



PHYSICALLY-BASED CALIBRATION

ACCURATE MATERIAL PRODUCTION IN FORZA HORIZON 4



The background of the image is a blurred, close-up view of a car's wheel and tire, likely from a Forza Horizon 4 game. The colors are predominantly dark blue and black, with some lighter blue highlights. The text is centered in the middle of the image.

VIDEO - Forza Horizon 4 Intro



PHYSICALLY-BASED CALIBRATION

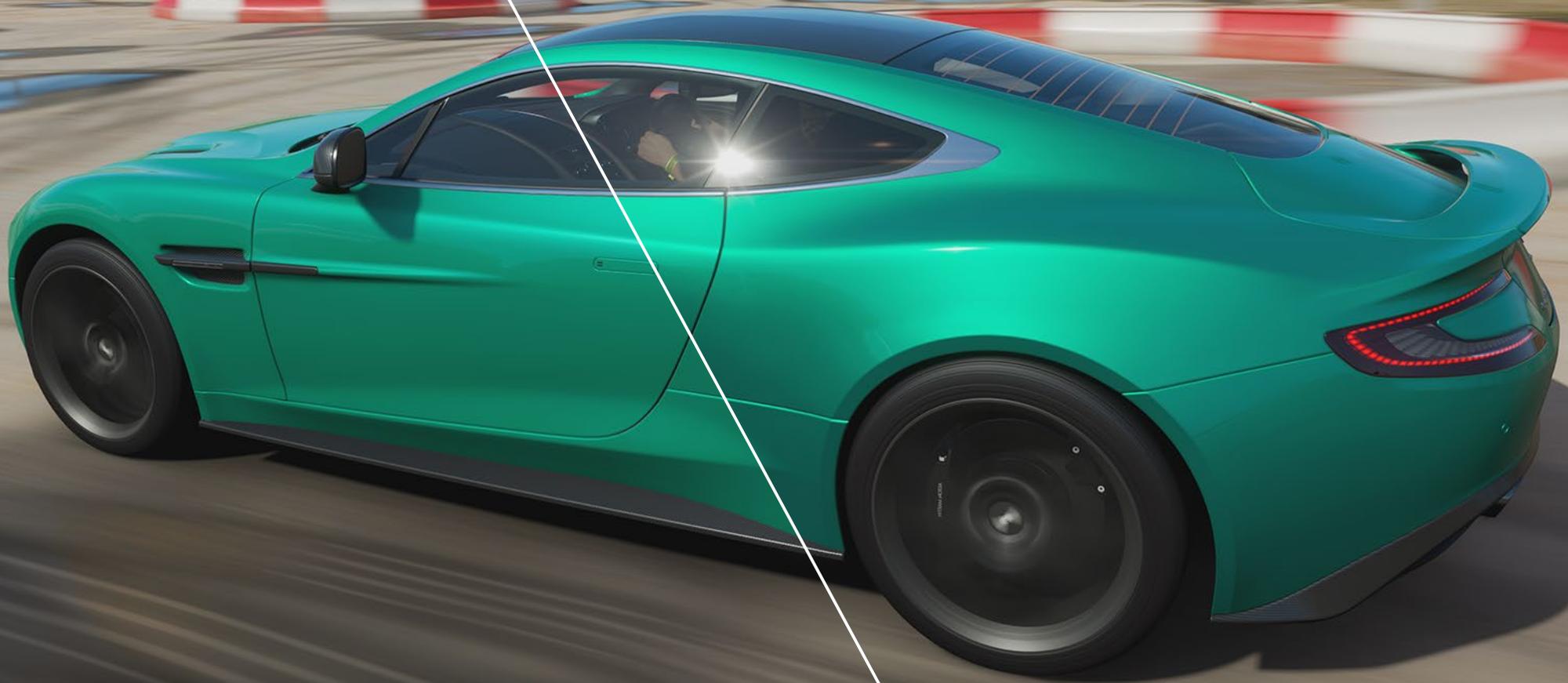
ACCURATE MATERIAL PRODUCTION IN FORZA HORIZON 4





OLD
(Hand-Tuned)

NEW
(Physically-Calibrated)



Manufacturer Paint: "Viridian Green Metallic" by Aston Martin™



YIBO LIU

SENIOR TECHNICAL ARTIST | PLAYGROUND GAMES



PLAYGROUND GAMES





FORZA HORIZON 4



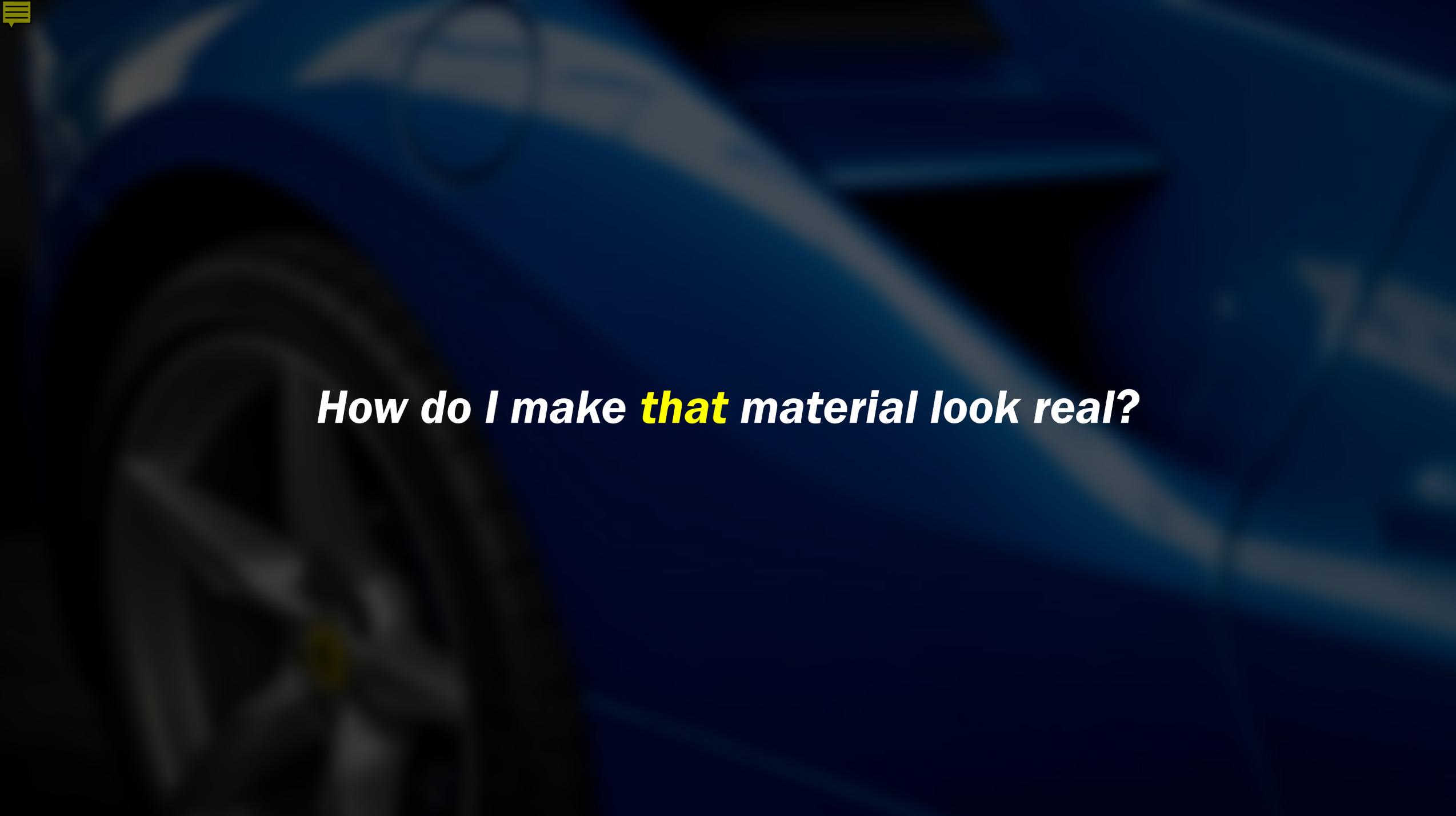
FORZA HORIZON 4

Xbox One & Windows 10 PC





How do I make that material look real?



*How do I make **that** material look real?*



Dev: *“My system can render a wide variety of horses.”*

Gamer: *“But what I want is **that** special horse from LOTR.”*



Dev: *“My system can render a wide range of cars.”*

Gamer: *“But what I want is **that** special car in BMW’s Space Grey Metallic paint.”*



'The Dress'

Went viral in 2015

- 1) Blue and Black (57%*)**
- 2) White and Gold (30%)**
- 3) Blue and Brown (11%)**
- 4) Something else (2%)**

What is Real \neq What is *Perceived* as Real

“The Calibration Problem”

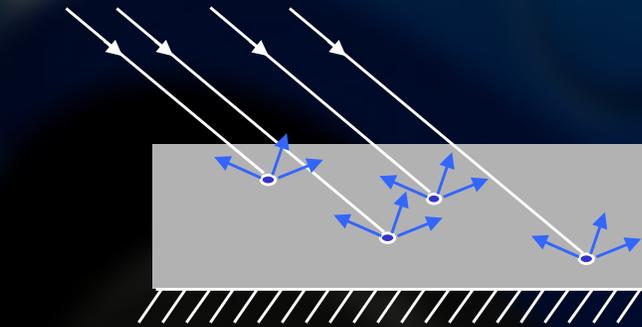
Automotive Paint



Automotive Paint is 'Gonioapparent'

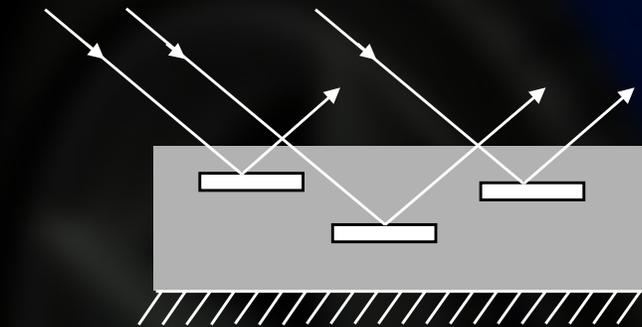


Automotive Paint is 'Gonioapparent'



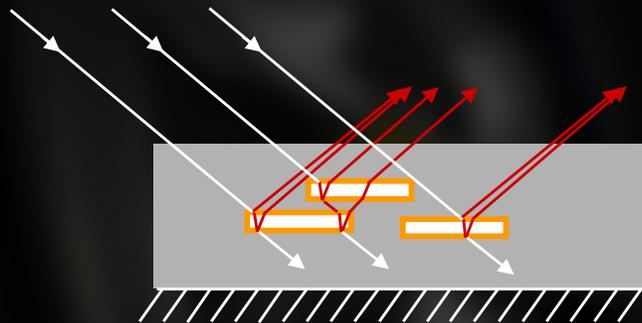
Absorption Pigments

Specific Colour –
Due to selective **absorption** and scattering of light



Metallic Pigments

Metallic Gloss –
Due to mirror-like **reflection** of light



Pearl Luster Pigments

Specific Colour, Luster and Colour Flop -
Due to **interference** of light

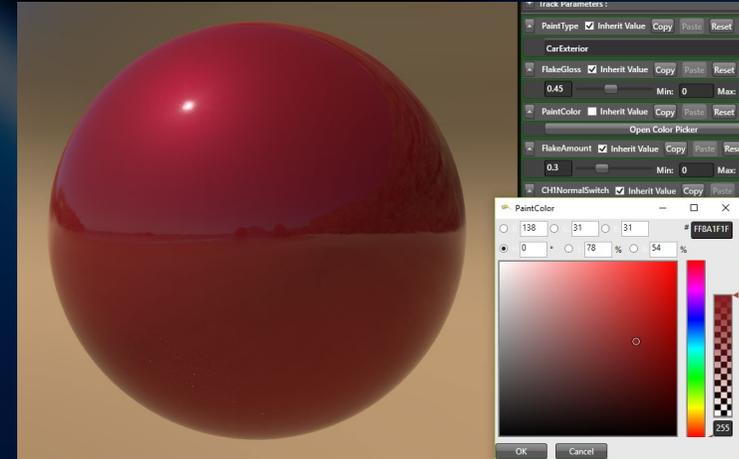
Many Biases in Traditional Workflow

REFERENCE



- **Photographs Only**
- **Unknown/Uncontrolled Factors**
 - Lighting Conditions
 - Reflected Environment
 - Camera Settings
 - Image Editing

