring illumination)	d:8°	45°c:0 (circumferential)
Light Source	Gas filled tungsten lamp and UV LED	Gas-filled tungsten lamp	3 point circle, 7-LED chip
Measurement Aperture	4.5 mm	4 or 8mm	2, 6 and 8 mm
Measurement Conditions	M0, M1, M2	n/a	M0, M1, M2, M3
Spectral range	380-730 nm	400-700nm	380-750nm
Short term repeatability	0.1 ΔE_{94}	0.05 ΔE_{ab}	0.05 ΔE_{00}
Inter-instrument agreement	Average 0.4 ΔE_{94} Max. 1.0 ΔE_{94}	Average 0.2 ΔE_{ab} Max. 0.4 ΔE_{ab}	Average 0.5 ΔE_{00} Max. 1.0 ΔE_{00}

More (Larger) Spectrophotometers

Perkin Elmer Lambda 1050

X-Rite Color i7

Agilent Cary 5000

- Used for applications where very high resolution is needed (chemistry, optics)
- Used for measuring Transmittance

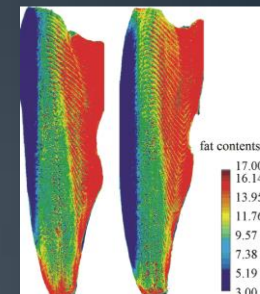
Transmittance Measurement

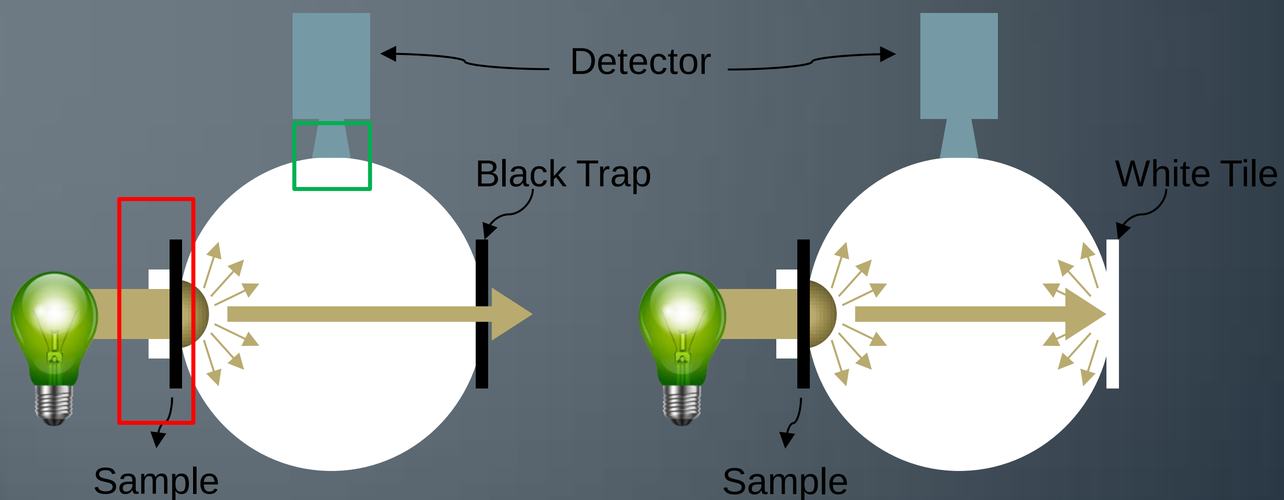
- When we need transmittance?

Light Filters

Printed Ads

Food Inspection





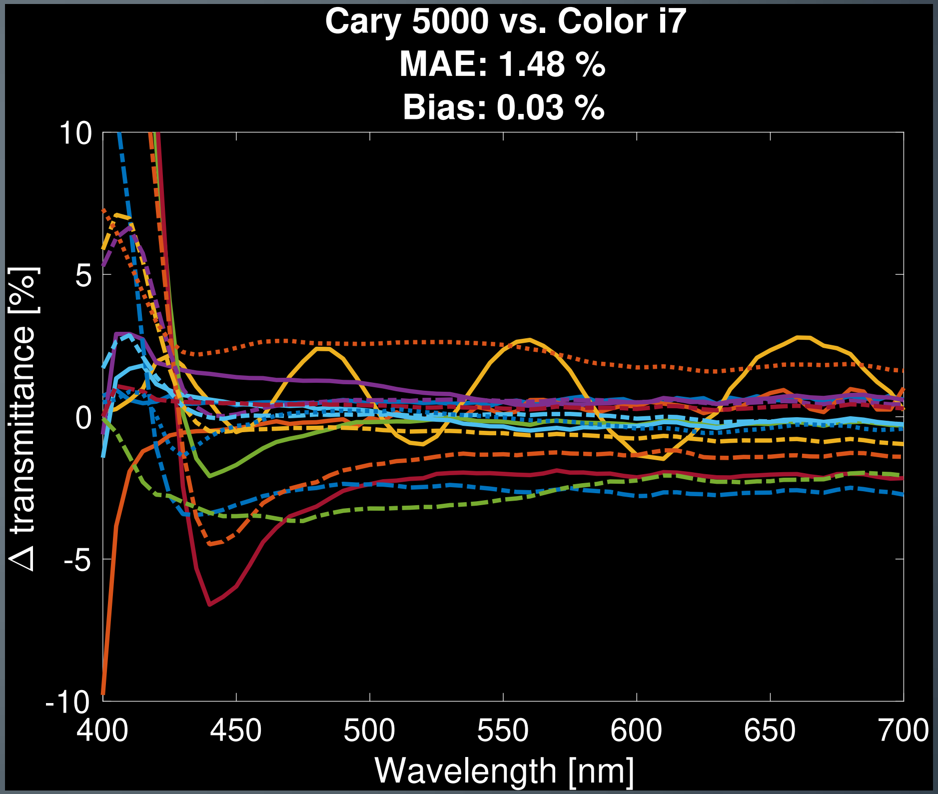
0°:d SPEX
Capture Diffuse Transmittance only

0°:d SPIN
Capture Diffuse + Specular Transmittance

Transmittance: Inter-instrument agreem.

- Compared measurements of 16 samples used for printing:

Agilent Cary 5000 vs X-Rite Color i7



Average ΔE_{00} = 1.7

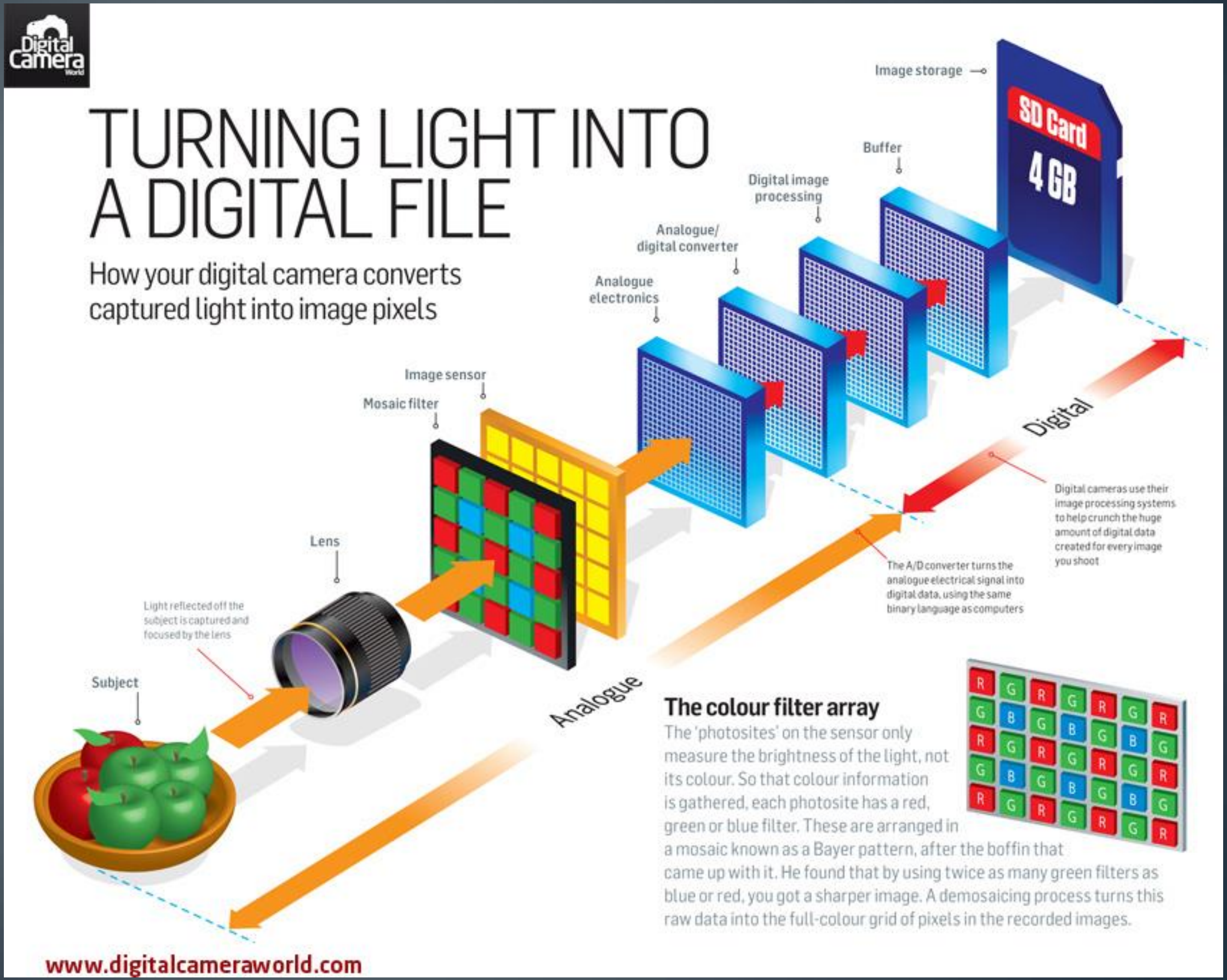
M. Shahpaski et al, "*Comparative analysis of transmittance measurement geometries and apparatus*", Electronic Imaging (2019)