TUNING

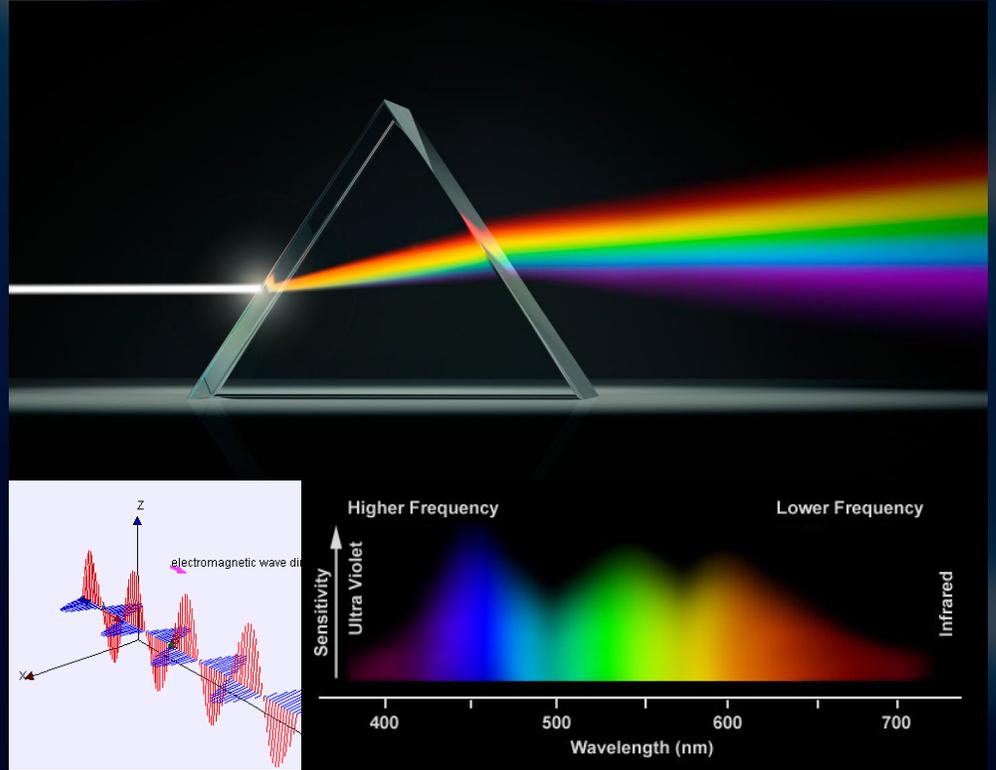
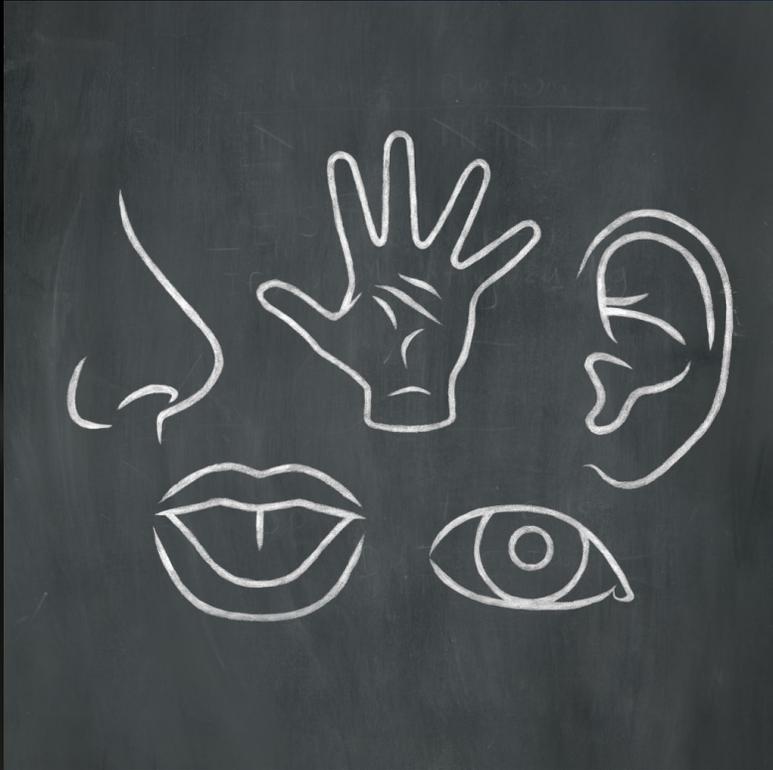


- **Based on 'Feelings'**
- **Difficult to Match Scientifically**
 - Monitor Conditions
 - Reflected Environment
 - Rendering Configurations
 - Viewing Conditions

Perceptually Based



Physically Based



Colour Management in the Automotive Industry



BYK-mac i

Total color impression of effect finishes

The appearance of effect finishes is influenced by different viewing angles and viewing conditions. Apart from a light-dark flop and color shift special sparkling effects can be created. The BYK-mac i spectrophotometer is unique as it measures both multi-angle color and flake characterization in one portable device.

- Traditional 5-angle color measurement: 15° / 25° / 45° / 75° / 110°
- Additional color measurement behind the gloss for color travel of interference pigments: -15°
- Sparkle and graininess measurement for flake characterization



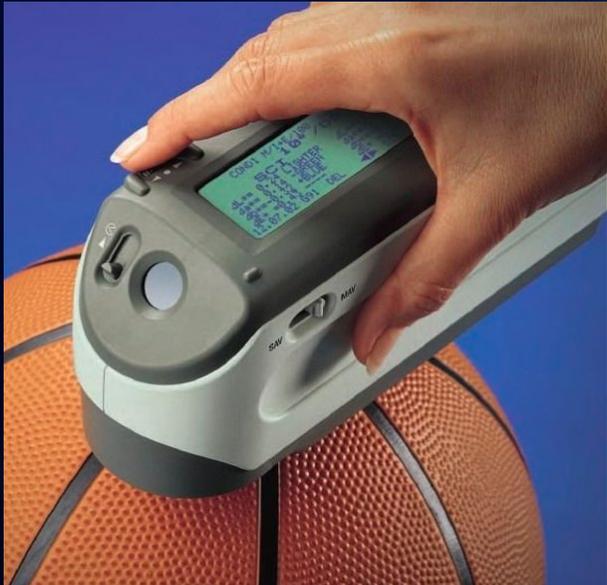
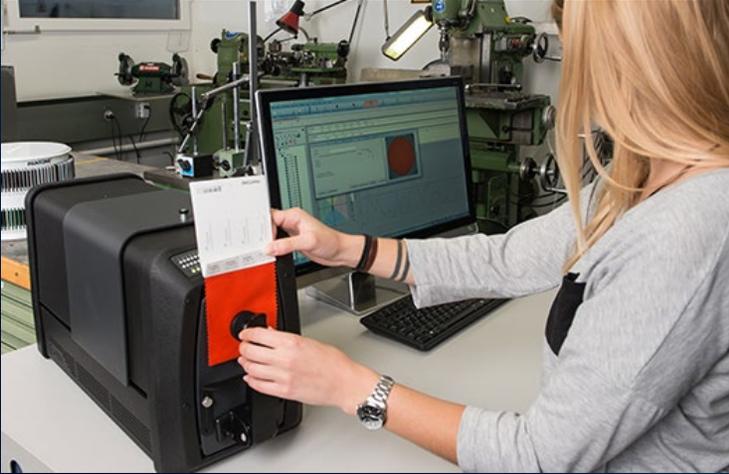
- Spectrophotometer
- NOT a camera
- Built-in D65 Light Source
- Multi-Angle Sensors
- For Quality Control Purposes
- ASTM International Standards



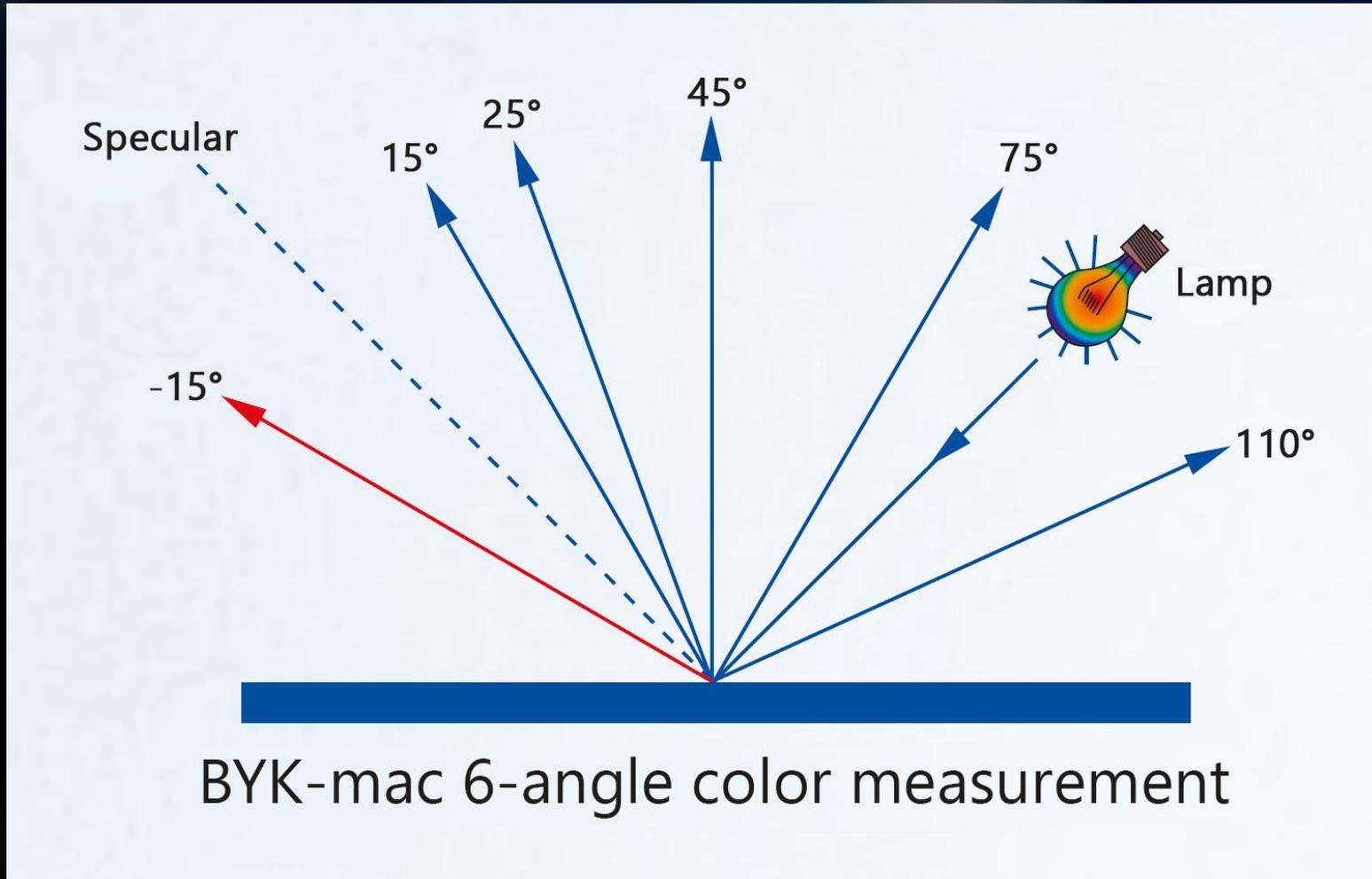
Colour Management in the Automotive Industry