Spectrophotometers: Recap

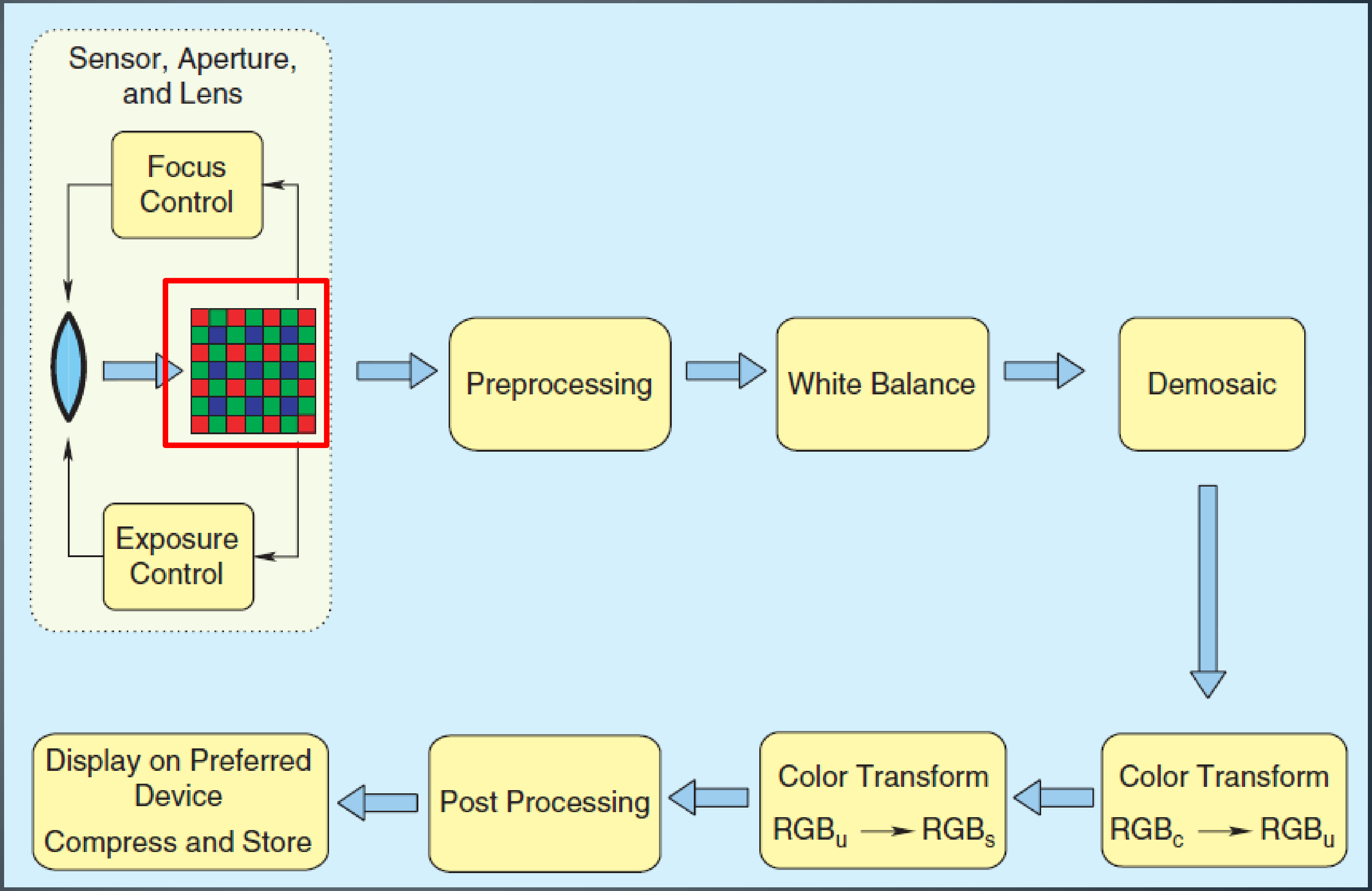
- Many different (standardized) methods to measure Reflectance (and Transmittance).
- Type of instrument to use depends on what you want to measure, and how frequent you want to measure (your workflow).
- Only measurements taken under the same conditions can be truly compared. Therefore, it is necessary to note the following information in a color measurement report:
  - Color instrument (geometry, aperture, measurement condition)
  - Illuminant / observer standards, if you give L*a*b* values

Measuring with RGB Cameras

The Imaging Flow



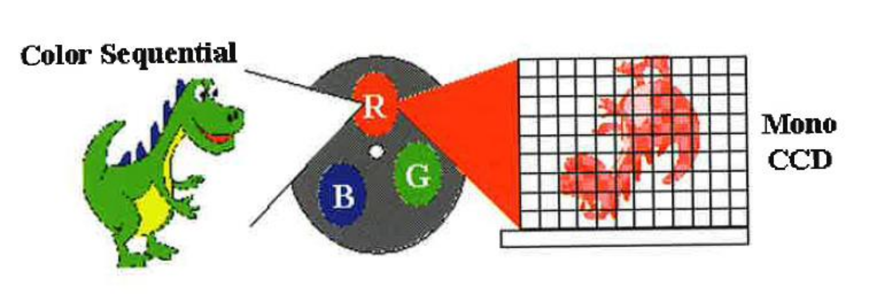
The Color Imaging Flow

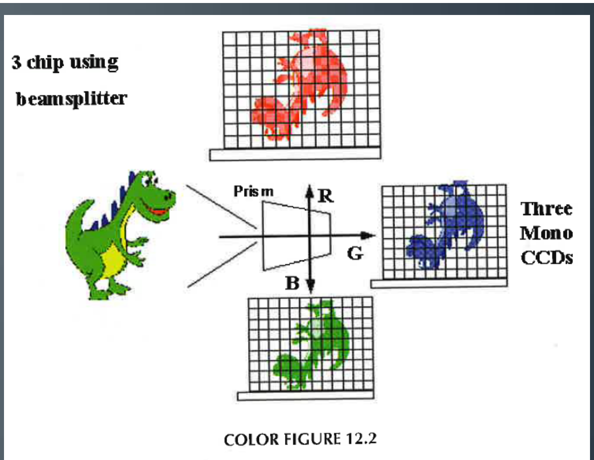


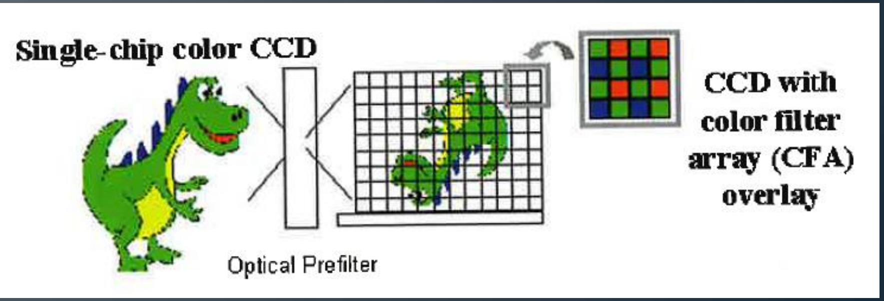
R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

Sensor

- Temporal Multiplexing
  Scan 3 times + Use 1 sensor
  - 3 real values per pixel
  - Only for static scenes
  - Slow
- Scan 1 time + Use 3 sensors
  - 3 real values per pixel
  - Costly
  - Space
- Spatial Multiplexing
  Scan 1 time + Use 1 sensor
  - Well-mastered technology
  - 1real value per pixel (interpolation)
  - Loss of light



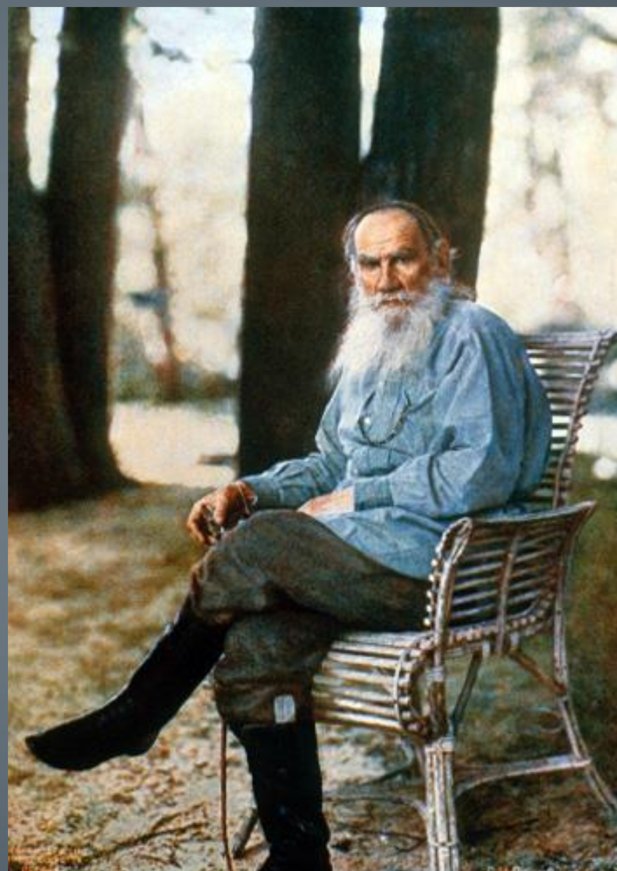




G. Sharma, "*Digital Color Imaging Handbook*" (2002)

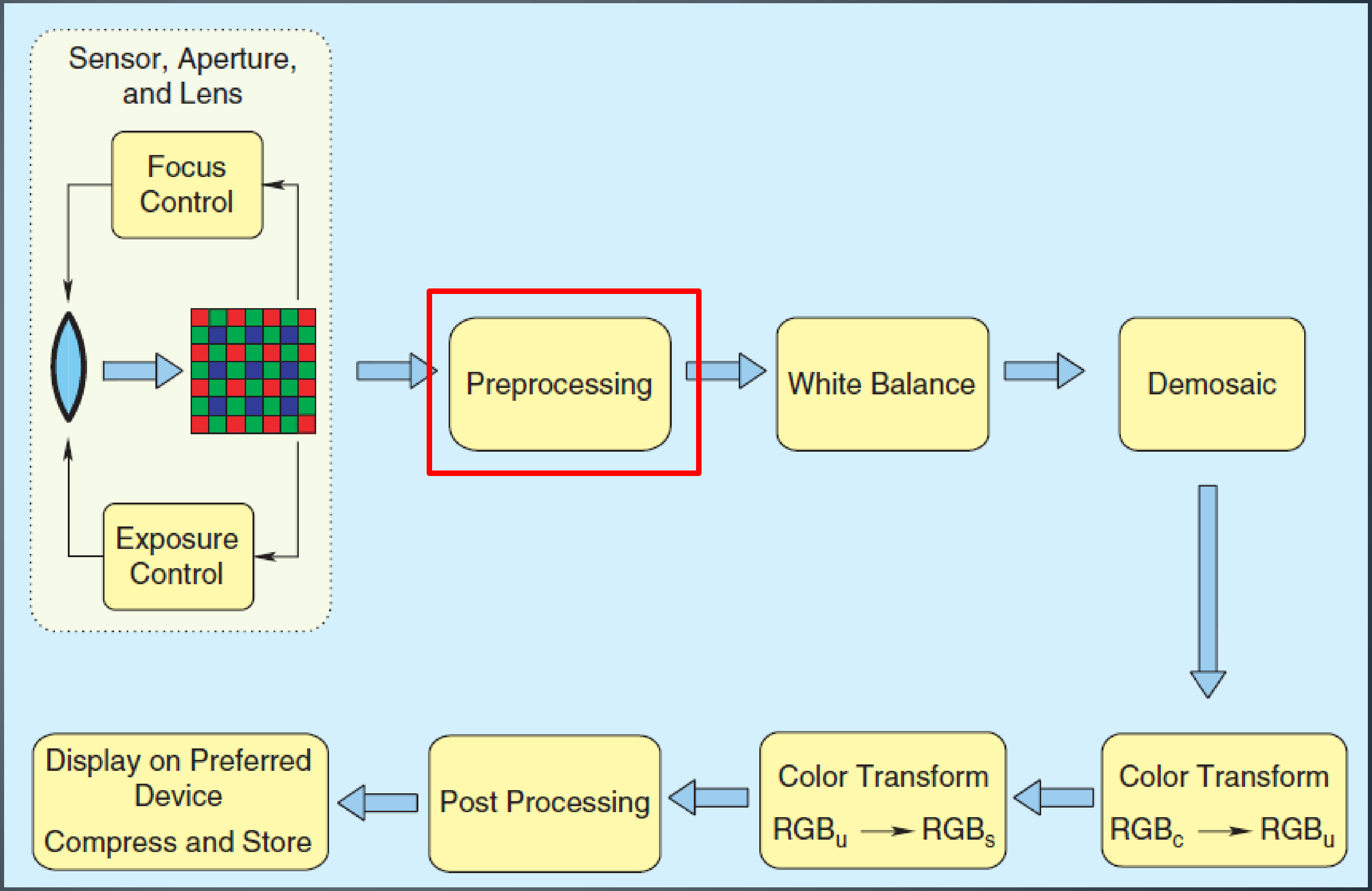
Sensor (from a hundred years ago)

Using Temporal Multiplexing



https://en.wikipedia.org/wiki/Sergey_Prokudin-Gorsky

The Color Imaging Flow



R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

Preprocessing

Defective Pixel Correction → Linearization → Dark Current Compensation → Vignetting Correction

Dark Current Compensation

- Signal present even when the lens is closed, which adds noise
  → Capture a dark image for the given exposure time

$$C_i(x, y) = R_i(x, y) - D_i(x, y)$$

i = Color Channel
(x, y) = Position of arbitrary pixel
C = Corrected Image
R = Input Image
D = Dark Current Image

Preprocessing

Defective Pixel Correction → Linearization → Dark Current Compensation → Vignetting Correction

Vignetting / Color Shading / Flat field Correction

- Image tends to darken on the corners / Non-uniform Illumination

  → Capture a white (flat field) image for the given exposure time

$$C_i(x,y) = \frac{R_i(x,y) - D_i(x,y)}{F_i(x,y) - D_i(x,y)}$$

i = Color Channel
(x,y) = Position of arbitrary pixel
C = Corrected Image
R = Input Image
D = Dark Current Image
F = Flat Field Image

Preprocessing

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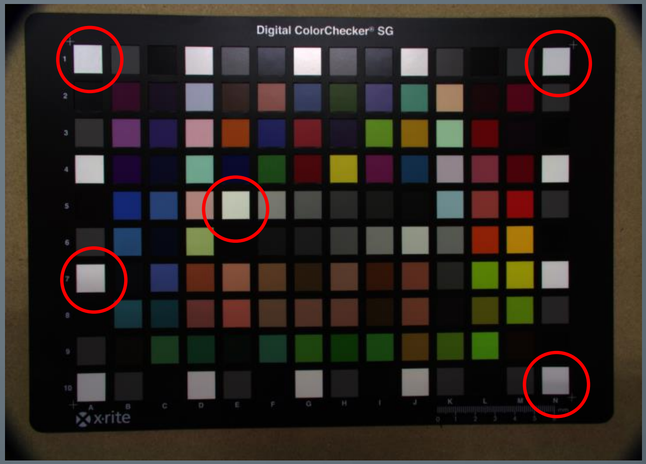
F = Flat Field Image

Preprocessing

Defective Pixel Correction → Linearization → Dark Current Compensation → Vignetting Correction

Before correction

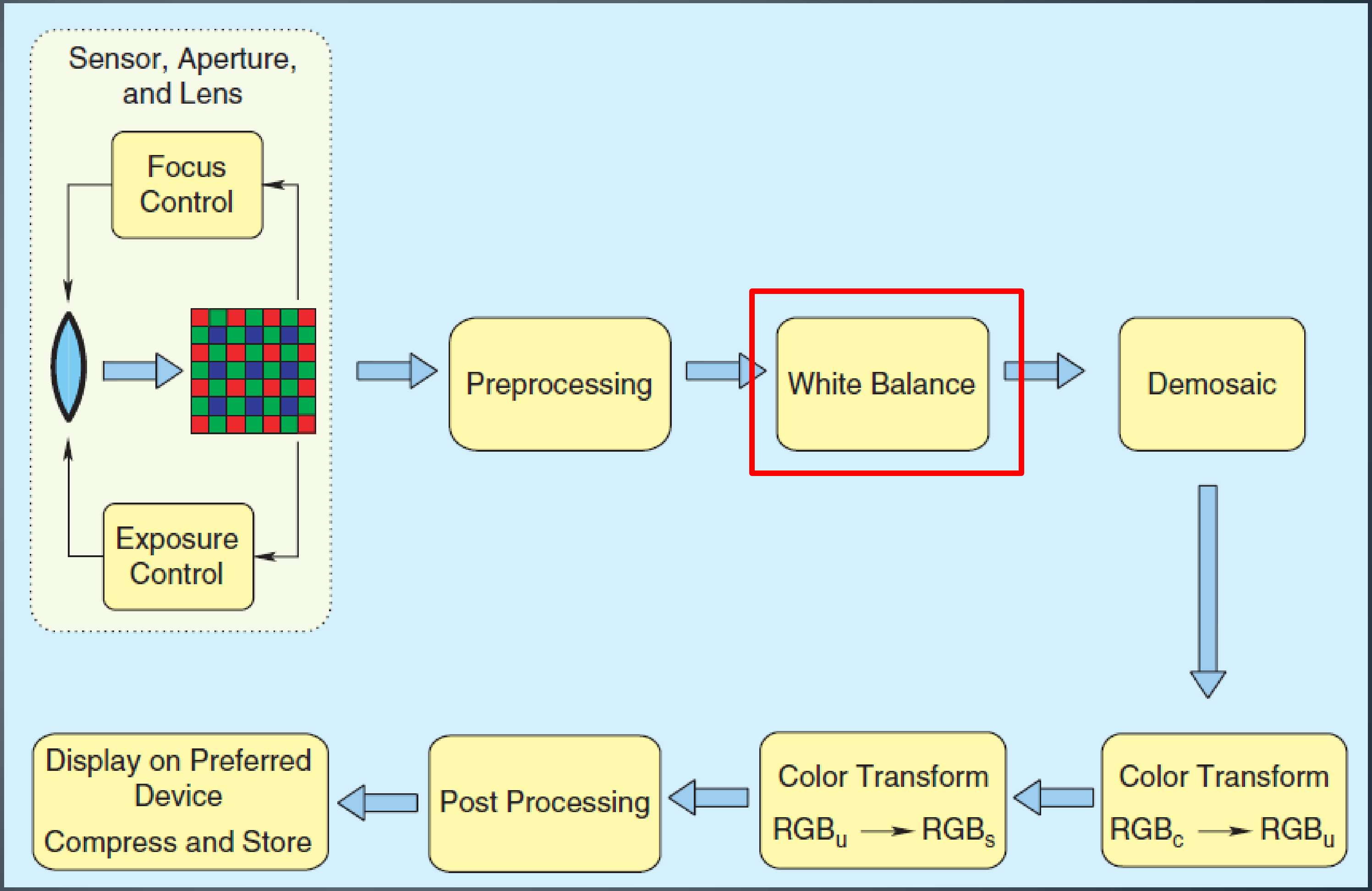


After correction

Compute average RGB value of 15 White Patches

	Statistic	Red	Green	Blue
Before correction	Mean	157.3	159.1	157.5
	St. Dev	28.3	28.6	31.7
After correction	Mean	249.5	250.3	249.5
	St. Dev	2.2	2.3	2.5

The Color Imaging Flow



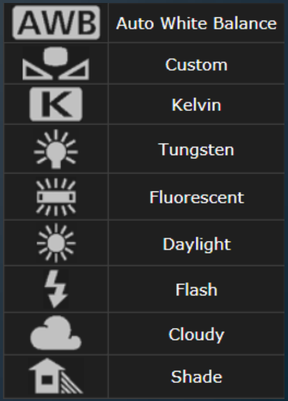
R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

White Balance

- White Balance is about compensating for the color of the light source in the image.
  → Objects which appear white in person are white in the image

- The eye cares more about he intrinsic color of the object, not the color of the light leaving the object.

- Easy for our eyes to judge what is white under different illuminants; but not so straightforward for cameras.



Needed when a Flat field image
cannot be taken during the PreProcessing

White Balance

<u>Gray World Assumption</u>

The average of all colors in the image is gray.

→ Channels are scaled based on their deviation from gray.

- Green channel is taken as “gray” reference.
- White-balanced image is: $k_r R, G, k_b B$

  where $k_r = \frac{G_{mean}}{R_{mean}}$ and $k_b = \frac{G_{mean}}{B_{mean}}$

Before

After

Before

After

White Balance

Ideally we would need to estimate the illuminant, and do a chromatic adaptation

<u>How GIMP does it?</u>

1. Discards pixels colors at the extremes of R,G,B histograms

→ Threshold of 0.05% of total pixel count

2. Do Histogram Stretching of remaining pixel colors, for each channel

Before

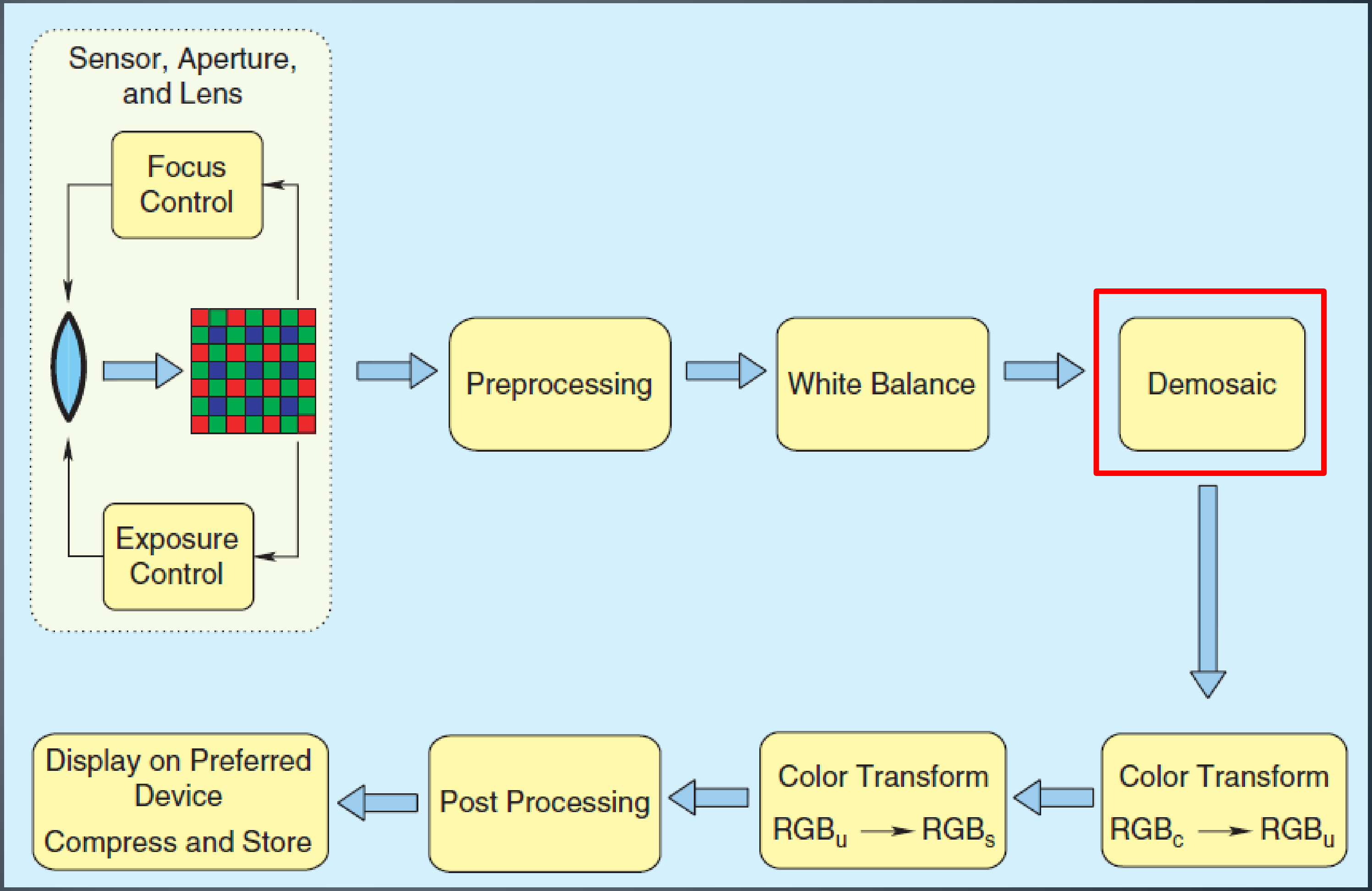
After

Before

After

K.Barnard et al., "*A comparison of computational color constancy algorithms*", IEEE TIP (2002)