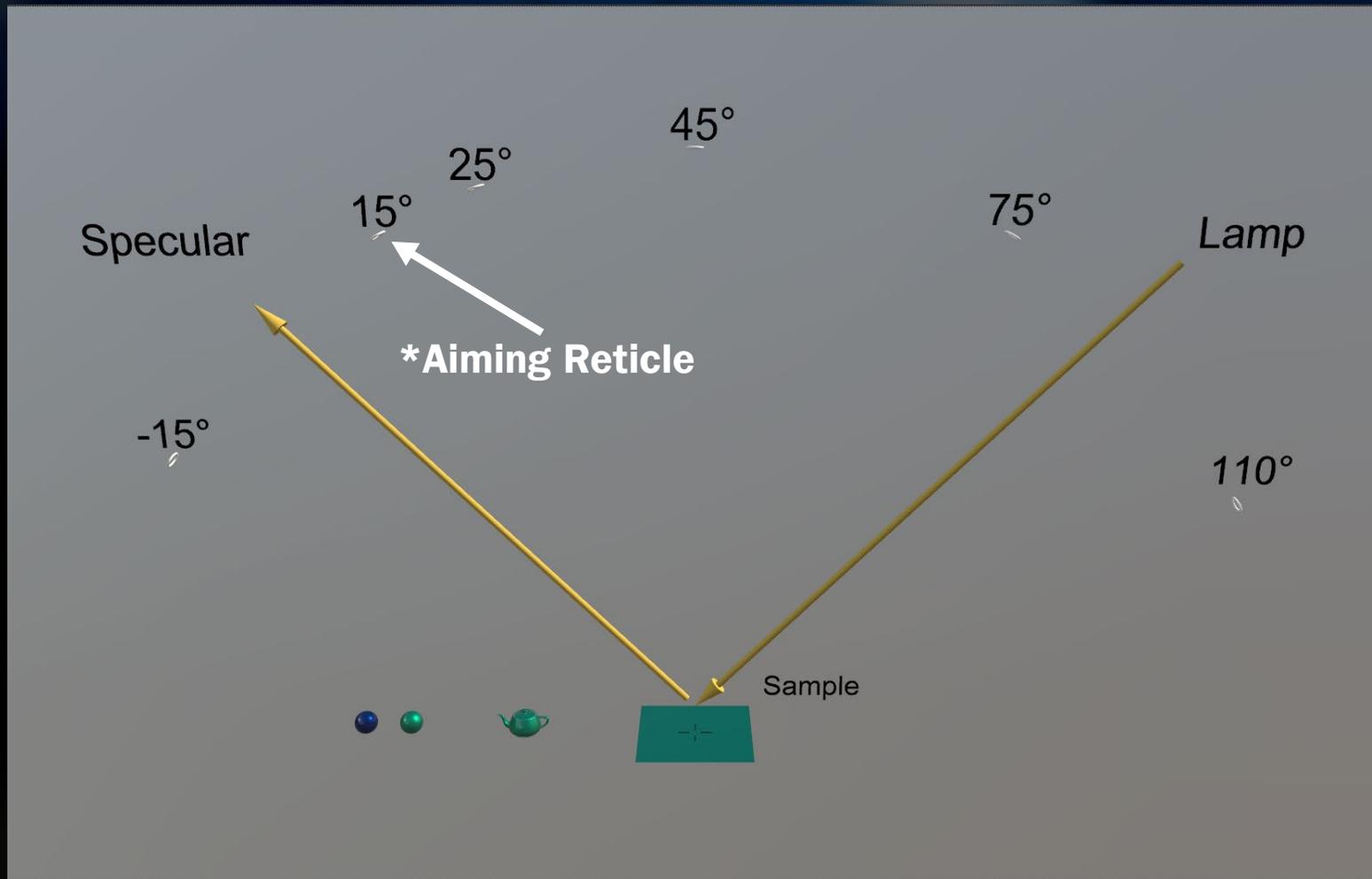
Other Applications



Multi-Angle Measurement – In Reality



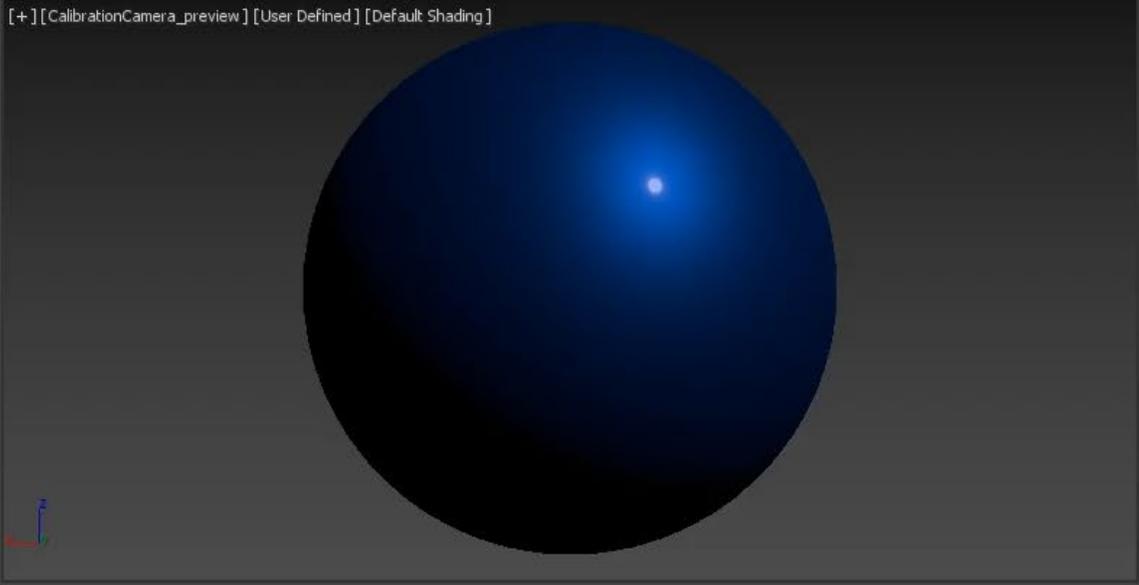
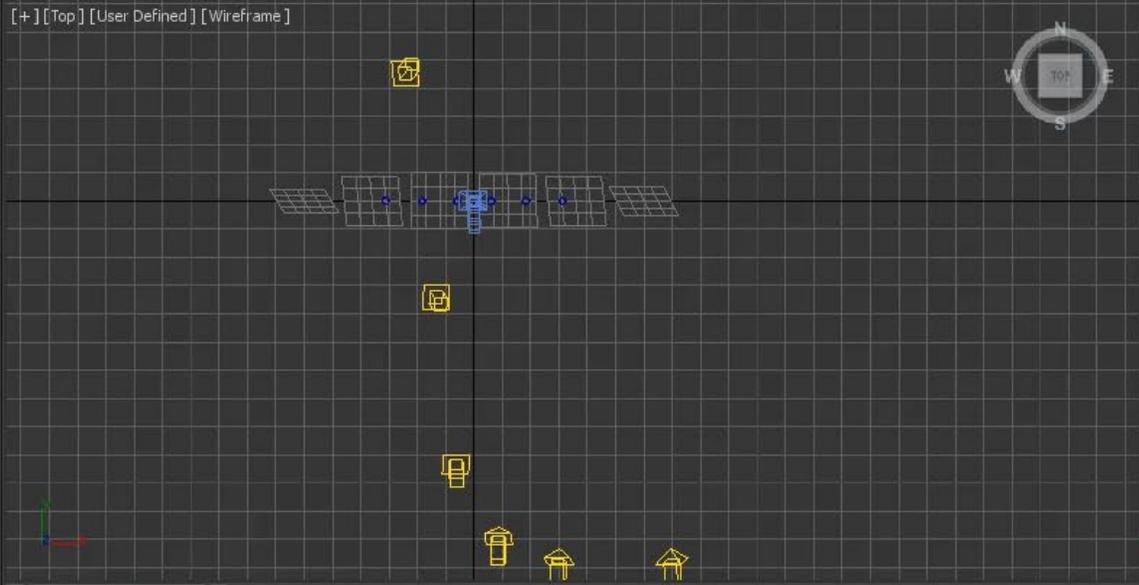
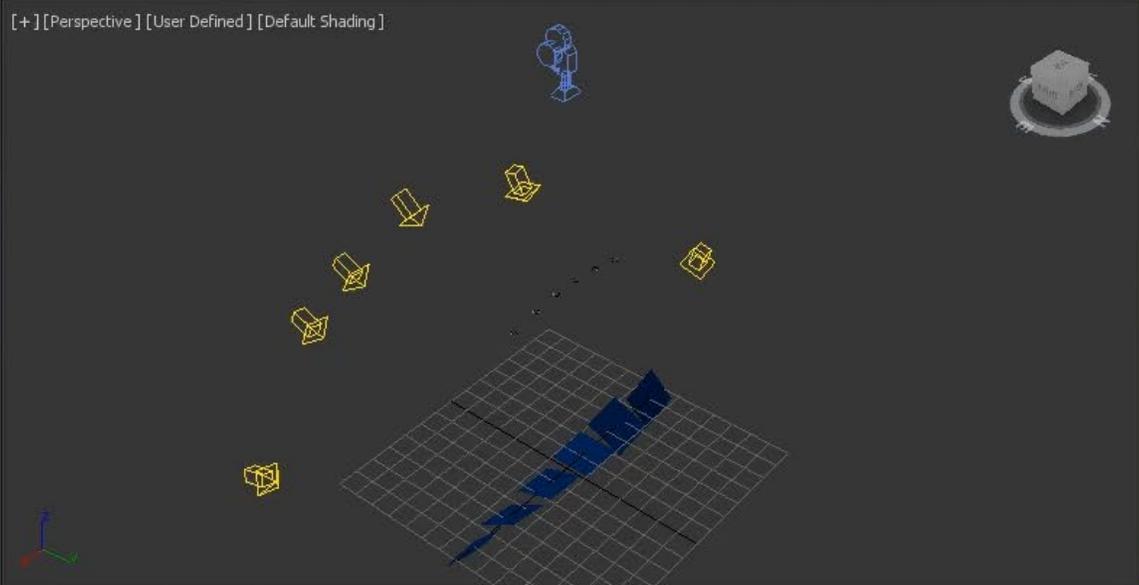
Multi-Angle Measurement – In Game



- **Early Game Material Measurement Test**



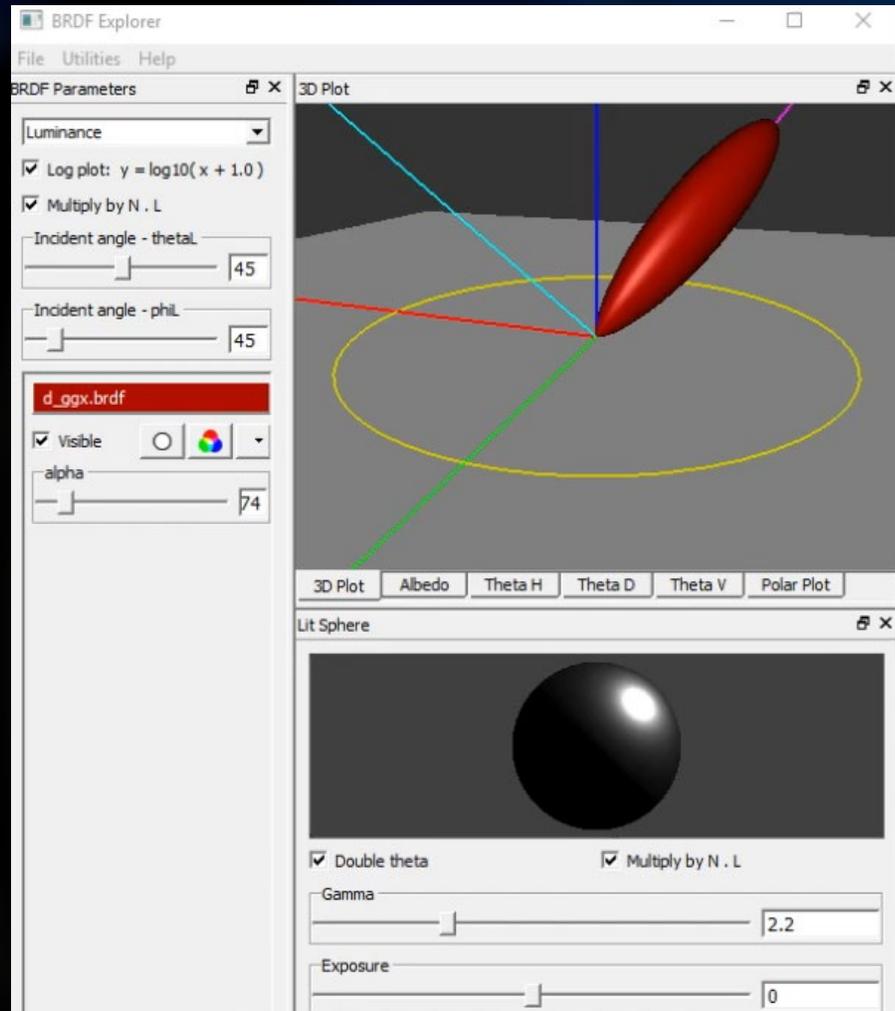
Multi-Angle Measurement – In Game (3Ds Max)



Inspiration - Visualising BRDF

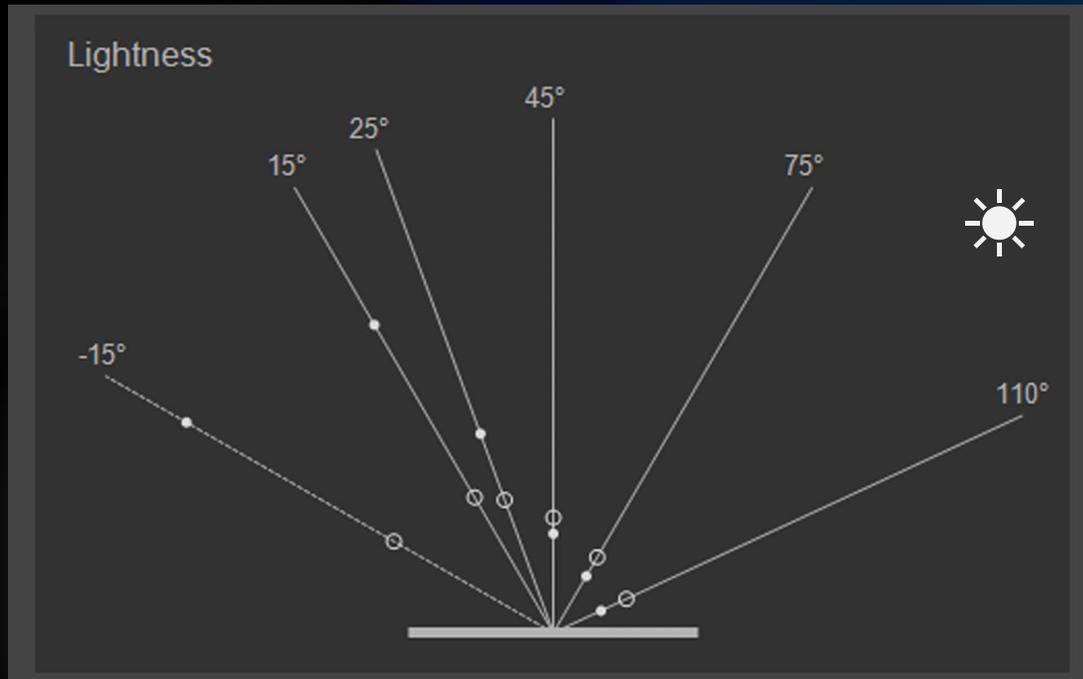


GGX Shading Model Visualisation



Bidirectional Reflectance Distribution Function

It's All About the Reflectance Distribution



***Match the Reflectance Distribution,
and you match the material***

- **Physical** Measurements
- **Game** Measurements

Apple-to-Apple Comparison – Quantitative Colour Analysis



Physical Measurements



SPD



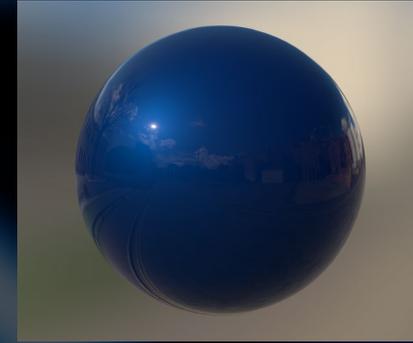
XYZ



Lab

Lab

Compare!



Game Measurements



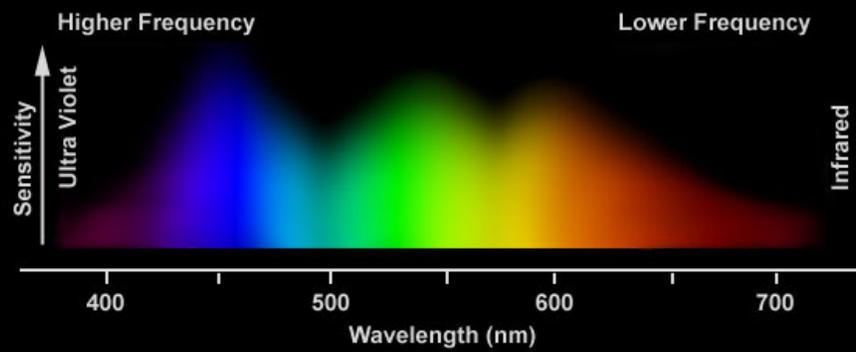
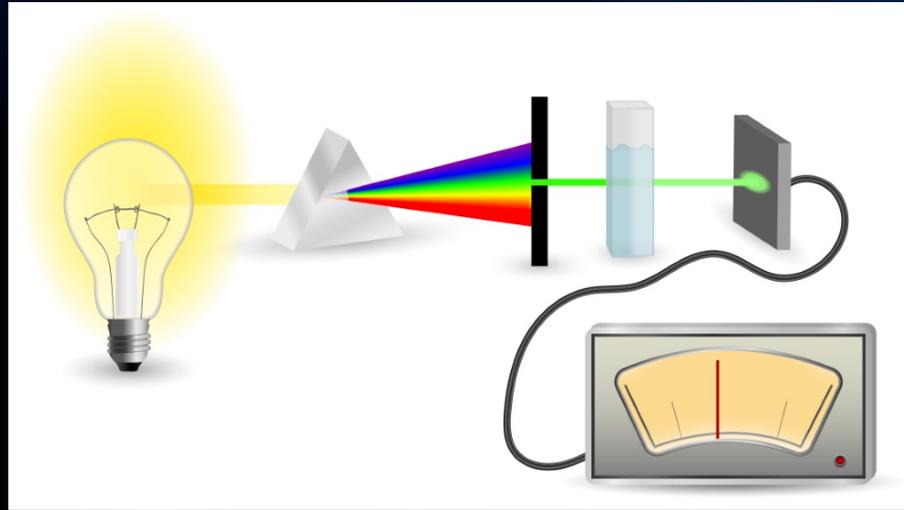
sRGB (or HDR Linear)