The Color Imaging Flow



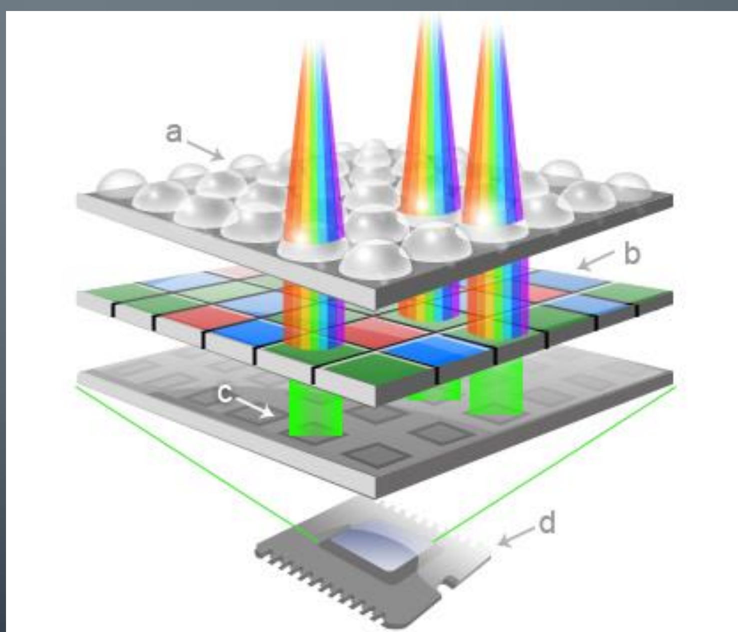
R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

Demosaicing

- Each pixel has a different color filter
- Bayer Pattern is the most used Color Filter Array (CFA)
- Why More Green?

G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

Frequency of the G color band is close to the peak of the human luminance frequency response → Better sharpness

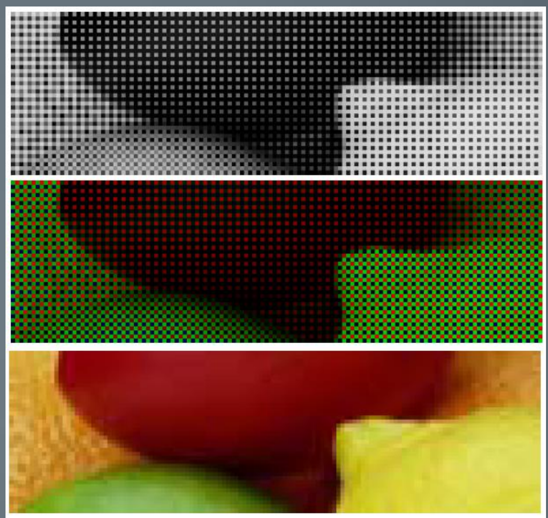


a	IR-Blocking filter
b	Color Filters
c	Color blind sensor converts light into electricity
d	Millions of Light sensors

Demosaicing

- Each pixel has a different color filter
- Bayer Pattern is the most used Color Filter Array (CFA)

G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G



Original CFA image

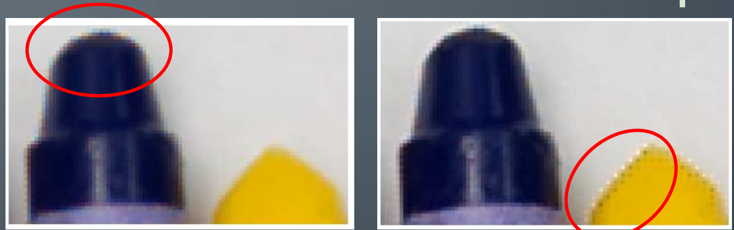
Original CFA image (colored)

Demosaiced Color image

R. Lukac, "*Color Filter Arrays: Design and Performance Analysis*" (2005)

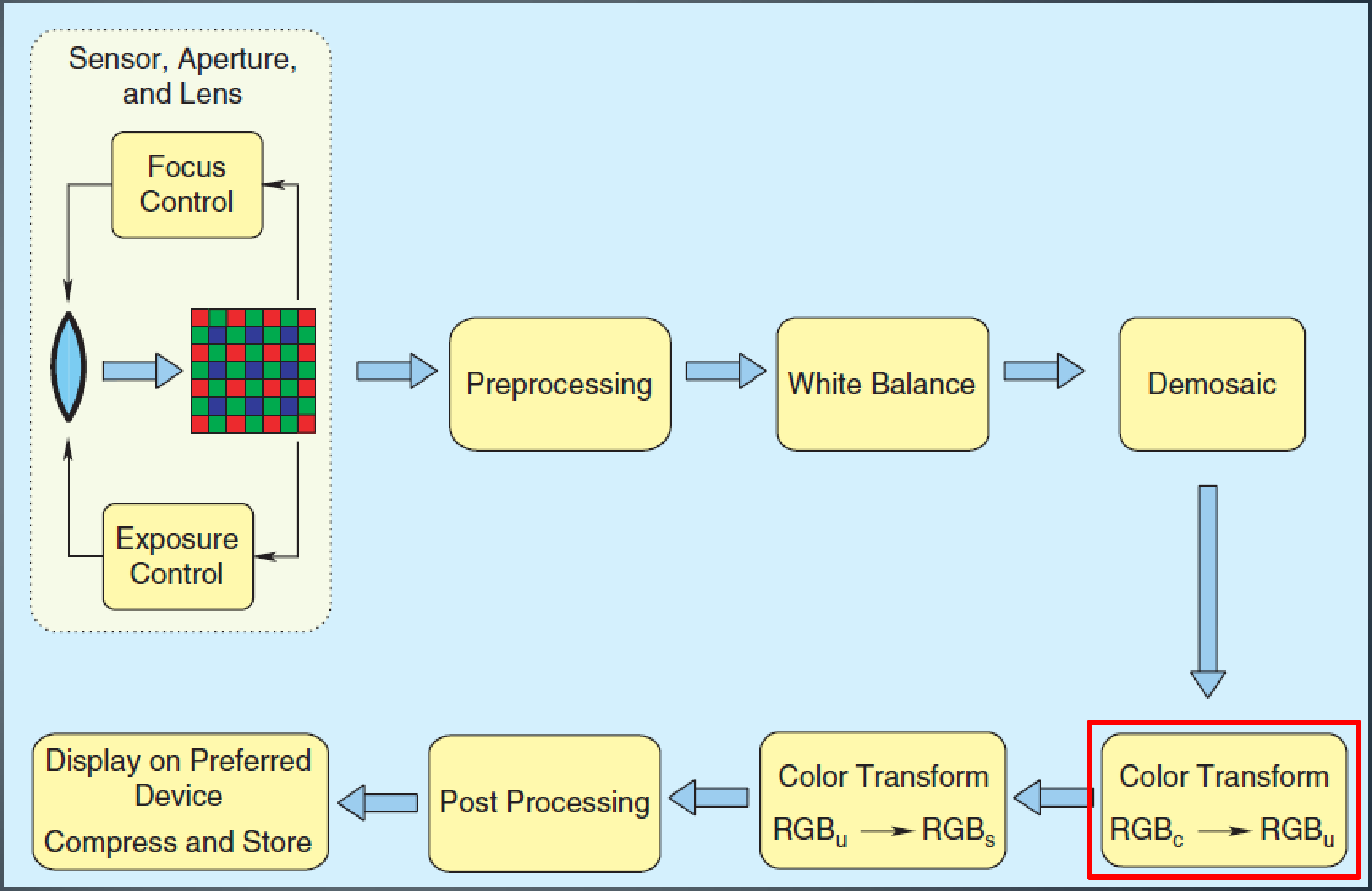
Problems

- Interpolation Methods are Patented or Propietary



B.K. Gunturk et al., "*Demosaicking: Color filter array interpolation*", IEEE Signal Processing (2005)

The Color Imaging Flow



Color Correction

R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

Color Correction

- Cameras are meant to produce pleasing scenes rather than colorimetrically accurate scenes.

  → Spectral Sensitivities of the camera are not identical to human color matching functions.

- To obtain colorimetric accuracy, we need to transform the image from the sensor's color space to the colorimetric (XYZ) space.

- Color Charts are used to obtain reference colors that need to be transformed.