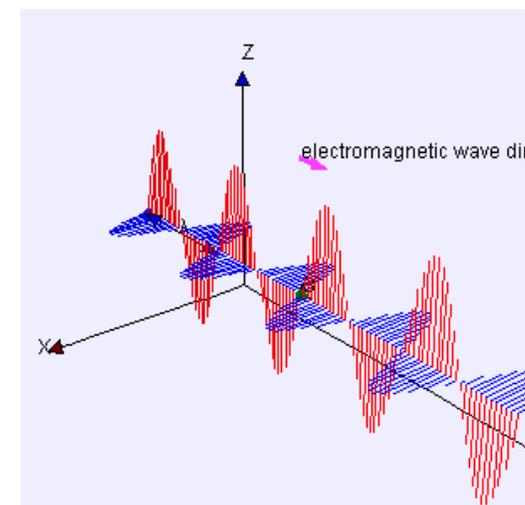
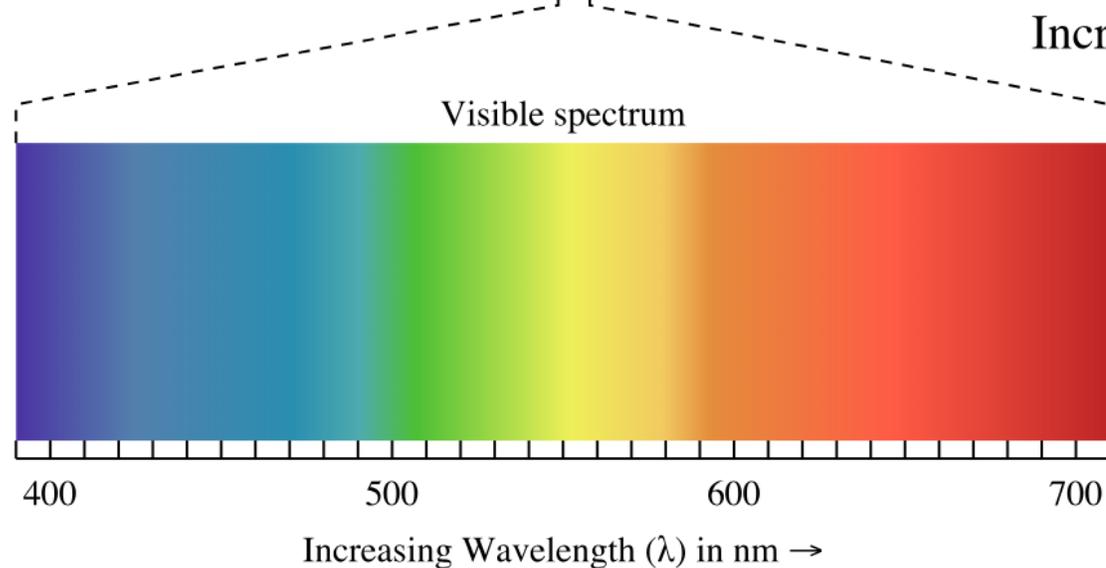
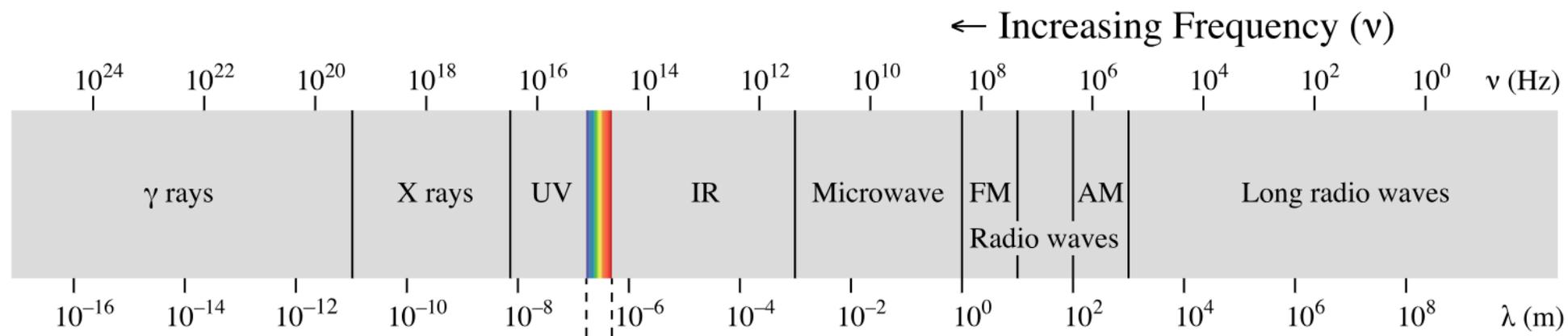
XYZ



Spectrophotometry



Spectrophotometry

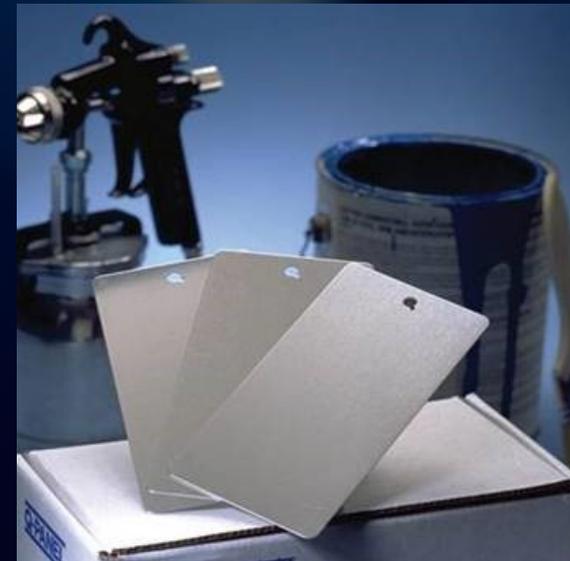


“Digital Masters”

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“Digital Masters” XML

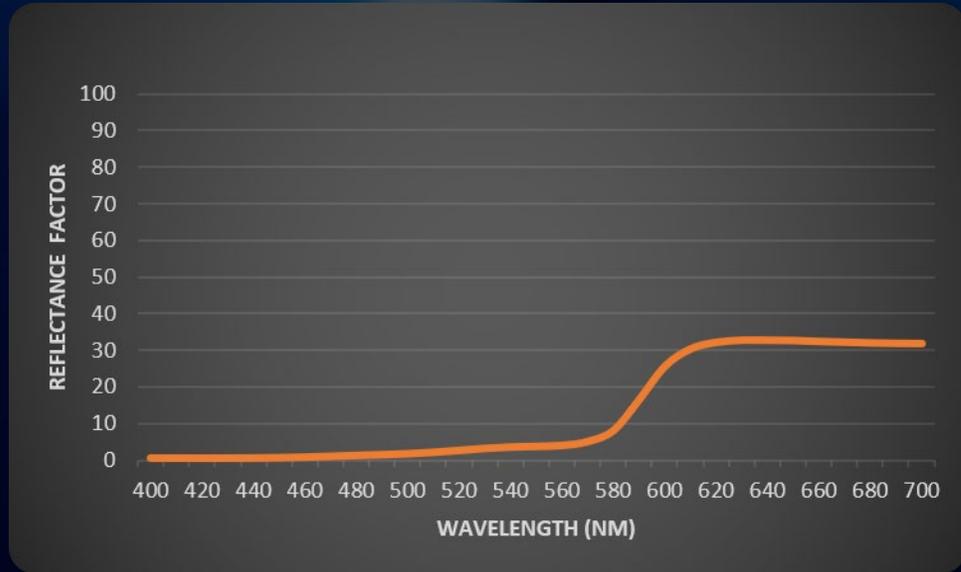
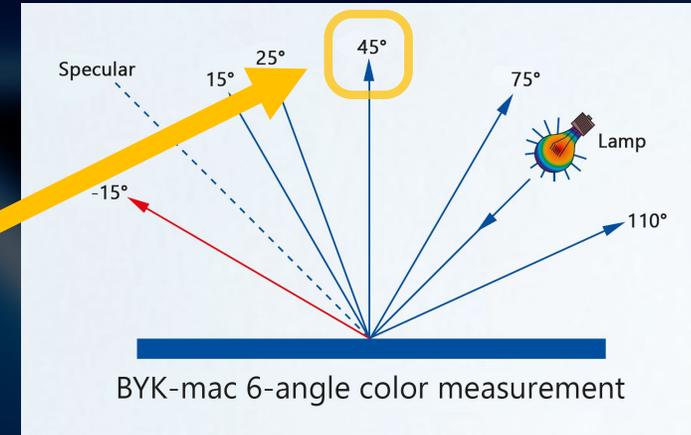


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One SPD for One Angle



ASTM E 308 Standard



Designation: E 308 – 01

Standard Practice for Computing the Colors of Objects by Using the CIE System¹

This standard is issued under the fixed designation E 308; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

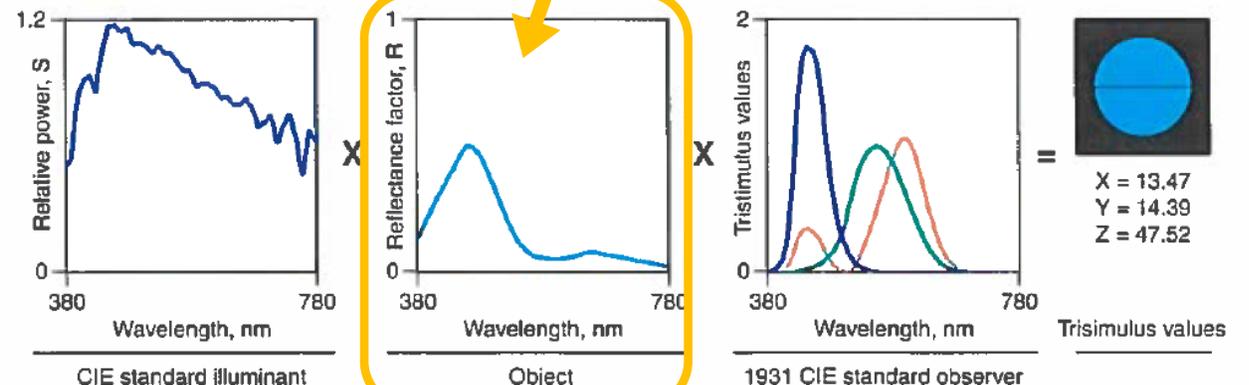
INTRODUCTION

Standard tables (Tables 1-4) of color matching functions and illuminant spectral power distributions have since 1931 been defined by the CIE, but the CIE has eschewed the role of preparing tables of tristimulus weighting factors for the convenient calculation of tristimulus values. There have subsequently appeared numerous compilations of tristimulus weighting factors in the literature with disparity of data resulting from, for example, different selections of wavelength intervals and methods of truncating abbreviated wavelength ranges. In 1970, Foster et al. (1)² proposed conventions to standardize these two features, and Stearns (2) published a more complete set of tables and later publications such as the 1985 revision of E 308 have greatly reduced variations in methods for tristimulus computation that existed several decades ago.

The disparities among earlier tables were largely caused by the introduction of color data on 20-nm wavelength intervals. With the increasing precision of modern instruments, the likelihood of a need for tables for narrower wavelength intervals. Stearns' tables, by their narrower interval, did not allow the derivation of consistent tables with wavelength intervals

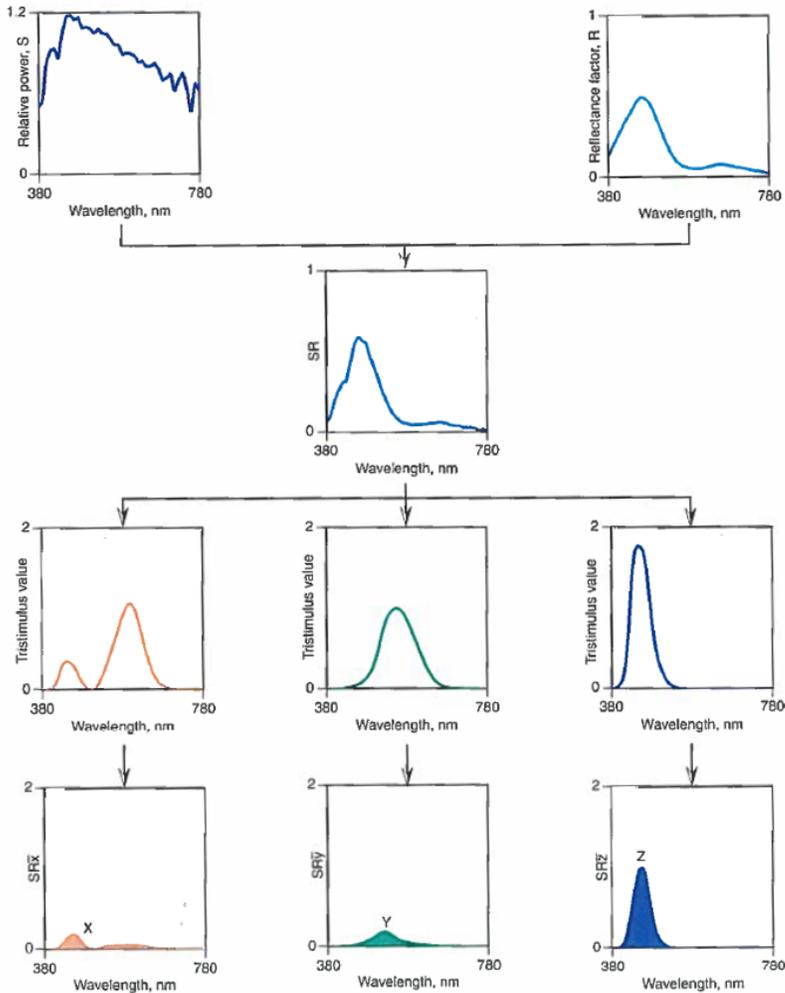
- From Spectral Power Distribution (SPD) to Colour Information
- SPD \rightarrow XYZ

SPD Data from "Digital Masters" XML



Source: Billmeyer and Saltzman's principles of color technology

From SPD to XYZ Colour



In a little more detail than in the figure on page 56, here are all the spectral curves needed to calculate CIE tristimulus values X, Y, and Z. Wavelength by wavelength, the values of the curves of S and R are multiplied together to give the curve, SR. Then this curve is multiplied, in turn, by x, by y, and by z, to obtain the curves SRx, SPY, and SPZ. The areas under these curves, followed by a normalization, are the tristimulus values X, Y, and Z.

- Integrating a continuous spectrum into merely 3 numbers (Tristimulus Integration)
- International Commission on Illumination (CIE)
- CIE 1931 XYZ Colour Space

$$X = \int \% \text{ reflectance} * \text{illuminant factor} * x \text{ factor of standard observer}$$

$$Y = \int \% \text{ reflectance} * \text{illuminant factor} * y \text{ factor of standard observer}$$

$$Z = \int \% \text{ reflectance} * \text{illuminant factor} * z \text{ factor of standard observer}$$

Merged as *W*

From SPD to XYZ Colour

Calculating tristimulus values using the ASTM E308 method:

$$X = \sum_{\lambda} R_{\lambda} W_x$$

$$Y = \sum_{\lambda} R_{\lambda} W_y$$

$$Z = \sum_{\lambda} R_{\lambda} W_z$$

- R_{λ} is Reflectance as a function of wavelength
- W_n is the **tristimulus weights** for the human eye under controlled D65 illuminant defined by ASTM E308 standard (shown on the right)

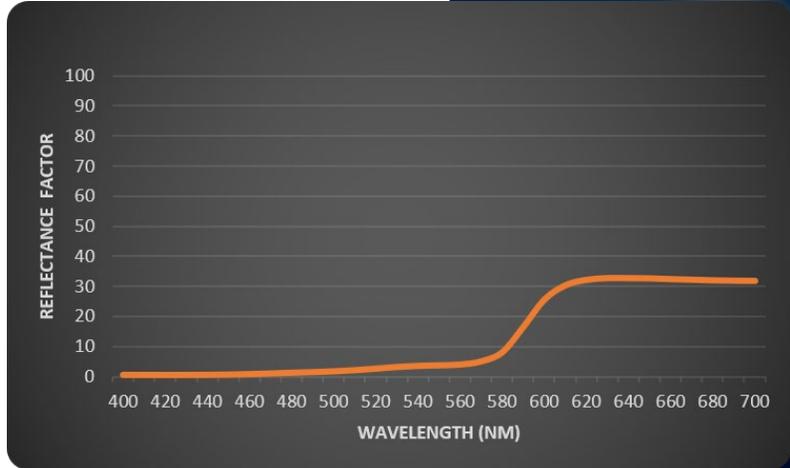


Table 5.17 Illuminant D65, 1931 Observer
10 nm Interval

nm	W_x	W_y	W_z
360	0.000	0.000	0.001
370	0.002	0.000	0.010
380	0.006	0.000	0.026
390	0.022	0.001	0.104
400	0.101	0.003	0.477
410	0.376	0.010	1.788
420	1.200	0.035	5.765
430	2.396	0.098	11.698
440	3.418	0.226	17.150
450	3.699	0.417	19.506
460	3.227	0.664	18.520
470	2.149	0.998	14.137
480	1.042	1.501	8.850
490	0.333	2.164	4.856
500	0.045	3.352	2.802
510	0.098	5.129	1.602
520	0.637	7.076	0.791
530	1.667	8.708	0.420
540	2.884	9.474	0.202
550	4.250	9.752	0.086
560	5.626	9.419	0.037
570	6.988	8.722	0.019
580	8.214	7.802	0.014
590	8.730	6.442	0.010
600	9.015	5.351	0.007
610	8.492	4.263	0.003
620	7.050	3.145	0.001
630	5.124	2.113	0.000
640	3.516	1.373	0.000
650	2.167	0.818	0.000
660	1.252	0.463	0.000
670	0.678	0.248	0.000
680	0.341	0.124	0.000
690	0.153	0.055	0.000
700	0.076	0.027	0.000
710	0.040	0.014	0.000

From SPD to XYZ Colour

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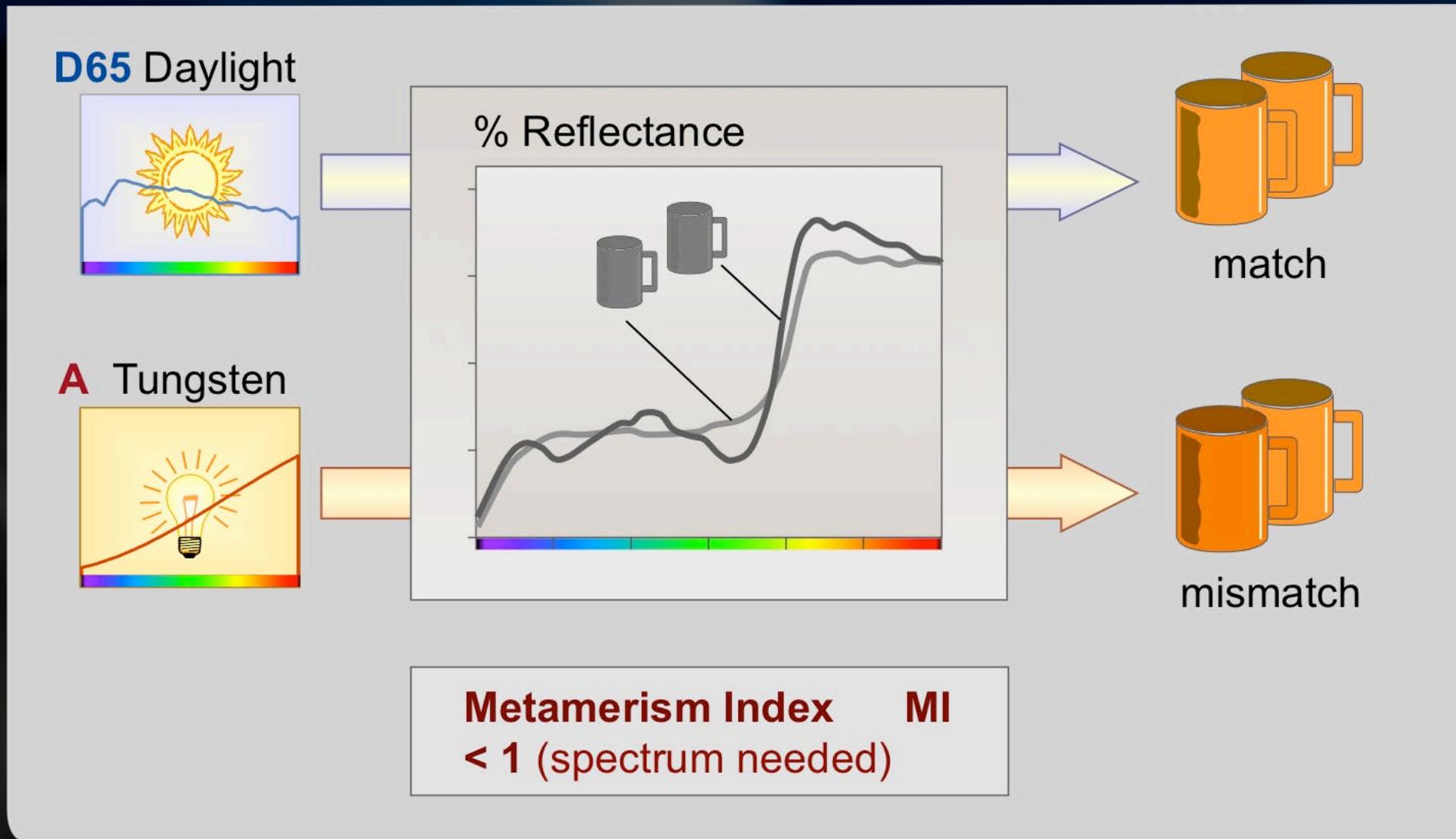


R: 155
G: 52
B: 2

XYZ Colour
[14.80, 9.45, 1.11]

- Side note – this is a lossy conversion (lookup *Metamerism* for details)

Metamerism



From XYZ to Lab

Reference white point for CIE 1931 observer (D65 2°):

$$X_n = 95.047$$

$$Y_n = 100.0$$

$$Z_n = 108.883$$

$$L^* = 166 \left[f \left(\frac{Y}{Y_n} \right) - \frac{16}{116} \right]$$

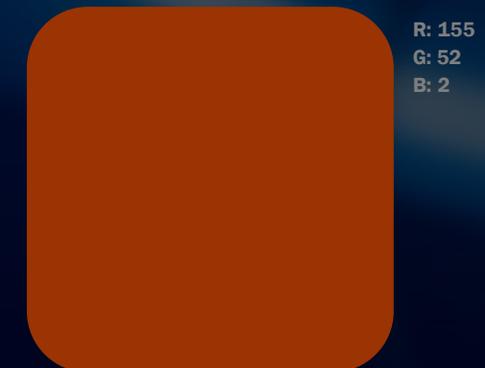
$$a^* = 500 \left[f \left(\frac{X}{X_n} \right) - f \left(\frac{Y}{Y_n} \right) \right]$$

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

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t < 0.008856 \\ 7.787t + \frac{16}{116} & \text{otherwise} \end{cases}$$

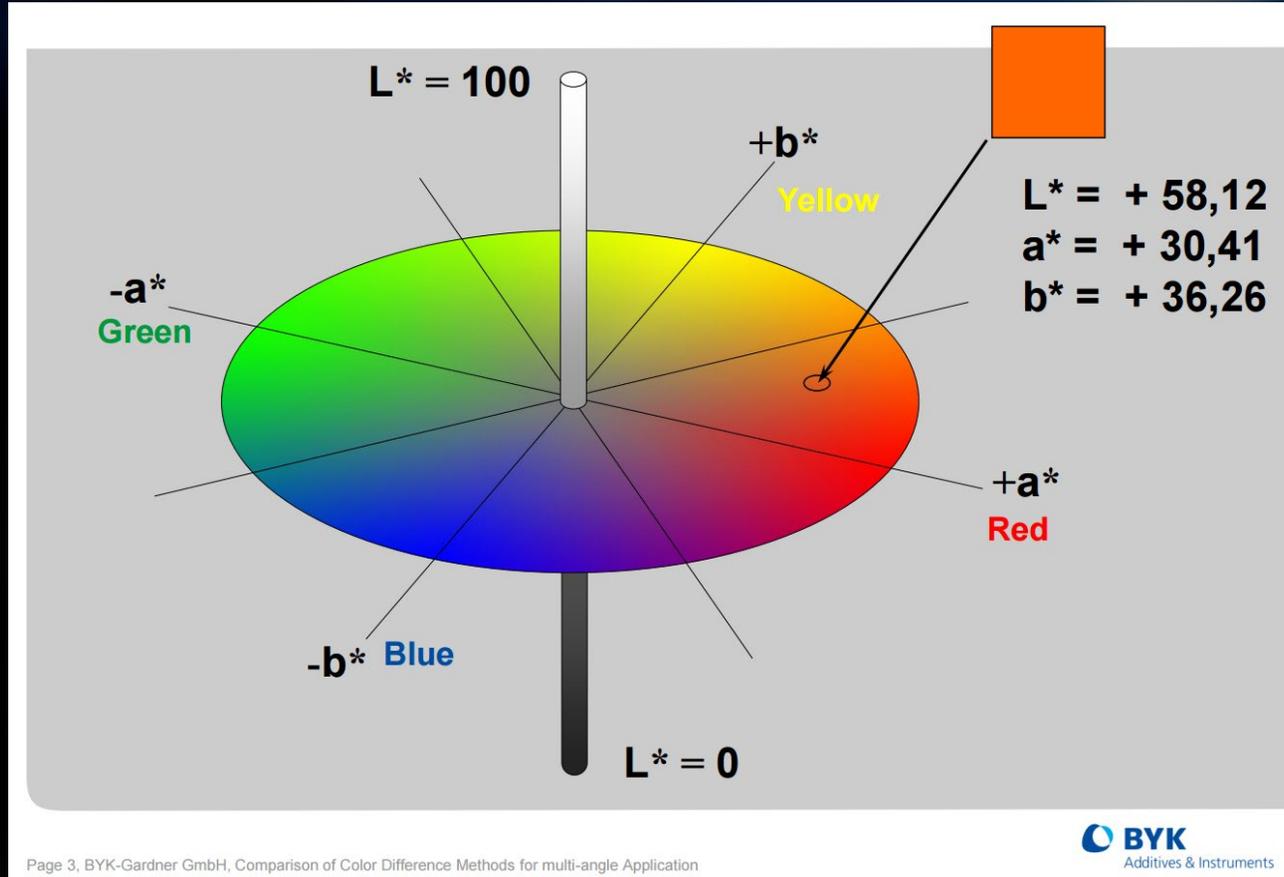


XYZ Colour
[14.80, 9.45, 1.11]