Color Correction Charts

ColorChecker Classic

https://xritephoto.com/colorchecker-classic

24 colors representing the actual color of natural objects:

- human skin
- foliage
- blue sky

No.	Number	sRGB R	sRGB G	sRGB B	CIE L*a*b* L*	CIE L*a*b* a*	CIE L*a*b* b*	Munsell Notation Hue	Munsell Notation Value / Chroma
1.	dark skin	115	82	68	37.986	13.555	14.059	3 YR	3.7 / 3.2
2.	light skin	194	150	130	65.711	18.13	17.81	2.2 YR	6.47 / 4.1
3.	blue sky	98	122	157	49.927	-4.88	-21.925	4.3 PB	4.95 / 5.5
4.	foliage	87	108	67	43.139	-13.095	21.905	6.7 GY	4.2 / 4.1
5.	blue flower	133	128	177	55.112	8.844	-25.399	9.7 PB	5.47 / 6.7
6.	bluish green	103	189	170	70.719	-33.397	-0.199	2.5 BG	7 / 6
7.	orange	214	126	44	62.661	36.067	57.096	5 YR	6 / 11
8.	purplish blue	80	91	166	40.02	10.41	-45.964	7.5 PB	4 / 10.7
9.	moderate red	193	90	99	51.124	48.239	16.248	2.5 R	5 / 10
10.	purple	94	60	108	30.325	22.976	-21.587	5 P	3 / 7
11.	yellow green	157	188	64	72.532	-23.709	57.255	5 GY	7.1 / 9.1
12.	orange yellow	224	163	46	71.941	19.363	67.857	10 YR	7 / 10.5
13.	blue	56	61	150	28.778	14.179	-50.297	7.5 PB	2.9 / 12.7
14.	green	70	148	73	55.261	-38.342	31.37	0.25 G	5.4 / 8.65
15.	red	175	54	60	42.101	53.378	28.19	5 R	4 / 12
16.	yellow	231	199	31	81.733	4.039	79.819	5 Y	8 / 11.1
17.	magenta	187	86	149	51.935	49.986	-14.574	2.5 RP	5 / 12
18.	cyan	8	133	161	51.038	-28.631	-28.638	5 B	5 / 8
19.	white (.05*)	243	243	242	96.539	-0.425	1.186	N	9.5 /
20.	neutral 8 (.23*)	200	200	200	81.257	-0.638	-0.335	N	8 /
21.	neutral 6.5 (.44*)	160	160	160	66.766	-0.734	-0.504	N	6.5 /
22.	neutral 5 (.70*)	122	122	121	50.867	-0.153	-0.27	N	5 /
23.	neutral 3.5 (1.05*)	85	85	85	35.656	-0.421	-1.231	N	3.5 /
24.	black (1.50*)	52	52	52	20.461	-0.079	-0.973	N	2 /

It matches the colors of representative samples of natural objects under any illumination.

Color Correction Charts

ColorChecker Digital SG (SG=Semi-Gloss)

https://xritephoto.com/colorchecker-digital-sg

140 patches (96 unique colors)

24 colors of Classic Chart + 116 additional patches

- larger gamut
- additional skin-tone
- additional grayscale

Color Correction Charts: Artists

Artist Paint Target

https://www.rit.edu/cos/colorscience/mellon/pubs.php

Similar to ColorChecker Classic

but using pigments used by artists

ColorBuild 300 Patch Target

http://www.imagescienceassociates.com/

Also containing pigments

used by artists, but 300 patches

Color Correction Methods

- 30+ years of continuous research on how to transform from RGB to XYZ spaces.

A lot of ways to do it!

- Most of them solve the following equation:

Solution

$$X = MP \qquad\qquad M = XP^T(PP^T)^{-1}$$

where:

X = Reference XYZ values [3 x m]

P = Camera RGB values [N x m]

M = Correction matrix [3 x N]

	ColorChecker Classic	ColorChecker Digital SG
m	24	140

m = # of data points

N = # of dimensions

N → Depends on the method

Color Correction Methods: Linear

$$X = MP$$

X = Reference XYZ values
P = Camera RGB values
M = Correction matrix

- Linear Color Correction[1]

Linear Mapping from RGB to XYZ

→ N = 3

Not affected by exposure changes

$$X = \begin{pmatrix} X_1 & X_2 & X_3 & \dots & X_m \\ Y_1 & Y_2 & Y_3 & \dots & Y_m \\ Z_1 & Z_2 & Z_3 & \dots & Z_m \end{pmatrix}$$

$$P = \begin{pmatrix} R_1 & R_2 & R_3 & \dots & R_m \\ G_1 & G_2 & G_3 & \dots & G_m \\ B_1 & B_2 & B_3 & \dots & B_m \end{pmatrix}$$

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix}$$

If ColorChecker:
- Classic → m=24
- Digital SG → m=140

[1]B.K.P.Horn, "*Exact reproduction of colored images*", Computer Graphics, Vision and Image Processing (1984)

Color Correction Methods: Polynomial

$$X = MP$$

X = Reference XYZ values
P = Camera RGB values
M = Correction matrix

- <u>Polynomial Color Correction</u>[2]

Linear Mapping from RGB to XYZ + add polynomial components to reduce errors

→ N = 9, if 2nd Order Polynomial

$$X = \begin{pmatrix} X_1 & X_2 & X_3 & \dots & X_m \\ Y_1 & Y_2 & Y_3 & \dots & Y_m \\ Z_1 & Z_2 & Z_3 & \dots & Z_m \end{pmatrix}$$

Affected by exposure changes

High polynomial degree tends to do overfitting

If ColorChecker:
- Classic → m=24
- Digital SG → m=140

$$P = \begin{pmatrix} R_1 & R_2 & R_3 & \dots & R_m \\ G_1 & G_2 & G_3 & \dots & G_m \\ B_1 & B_2 & B_3 & \dots & B_m \\ R_1^2 & R_2^2 & R_3^2 & \dots & R_m^2 \\ G_1^2 & G_2^2 & G_3^2 & \dots & G_m^2 \\ B_1^2 & B_2^2 & B_3^2 & \dots & B_m^2 \\ R_1G_1 & R_2G_2 & R_3G_3 & \dots & R_mG_m \\ R_1B_1 & R_2B_2 & R_3B_3 & \dots & R_mB_m \\ G_1B_1 & G_2B_2 & G_3B_3 & \dots & G_mB_m \end{pmatrix} \qquad M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \\ m_{41} & m_{42} & m_{43} \\ m_{51} & m_{52} & m_{53} \\ m_{61} & m_{62} & m_{63} \\ m_{71} & m_{72} & m_{73} \\ m_{81} & m_{82} & m_{83} \\ m_{91} & m_{92} & m_{93} \end{pmatrix}$$

3rd Degree Polynomial ? N = 19

[2]G.Hong et al., "*A study of digital camera colorimetric characterisation based on polynomial modelling*", Color Research and Application (2001)

Color Correction Methods: Root Polynom.

$$X = MP$$

X = Reference XYZ values
P = Camera RGB values
M = Correction matrix

- Root Polynomial Color Correction[3]

Linear Mapping from RGB to XYZ + add root polynomial components

→ N = 6, if 2nd Order Polynomial

$$X = \begin{pmatrix} X_1 & X_2 & X_3 & \dots & X_m \\ Y_1 & Y_2 & Y_3 & \dots & Y_m \\ Z_1 & Z_2 & Z_3 & \dots & Z_m \end{pmatrix}$$

Not affected by exposure changes

$$\begin{array}{cc} P & M \\ \begin{pmatrix} R_1 & R_2 & R_3 & \dots & R_m \\ G_1 & G_2 & G_3 & \dots & G_m \\ B_1 & B_2 & B_3 & \dots & B_m \\ \sqrt{R_1G_1} & \sqrt{R_2G_2} & \sqrt{R_3G_3} & \dots & \sqrt{R_mG_m} \\ \sqrt{R_1B_1} & \sqrt{R_2B_2} & \sqrt{R_3B_3} & \dots & \sqrt{R_mB_m} \\ \sqrt{G_1B_1} & \sqrt{G_2B_2} & \sqrt{G_3B_3} & \dots & \sqrt{G_mB_m} \end{pmatrix} & \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \\ m_{41} & m_{42} & m_{43} \\ m_{51} & m_{52} & m_{53} \\ m_{61} & m_{62} & m_{63} \end{pmatrix} \end{array}$$

If ColorChecker:
- Classic → m=24
- Digital SG → m=140

3rd Degree Root Polynomial ? N = 12

[3]G.D.Finlayson et al., "*Color Correction Using Root-Polynomial Regression*", IEEE Transactions on Image Processing (2015)