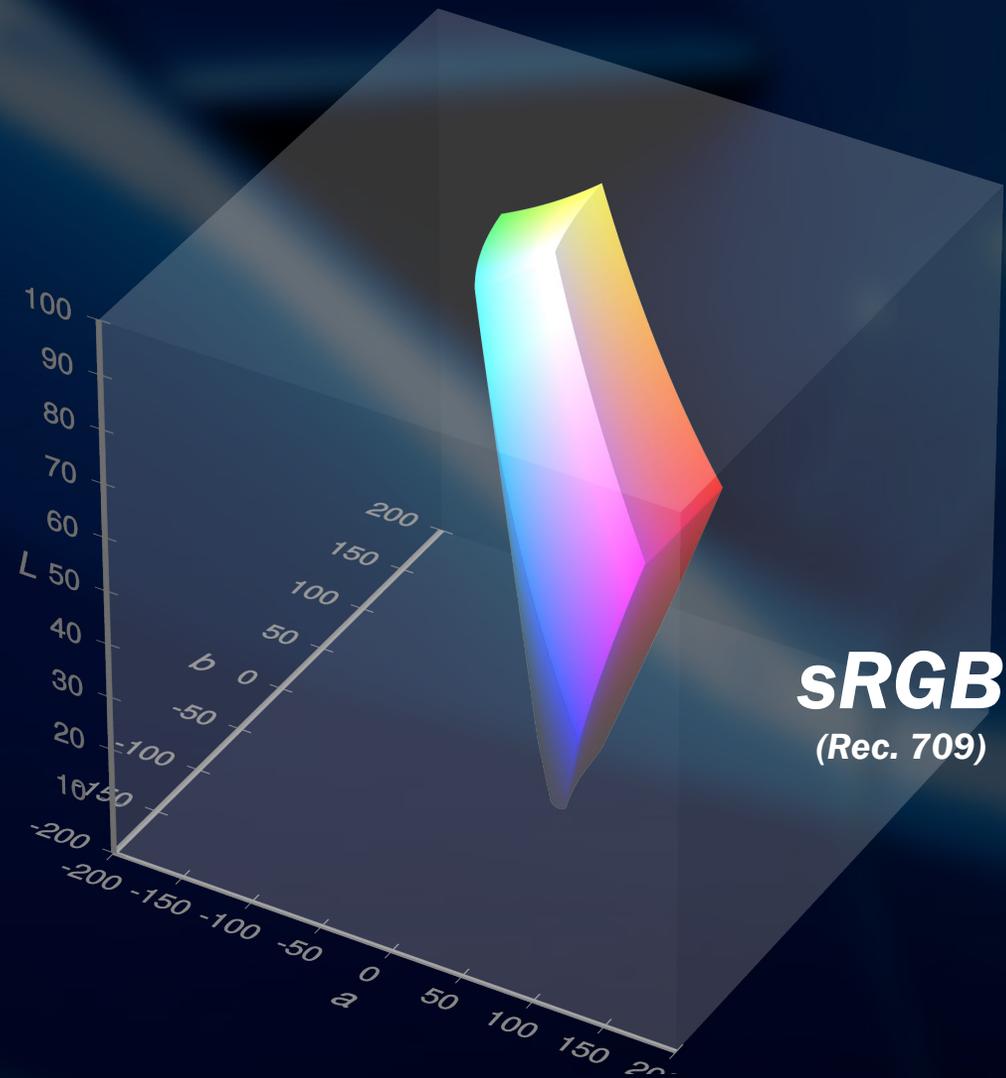
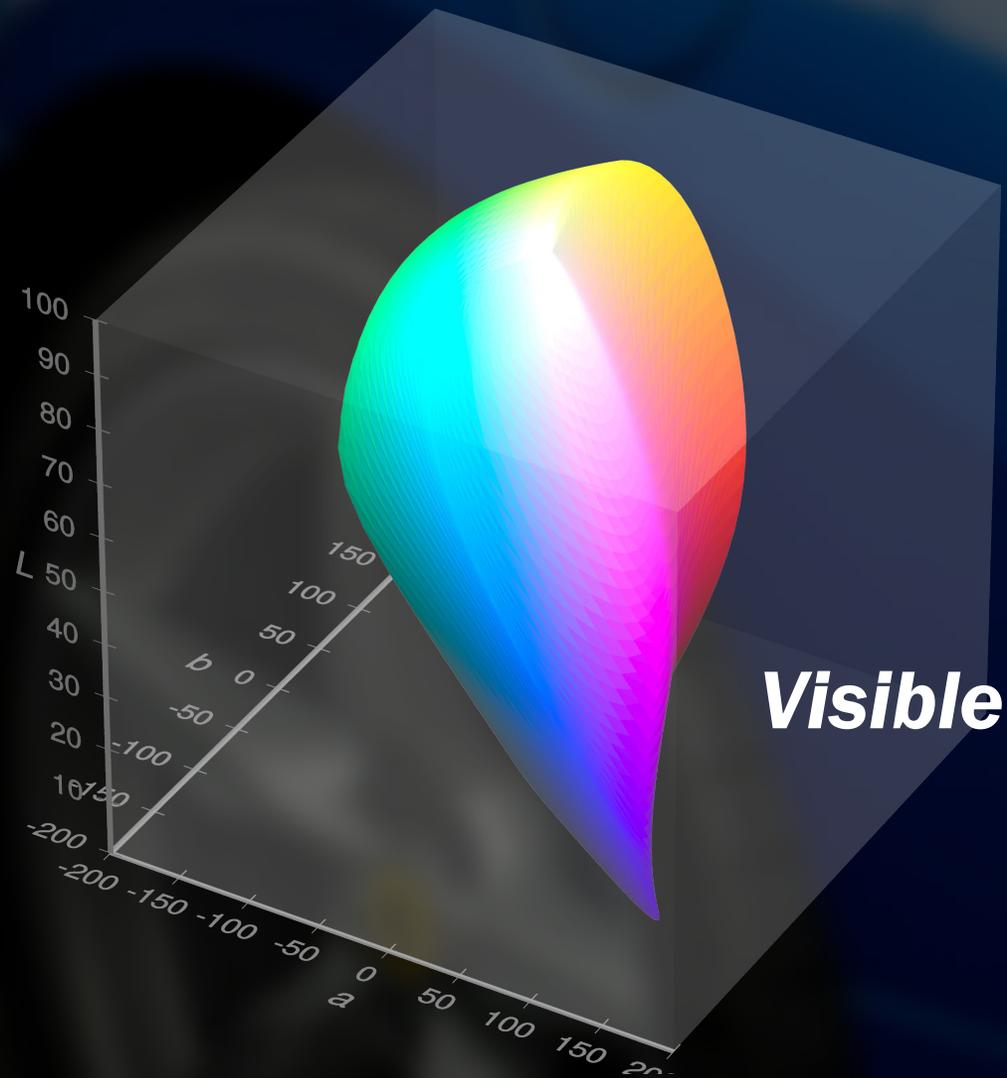
Lab Colour
[36.8, 41.3, 47.7]

Lab (CIELAB) Colour Space

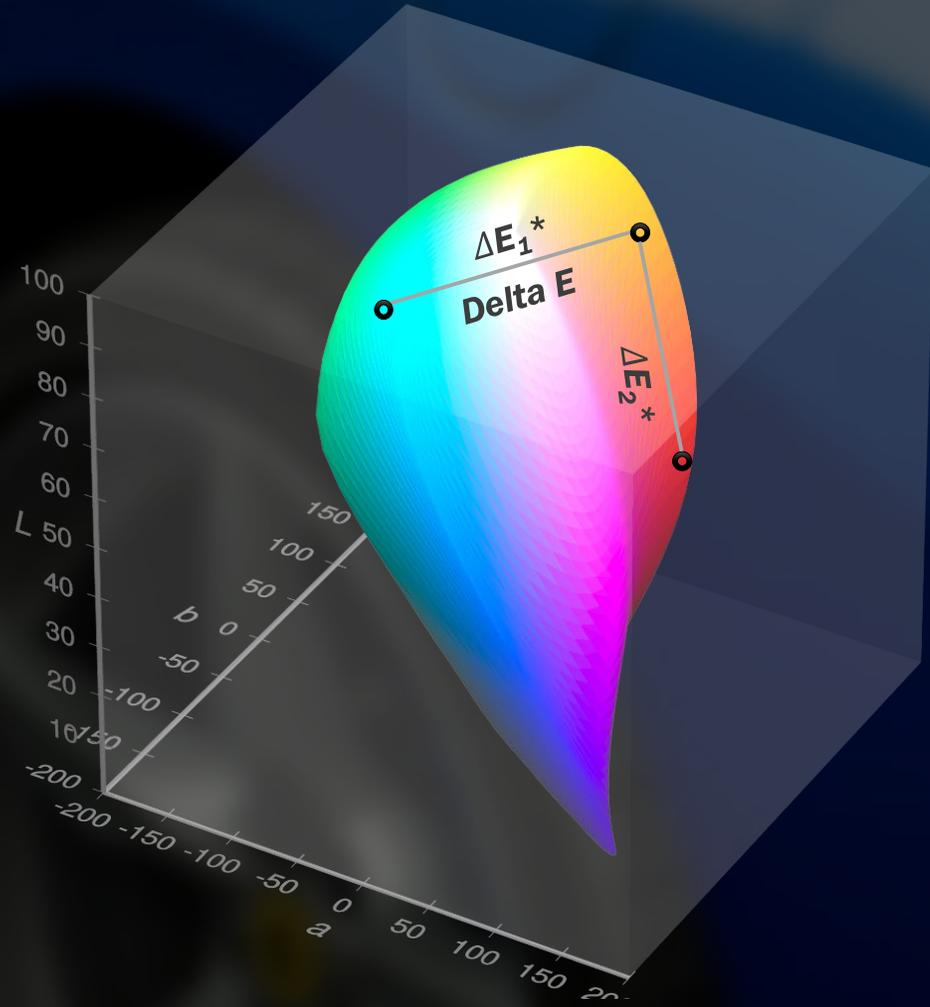


- Most common colour space for colour comparisons
- 3 Components:
 - L^*
 - a^*
 - b^*
- Advantages:
 - Covers All Visible Colours
 - Perceptually Uniform (almost*)
 - “Delta E” (ΔE)

Lab (CIELAB) Colour Space



Delta E



- Key feature of Lab colour space
- Just a distance between 2 points
- Colour difference, **quantified**

$$\Delta E_1^* = \text{Yellow} - \text{Cyan} = 98$$

L* = 83.49	L* = 91.09
a* = 7.57	a* = -48.37
b* = 66.69	b* = -13.65

$$\Delta E_2^* = \text{Yellow} - \text{Red} = 73$$

L* = 83.49	L* = 43.80
a* = 7.57	a* = 69.20
b* = 66.69	b* = 58.06

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Delta E – Another Example



R: 142
G: 149
B: 105

Reference Colour

Q: Which one is closer to the reference, A or B?

R: 143
G: 150
B: 102

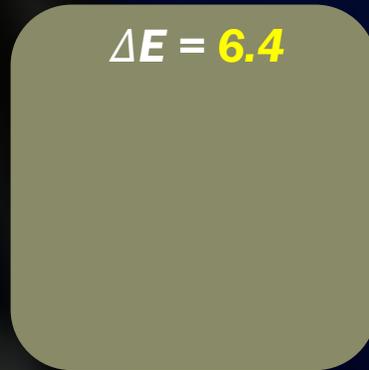
$\Delta E = 2.2$



A



$\Delta E = 6.4$

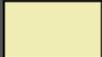
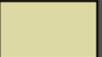
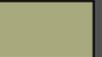
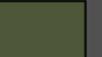
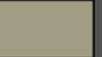
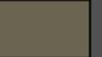
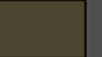


B

R: 137
G: 138
B: 103

Delta E – Total Colour Difference Analysis

$$\Delta E_{Total} = \sqrt{\frac{\Delta E_{p15^\circ}^2 + \Delta E_{p25^\circ}^2 + \Delta E_{p45^\circ}^2 + \Delta E_{p75^\circ}^2 + \Delta E_{p110^\circ}^2}{5}}$$

Reference sRGB						
Current sRGB						
	dE -15°	dE 15°	dE 25°	dE 45°	dE 75°	dE 110°
Delta E:	13.931 ↓	15.104 ↓	10.883 ↓	10.263 ↓	11.585 ↓	12.236 ↓
						-> Delta E Total (15°, 25°, 45°, 75° & 110°): 12.131 ↓

Multiple ΔE values combined into a single ΔE_{Total}

Apple-to-Apple Comparison – Part II



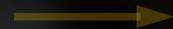
Physical Measurements



SPD



XYZ



ΔE Compare!



Game Measurements



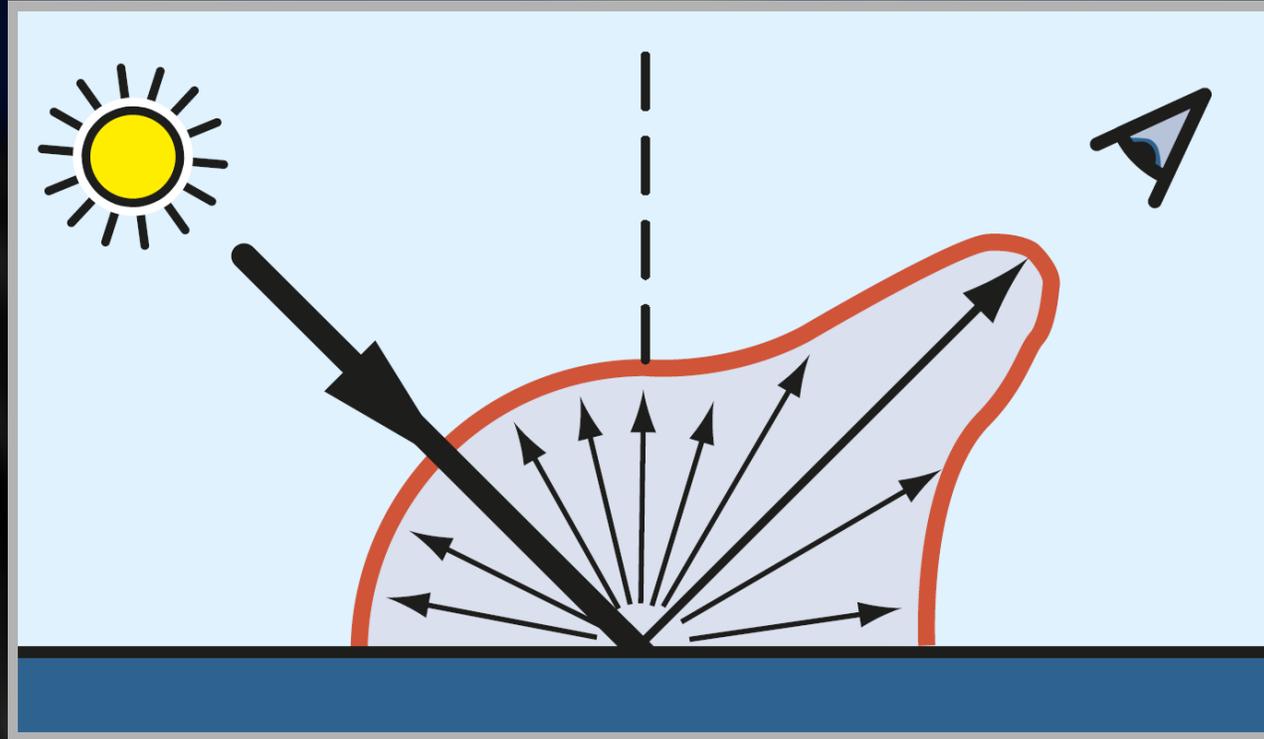
sRGB (or HDR Linear)



XYZ



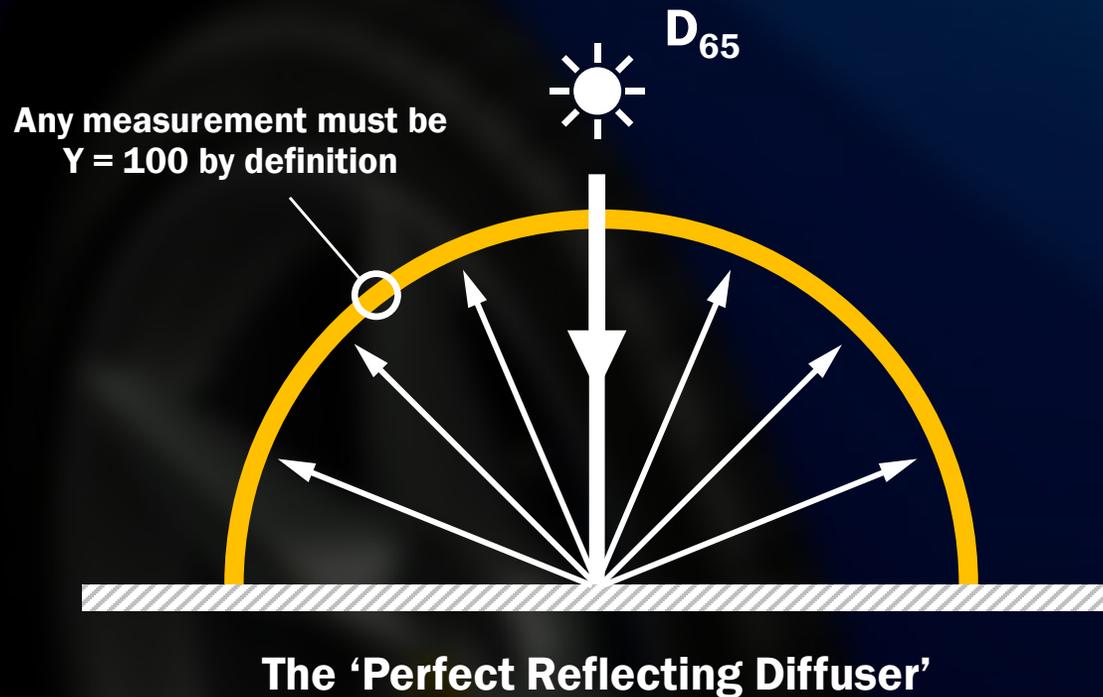
Illumination Information is Essential



Incident Light* × *Material Properties* = *Reflected Light

(This is an irreversible operation – it is *impossible* to work out material information without incident lighting information)

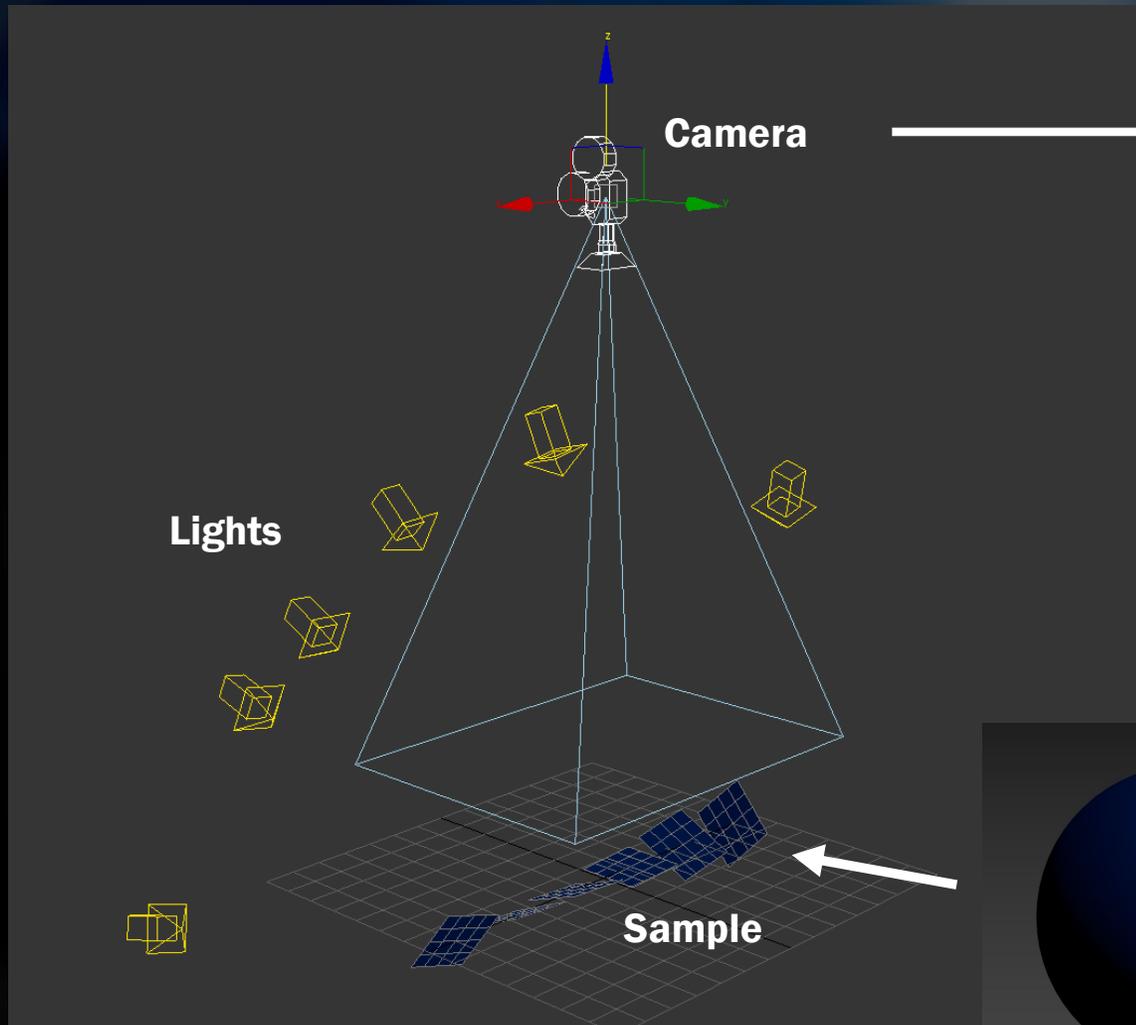
Incident Light Control



To mimic a D65:

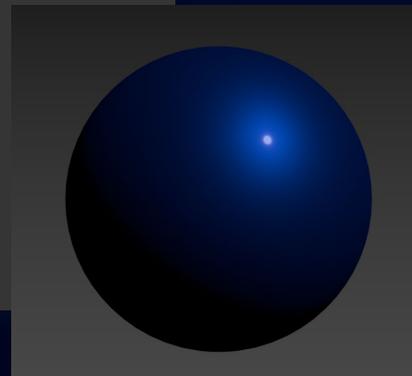
- Light Type: **Directional**
- Light Colour (sRGB): [**255, 255, 255**]
- Light Intensity?
- Relative luminance $Y = 100$ is assigned to the *Perfect Reflecting Diffuser* that reflects 100% at all wavelengths
- Conclusion – intensity should be exactly **1.0**

Virtual Measurement Apparatus



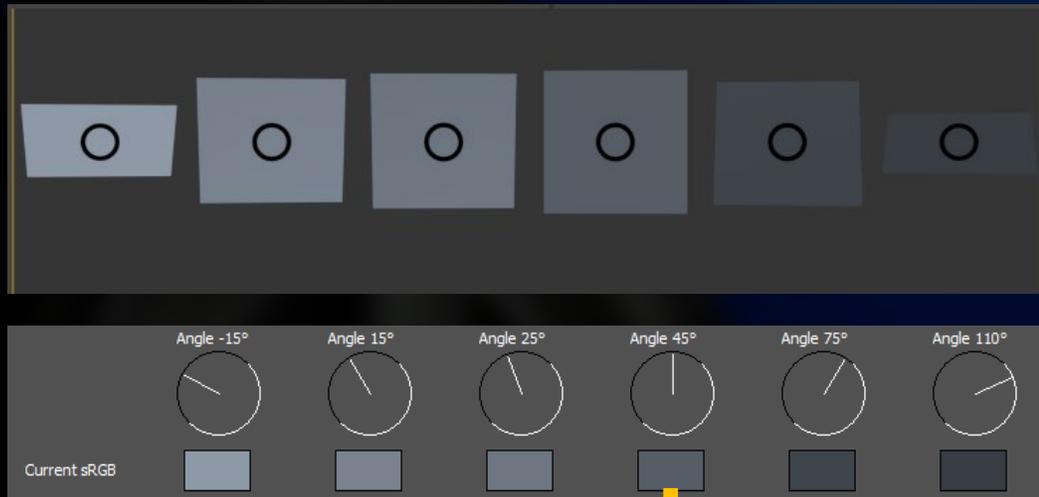
Rendering Environment?

- Maya/**Max**
- Game Editor
- Game (recommended)



From Game Measurements to Lab

- Reading Pixels on Game Material Samples
- sRGB Colours



sRGB to Linear RGB then to XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1804 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9503 \end{bmatrix} \begin{bmatrix} R_{linear} \\ G_{linear} \\ B_{linear} \end{bmatrix}$$

XYZ to Lab:

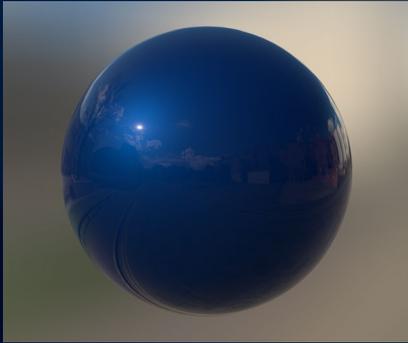
(same procedure as previous)



R: 86
G: 93
B: 102

Lab Colour
[39.2, -0.6, -6.1]

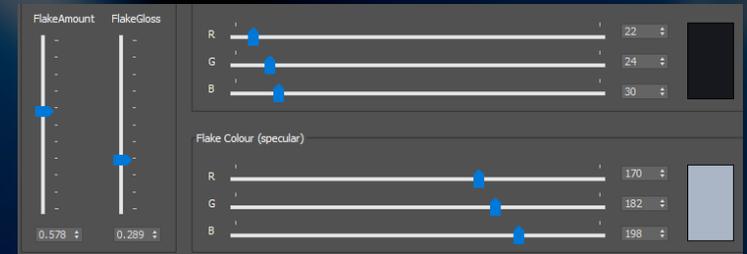
Calibration Pipeline



Artist

Physical Measurements

Game Measurements



Game Material Inputs

SPD

sRGB (or HDR Linear)

Shading Model Calculations

XYZ

XYZ

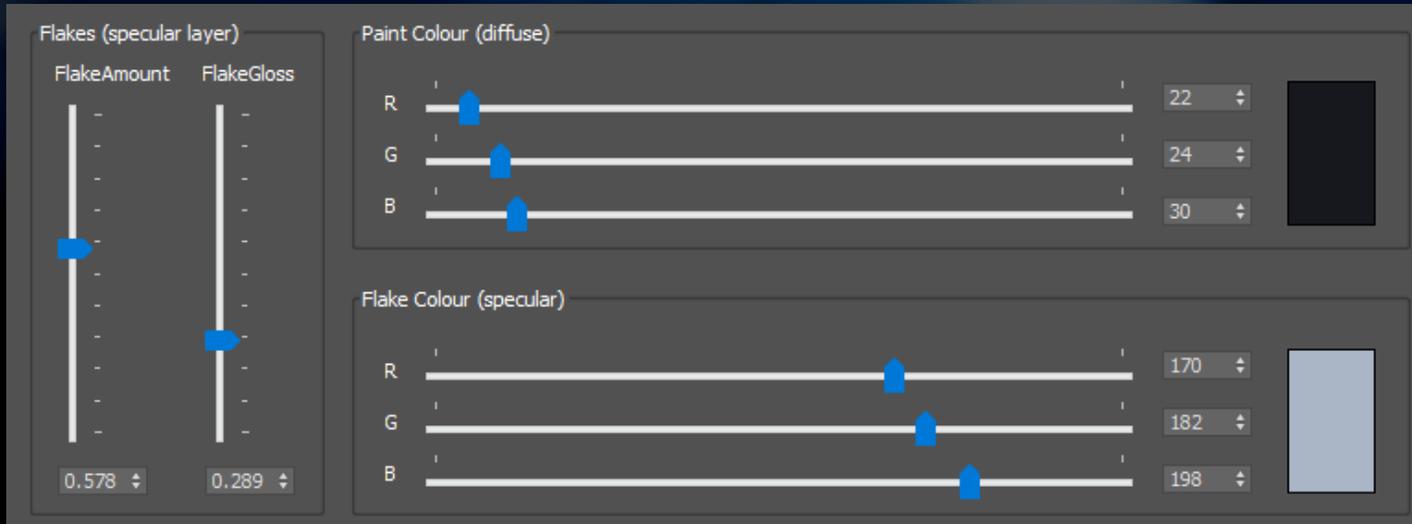
Lab

Lab

ΔE Compare!



Shading Inputs, Not Shading Models



Forza car paint material has 8 inputs



...but 8 inputs can produce a gazillion of combinations (8 degrees of freedom)

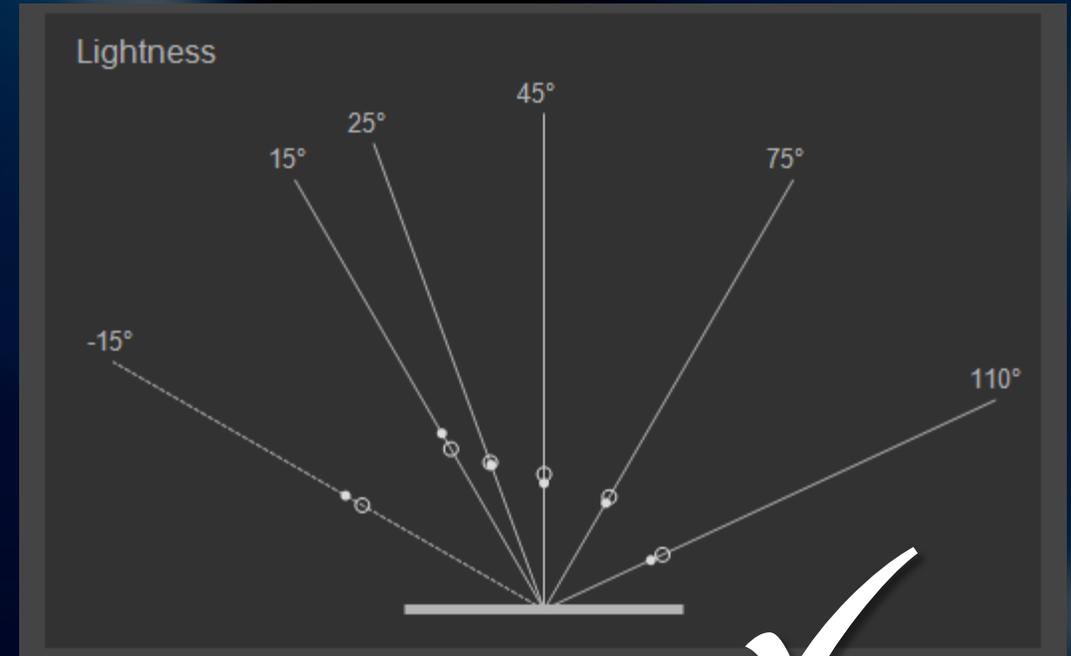
- It's about finding optimal inputs **NOT** models
- Using the shading model of **your choice**
- It's okay to have different input parameters

Macro vs Micro Adjustments

Which material configuration is better?



$$\Delta E_{Total} = 14.3$$



$$\Delta E_{Total} = 7.8$$



The most optimal configuration can always be determined with ΔE_{Total}

Delta E (Advanced)

- Better and better formula:

Delta E 76:

$$\Delta E_{76}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Delta E 94:

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

$$\begin{aligned} \Delta L^* &= L_1^* - L_2^* \\ C_1^* &= \sqrt{a_1^{*2} + b_1^{*2}} \\ C_2^* &= \sqrt{a_2^{*2} + b_2^{*2}} \\ \Delta C_{ab}^* &= C_1^* - C_2^* \\ \Delta H_{ab}^* &= \sqrt{\Delta E_{ab}^{*2} - \Delta L^{*2} - \Delta C_{ab}^{*2}} = \sqrt{\Delta a^{*2} + \Delta b^{*2} - \Delta C_{ab}^{*2}} \\ \Delta a^* &= a_1^* - a_2^* \\ \Delta b^* &= b_1^* - b_2^* \\ S_L &= 1 \\ S_C &= 1 + K_1 C_1^* \\ S_H &= 1 + K_2 C_1^* \end{aligned}$$