Color Correction: Comparison

Original

Polynomial 2^{nd}

Root Polynomial 2^{nd}

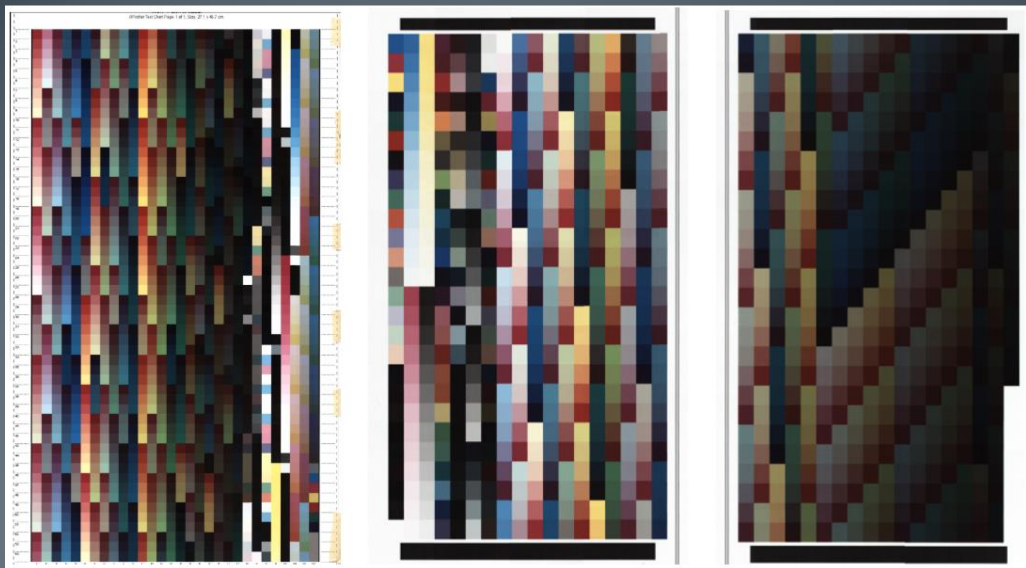
Linear

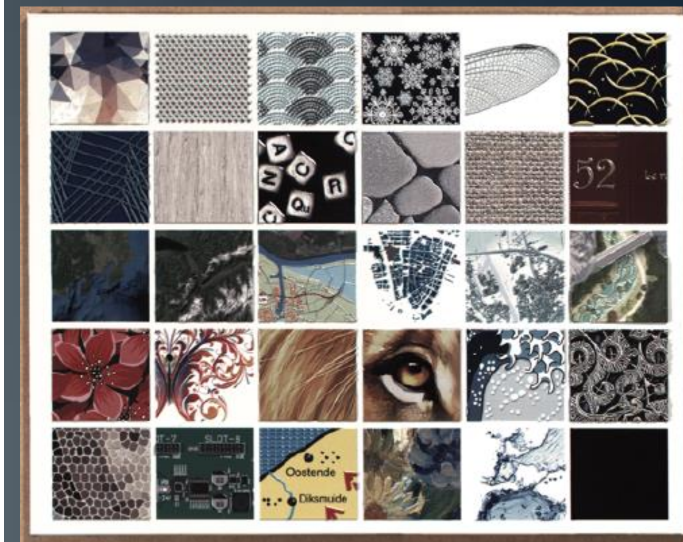
Polynomial 2^{nd}

Root Polynomial 3^{nd}

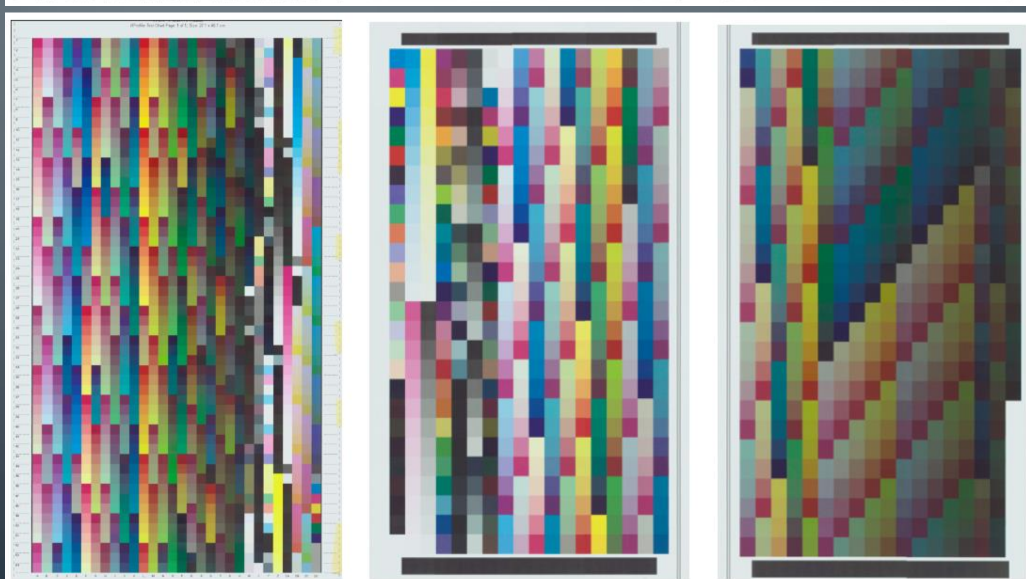
Color Correction Examples

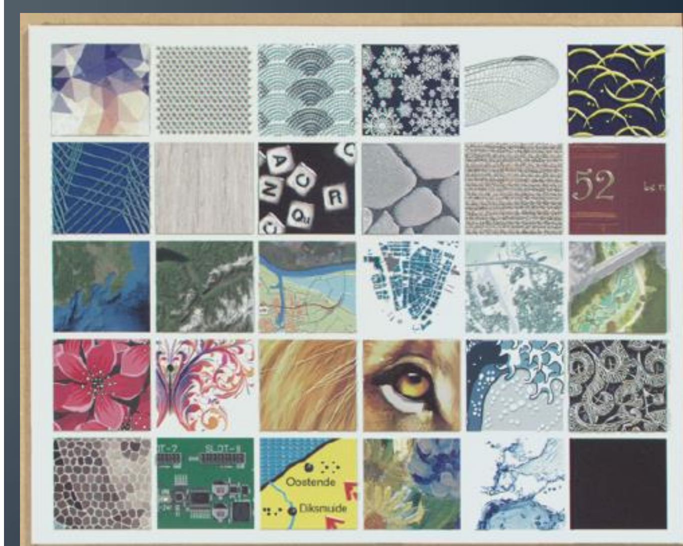
Before



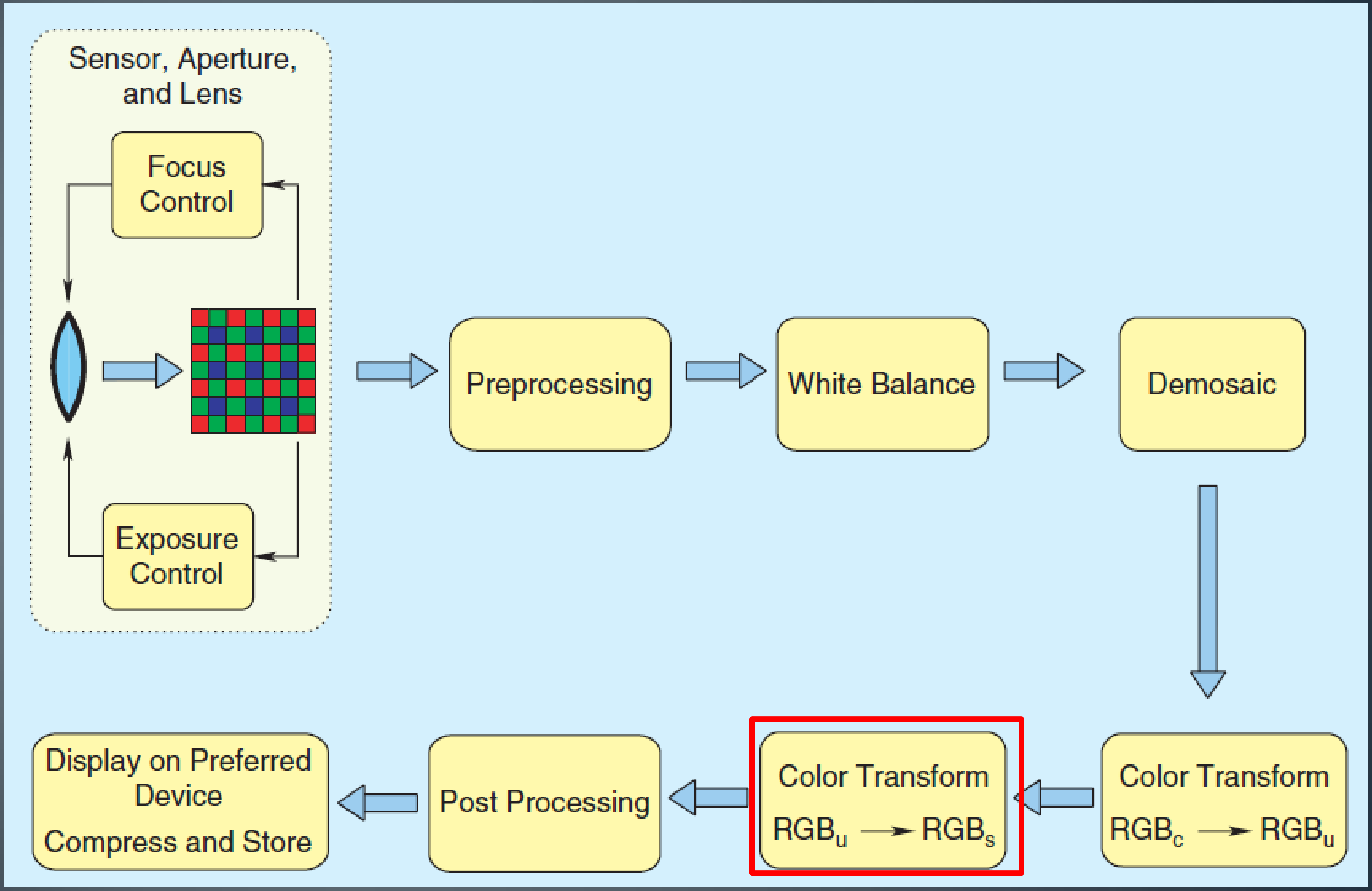


After





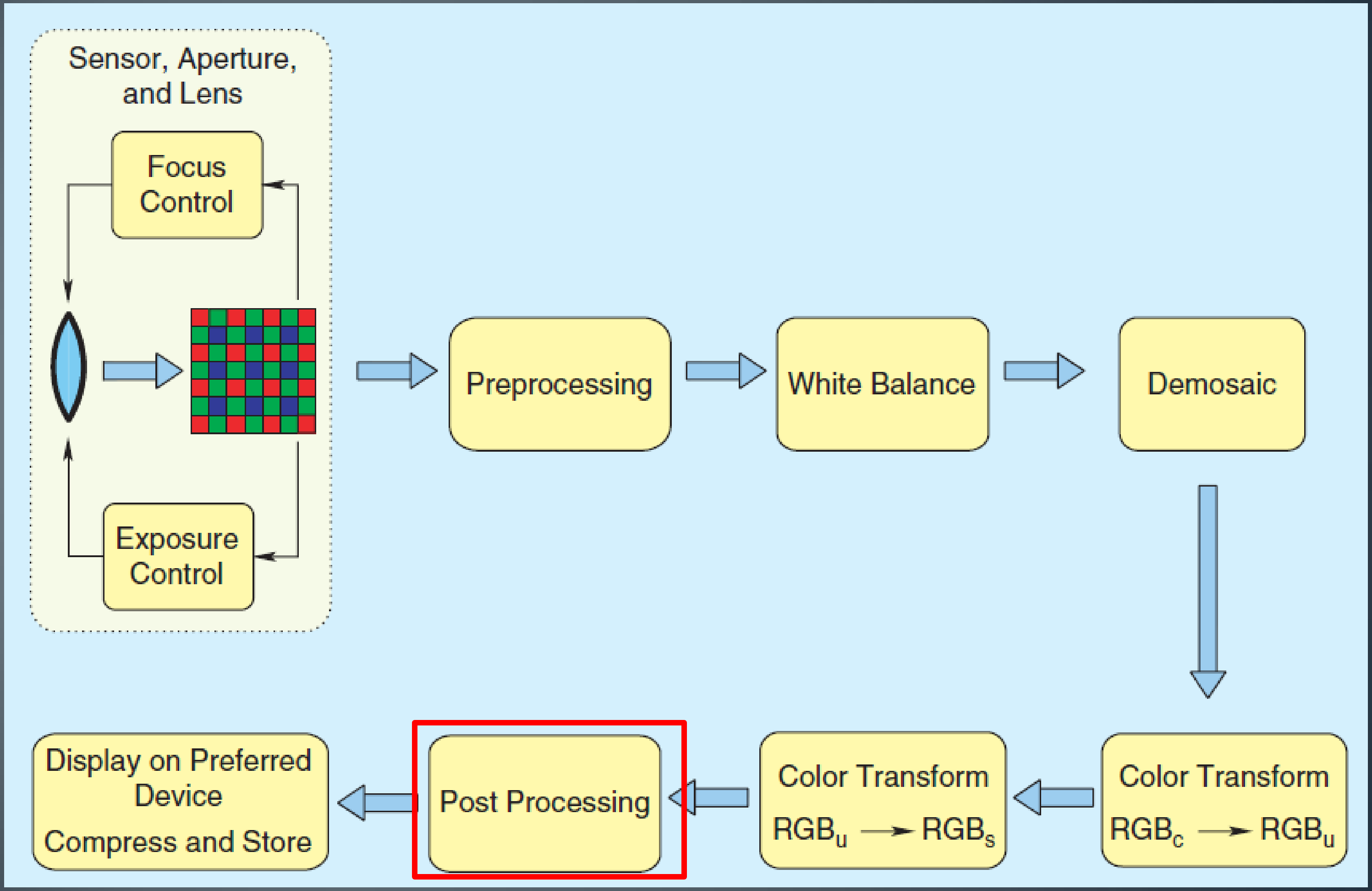
The Color Imaging Flow



Converting the image to a standard Color Space (sRGB)

R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

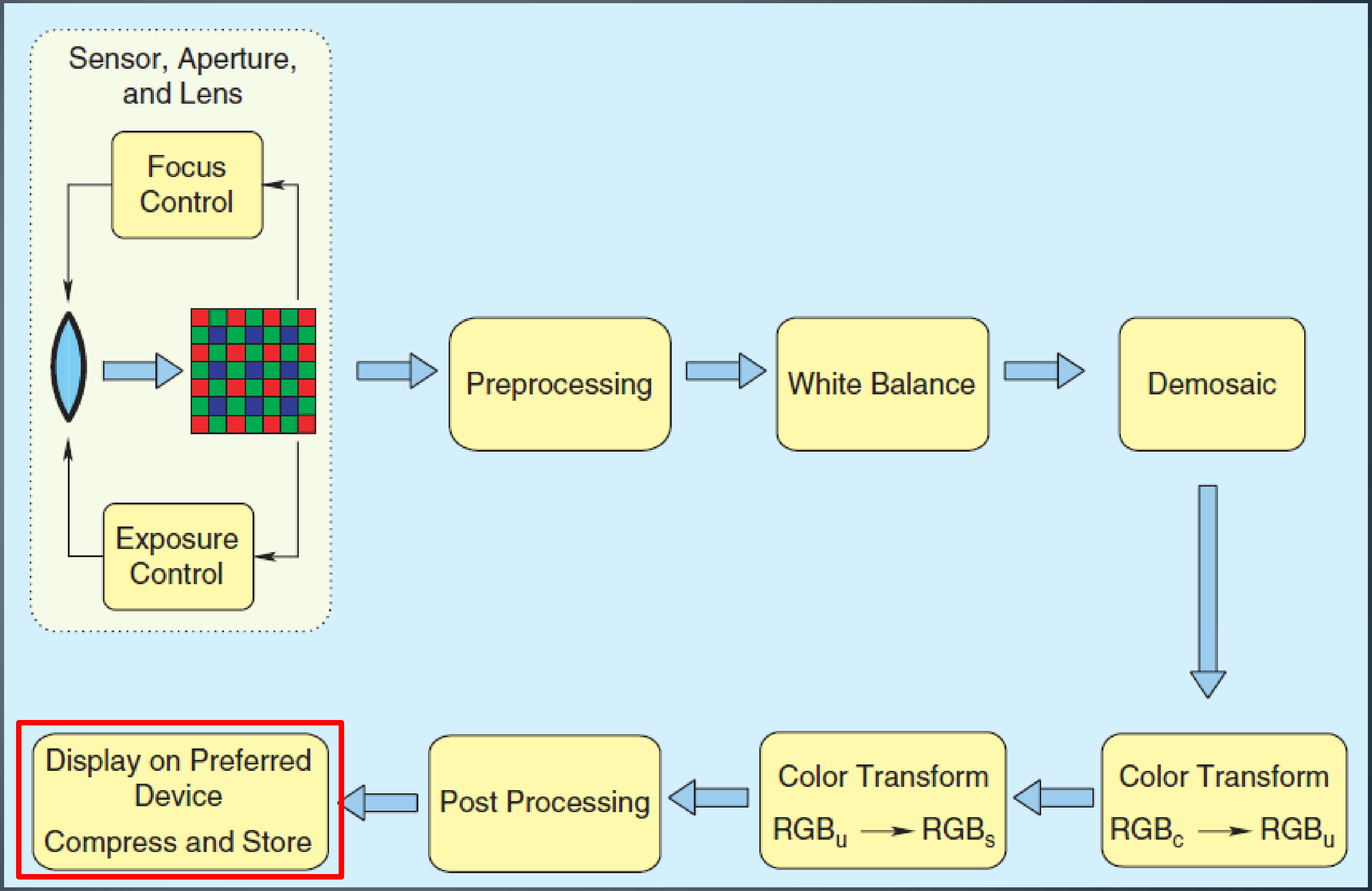
The Color Imaging Flow



Edge Enhancement / Artifact and Noise Removal

R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

The Color Imaging Flow



Save Image as TIFF, JPEG

R. Ramanath et al, "*Color image processing pipeline*", IEEE Signal Processing (2005)

Measuring with RGB Cameras: Recap

- From the moment an image is captured by the sensor, there are a lot of steps which could impact the final color rendition.
- If our purpose is for the image to "*look*" good, then we only need to correct for White Balance.
- If we want the image to be colorimetrically accurate, then we need to calibrate and correct the colors using a Chart, which we choose according to our application.

Future Trends?

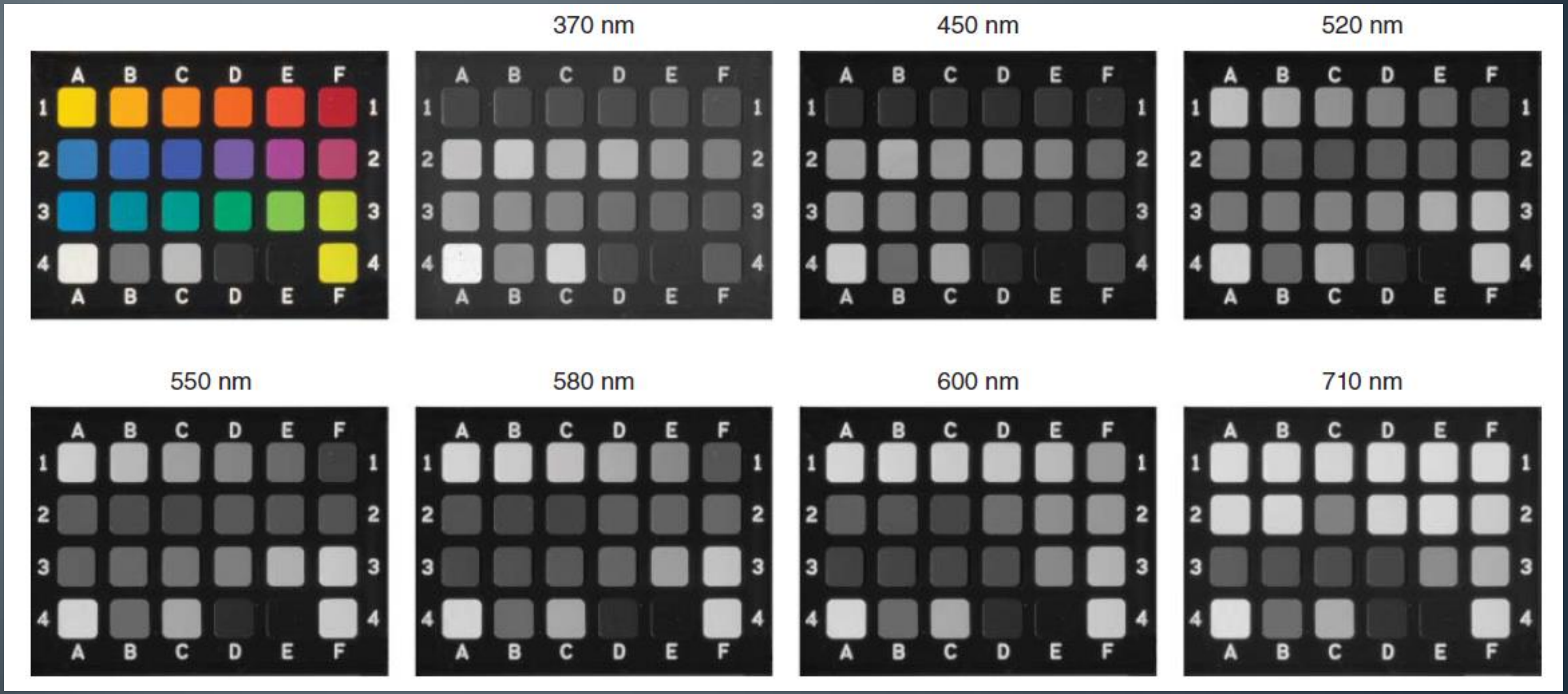
HDR Imaging

- HDR Imaging is quite mature
- Some challenges when acquiring moving scenes or shooting a video
- HDR from a single image using Deep Learning ?

G. Eilertsen, "*HDR image reconstruction from a single exposure using deep CNNs*", SIGGRAPH Asia (2017)

Hyperspectral Imaging

- Used mostly for quality inspection and classification of materials
- In principle, it could be used for measuring Reflectance too (if well calibrated)

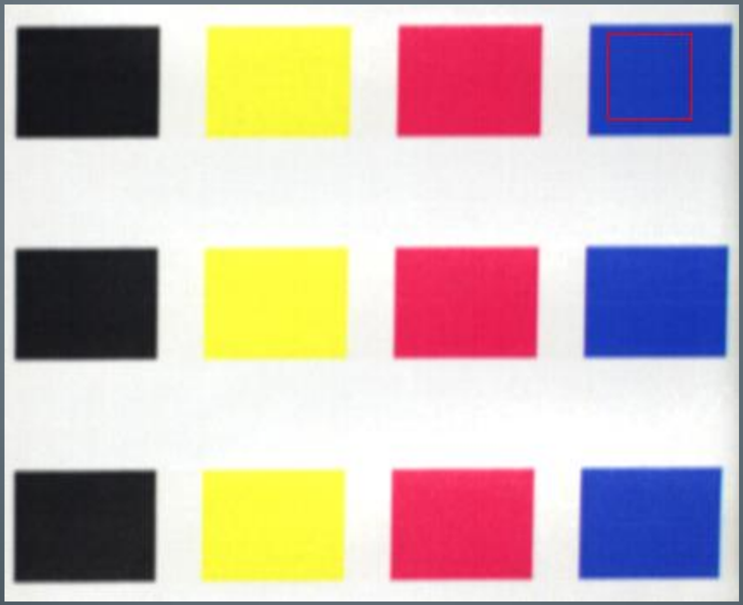


RGB image calculated from the Reflectances estimated from the camera

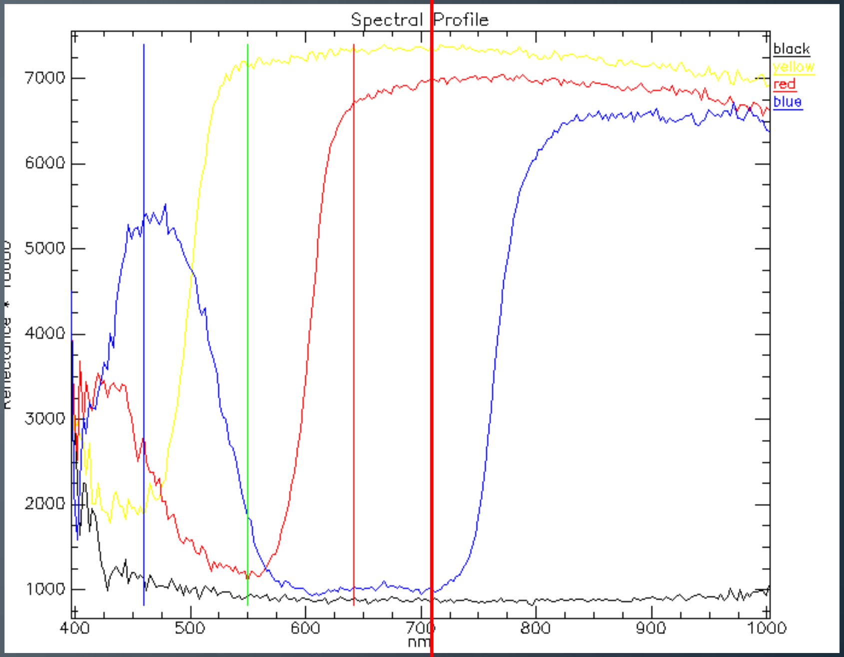
R. Berns, "*Billmeyer and Saltzman's Principles of Color Technology*" (2017)

Hyperspectral Imaging

- Used mostly for quality inspection and classification of materials
- In principle, it could be used for measuring Reflectance too (if well calibrated)



RGB Image calculated from Spectral Data

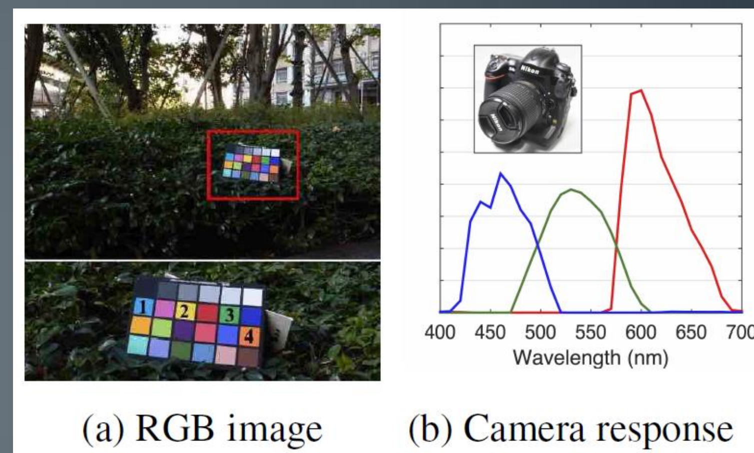


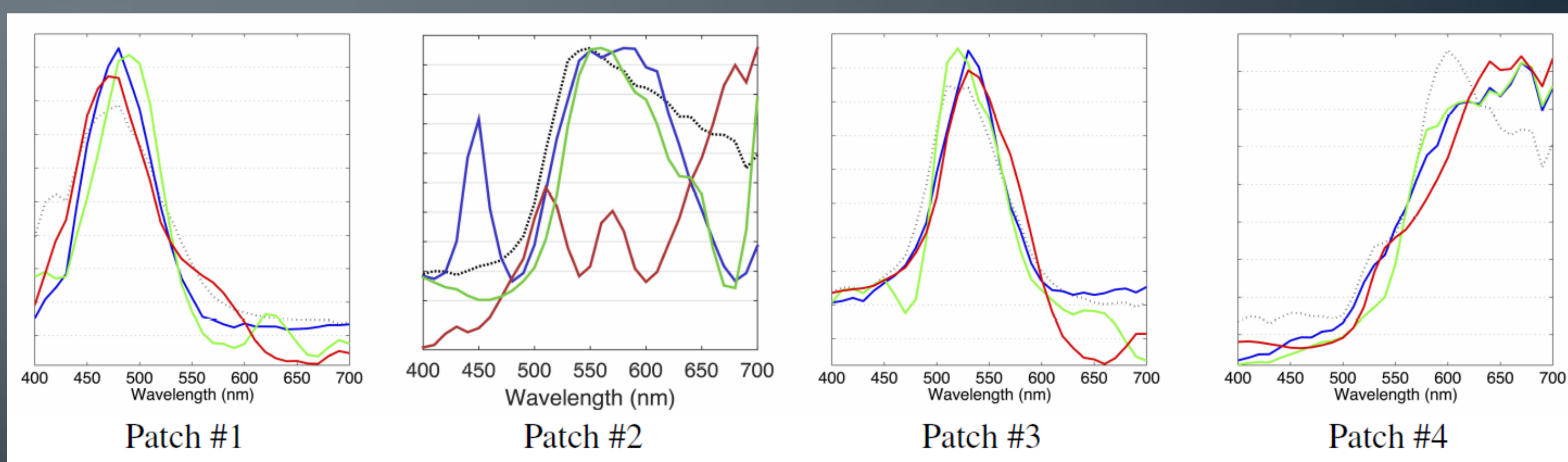
Reflectances of Cyan, Magenta, Yellow and Black Patches

Spectra from RGB

- When measuring color with an RGB camera, we measure the light response in 3 wavelengths.

Research done to estimate the spectral response from an RGB image.





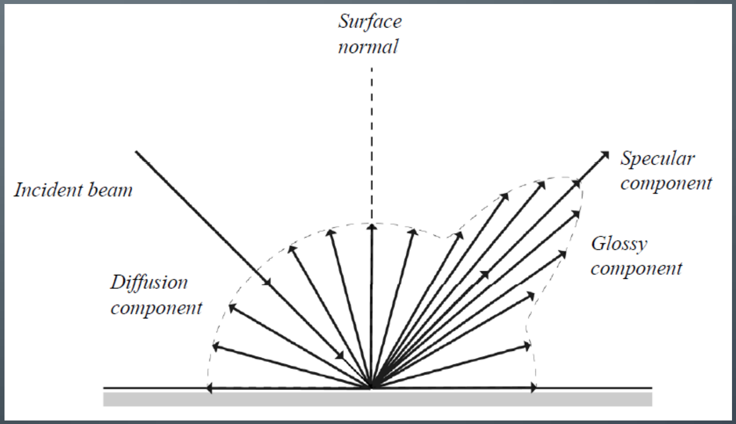
Y. Jia, "*From RGB to Spectrum for Natural Scenes via Manifold-based Mapping*", International Conference on Computer Vision (2017)

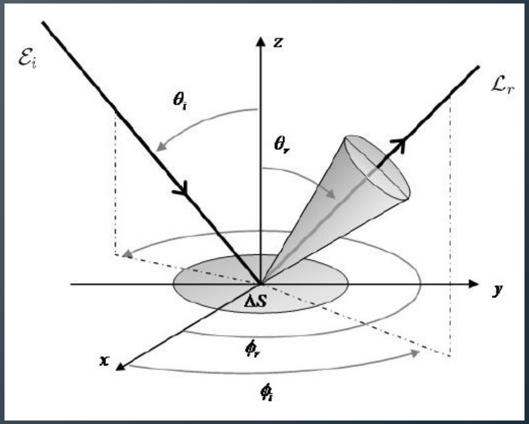
BRDF Measurement

- Remember this example ?

The material appearance of the sample is different.

- Bi-directional Reflectance Distribution Function (BRDF) gives a more complete characterization of light interaction with the surface.





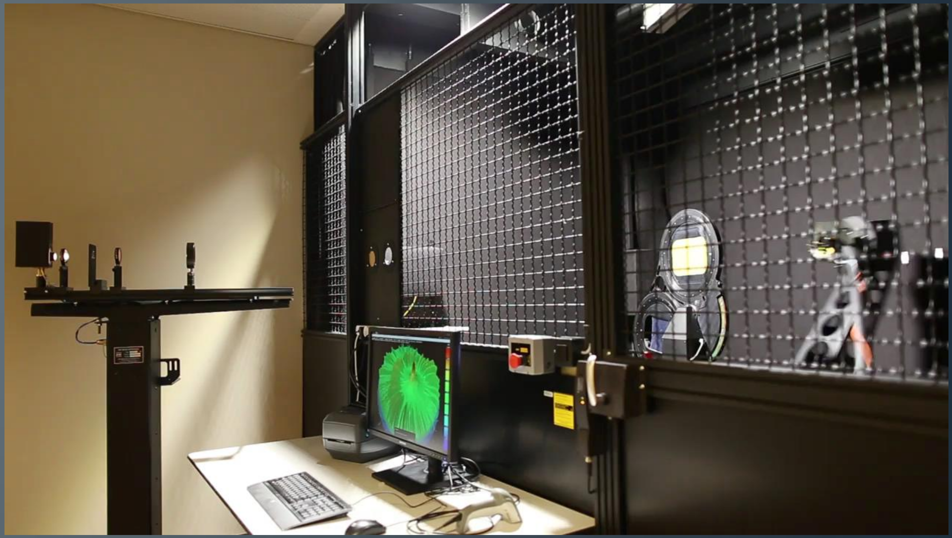
We measure how light reflects in all directions

BRDF Measurement

- BRDF allows characterizing the surface appearance at a microscopic level (used in Computer Graphics to render objects).

- Measurable with Goniophotometers (very expensive!!)

STIL Reflet 180



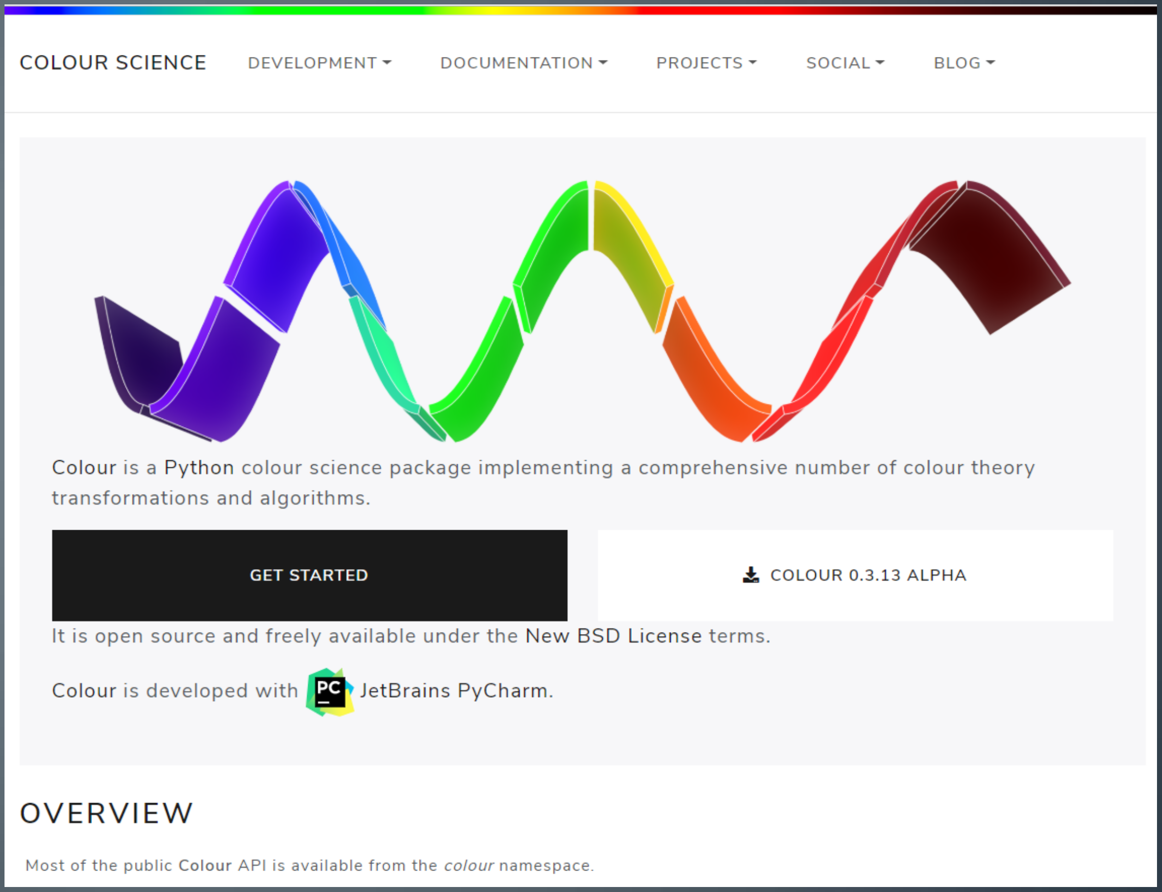
PAB pgII (RGL Lab@EPFL)

How to measure BRDF faster (and cheaper) ?

BRDF Standard ?
BxDiff @ CNAM

Color Science Toolbox

- https://www.colour-science.org/



The End