Delta E 2000:

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2} + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}$$

$$\Delta L' = L_2^* - L_1^*$$

$$\bar{L} = \frac{L_1^* + L_2^*}{2} \quad \bar{C} = \frac{C_1^* + C_2^*}{2}$$

$$a_1' = a_1^* + \frac{a_1^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a_2' = a_2^* + \frac{a_2^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C_1' + C_2'}{2} \quad \text{and} \quad \Delta C' = C_2' - C_1' \quad \text{where} \quad C_1' = \sqrt{a_1'^2 + b_1'^2} \quad C_2' = \sqrt{a_2'^2 + b_2'^2}$$

$$h_1' = \text{atan2}(b_1', a_1') \pmod{360^\circ}, \quad h_2' = \text{atan2}(b_2', a_2') \pmod{360^\circ}$$

$$\Delta h' = \begin{cases} h_2' - h_1' & |h_1' - h_2'| \leq 180^\circ \\ h_2' - h_1' + 360^\circ & |h_1' - h_2'| > 180^\circ, h_2' \leq h_1' \\ h_2' - h_1' - 360^\circ & |h_1' - h_2'| > 180^\circ, h_2' > h_1' \end{cases}$$

$$\Delta H' = 2\sqrt{C_1' C_2'} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h_1' + h_2' + 360^\circ)/2 & |h_1' - h_2'| > 180^\circ \\ (h_1' + h_2')/2 & |h_1' - h_2'| \leq 180^\circ \end{cases}$$

$$T = 1 - 0.17 \cos(\bar{H}' - 30^\circ) + 0.24 \cos(2\bar{H}') + 0.32 \cos(3\bar{H}' + 6^\circ) - 0.20 \cos(4\bar{H}' - 63^\circ)$$

$$S_L = 1 + \frac{0.015 (\bar{L} - 50)^2}{\sqrt{20 + (\bar{L} - 50)^2}} \quad S_C = 1 + 0.045 \bar{C}' \quad S_H = 1 + 0.015 \bar{C}' T$$

$$R_T = -2 \sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}} \sin \left[60^\circ \cdot \exp \left(- \left[\frac{\bar{H}' - 275^\circ}{25^\circ} \right]^2 \right) \right]$$

Delta E (Advanced)

Measurement of Color: Color Systems for Automotive Exterior Applications

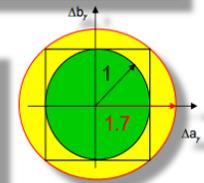
■ DIN 6175-2 System

- ΔE_{DIN} Scales
- Developed by European OEM's
- Based on Metallics
- Good ΔE_{DIN} Visual Correlation
- Weighting Factors

- Angle (γ)
- Application (g)
- Color (S)

DIN 6175-2 System Allows Use of
Red Yellow Green
Zones with a Single Tolerance

$\Delta E_p > 1.7$ **STOP**
 $1.0 < \Delta E_p \leq 1.7$ **Evaluate**
 $\Delta E_p \leq 1.0$ **GO**



Non-chromatic:

$$\Delta E_{\gamma}^2 = \left(\frac{\Delta L^*_{\gamma}}{g_L S_L \gamma} \right)^2 + \left(\frac{\Delta a^*_{\gamma}}{g_a S_a \gamma} \right)^2 + \left(\frac{\Delta b^*_{\gamma}}{g_b S_b \gamma} \right)^2$$

Chromatic:

$$\Delta E_{\gamma}^2 = \left(\frac{\Delta L^*_{\gamma}}{g_L S_L \gamma} \right)^2 + \left(\frac{\Delta C^*_{\gamma}}{g_C S_C \gamma} \right)^2 + \left(\frac{\Delta H^*_{\gamma}}{g_H S_H \gamma} \right)^2$$

$S_L = 0.15\sqrt{L^*} + \frac{31.5}{L^*}$
 $S_C = \max\left(0.7, 0.48\sqrt{C^*} - 0.35\sqrt{L^*} + \frac{42}{L^*}\right)$
 $S_H = \max\left(0.7, 0.7 + 0.14\sqrt{C^*} - 0.20\sqrt{L^*} + \frac{21}{L^*}\right)$

Chromatic:
 $C^* \geq 18$ or
 $C^* \geq 10$ and $L^* < 27$

Application Factors:	g_L	g_a	g_b	g_C	g_H	Normalized Tolerance
Paint Batch Application	1.0	1.0	1.0	1.0	1.0	$\Delta E_C = 1.0$
Paint Line Body	2.0	1.2	1.2	1.8	1.2	$\Delta E_p = 1.0$
Repair Line	2.0	1.2	1.2	1.8	1.2	$\Delta E_p = 1.5$
Repair Line with Gap	2.0	1.2	1.2	1.8	1.2	$\Delta E_p = 3.0$

$\Delta E_p \rightarrow$

- Final choice: DIN 6175-2
- Best for metallic paints
- Used by VW, Audi, GM etc.
- Not necessary, but nice-to-have
- Prioritises specular angles



VIDEO – Calibration in Action

Car Paint Physical Calibration Tool

Digital Masters
 Browse File... [Src\cars\Assets\CarPaintDigitalMasters\Jaguar_Land_Rover\JLR Prod Light Metallics.xml]
 Paint: Mauritius Blue JYB 2 070217 Compute Colours from Spectral Power Distributions (SPD) >>

Advanced Colour Data

Overview

Angle	-15°	15°	25°	45°	75°	110°
Target sRGB						
Current sRGB						

Colour Difference Analysis : Standard

LDR Clamp:

Delta E:	dE -15°	dE 15°	dE 25°	dE 45°	dE 75°	dE 110°
	67.377	44.897	38.093	36.049	35.243	34.525

Delta E Formula: DIN 6175-2 (production) -> Delta E Total (15°, 25°, 45°, 75° & 110°): 37.948

HDR Extrapolation - Illuminant Power Override

Calibration Inputs

Flakes (specular layer)
 FlakeAmount: 0.5
 FlakeGloss: 0.5

Paint Colour (diffuse)
 R: 128
 G: 128
 B: 128

Flake Colour (specular)
 R: 128
 G: 128
 B: 128

Clear Coat: Satin Finish > Apply Estimates < Schematics >>

Advanced Options

Forza Materials
 Load Calibration from Material... Save As Cheaper Traffic Material... Save Calibration As...

About
 © Playground Games

[+][CalibrationCamera] [High Quality] [Default Shading]

[+][CalibrationCamera_preview] [User Defined] [Default Shading]

Standard Primitives
 Object Type: AutoGrid, Box, Cone, Sphere, GeoSphere, Cylinder, Tube, Torus, Pyramid, Teapot, Plane, TextPlus
 Name and Color:

X: 3.6m Y: 0.368m Z: 0.0m Grid = 0.5m + Auto Key Selected ⏪ ⏩

Manufacturer Paint - "Firesand Metallic"

The screenshot displays the 'Car Paint Physical Calibration Tool' interface. The main window is titled 'Car Paint Physical Calibration Tool' and contains several sections:

- Digital Masters:** Includes a file path and a 'Paint' dropdown set to 'Firesand Phoenix EAT 2 070217'. A button 'Compute Colours from Spectral Power Distributions (SPD) >>' is visible.
- Advanced Colour Data:** A section for detailed color calibration.
- Overview:** Features six circular gauges for different viewing angles: -15°, 15°, 25°, 45°, 75°, and 110°. Below each gauge are 'Target sRGB' and 'Current sRGB' color swatches.
- Colour Difference Analysis : Standard:** Shows 'LDR Clamp' sliders and a table of Delta E values for each angle. The 'Delta E Formula' is set to 'DIN 6175-2 (production)'. The 'Delta E Total (15°, 25°, 45°, 75° & 110°)' is 38.918.
- HDR Extrapolation - Illuminant Power Override:** A section for advanced lighting settings.
- Calibration Inputs:** Includes sliders for 'Flake Amount' and 'FlakeGlos', and color pickers for 'R', 'G', and 'B' channels. A 'Clear Coat' section is also present.
- Advanced Options:** Includes buttons for 'Apply Estimates <' and 'Schematics >>'.
- Forza Materials:** Includes buttons for 'Load Calibration from Material..', 'Save As Cheaper Traffic Material..', and 'Save Calibration As..'.
- About:** A section at the bottom with the copyright notice '© Playground Games'.

Overlaid on the interface is a large white callout box with the text: **Old ΔE_{Total} was 38.9** and ***Graphic arts industry tolerance: 6 units**. To the right of the tool, a 3D scene shows a series of orange rectangular blocks with circular cutouts, arranged in a row. Below this, four circular diagrams illustrate the viewing angles for the color difference analysis: 'Lightness' (white), 'R' (red), 'G' (green), and 'B' (blue). Each diagram shows a central vertical axis and several radial lines representing the viewing angles: -15°, 15°, 25°, 45°, 75°, and 110°.

Manufacturer Paint - "Firesand Metallic"

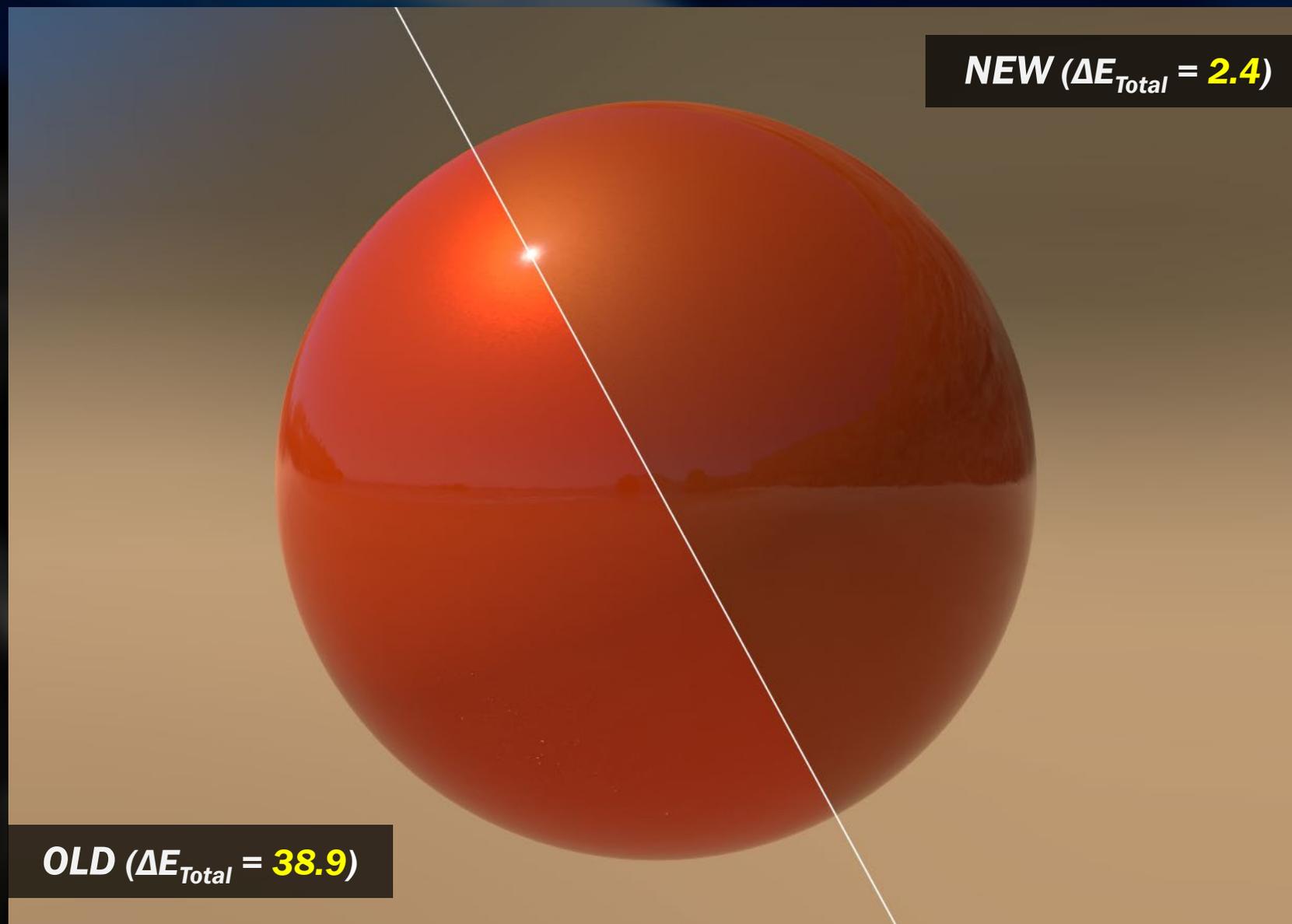
The screenshot displays the 'Car Paint Physical Calibration Tool' interface. The main window shows calibration data for 'Firesand Metallic' paint. The 'Advanced Colour Data' section includes six viewing angles: -15°, 15°, 25°, 45°, 75°, and 110°. The 'Colour Difference Analysis : Standard' section shows Delta E values for each angle and a total Delta E of 2.427. A callout box highlights that the new ΔE_{Total} is only 2.4, which is significantly lower than the 6 units tolerance for the graphic arts industry. The 'Calibration Inputs' section shows sliders for 'Flake Amount' and 'Flake Gloss', and a 'Clear Coat' section with a 'Satin Finish' option. The 'Advanced Options' section includes buttons for 'Apply Estimates' and 'Schematics'. The right side of the interface shows a 3D view of the calibration setup with a camera and a series of orange rectangular panels with circular targets. Below the 3D view are four color difference analysis plots for Lightness, R, G, and B channels, each showing viewing angles and corresponding color values.

New ΔE_{Total} is only 2.4!

***Graphic arts industry tolerance: 6 units**

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Manufacturer Paint - "Firesand Metallic"



Manufacturer Paint - "Estoril Blue Metallic"

The screenshot displays the 'Car Paint Physical Calibration Tool' interface. The main window is titled 'Car Paint Physical Calibration Tool' and contains several panels:

- Digital Masters:** Shows the file path 'Src\cars_Assets\CarPaintDigitalMasters\Jaguar_Land_Rover\LR_Prod_Light_Metallics.xml' and the paint name 'Estoril Blue JAE 2.070217'. A button 'Compute Colours from Spectral Power Distributions (SPD) >>' is visible.
- Advanced Colour Data:** Contains an 'Overview' section with six circular gauges for angles: -15°, 15°, 25°, 45°, 75°, and 110°. Below each gauge are 'Reference sRGB' and 'Current sRGB' color swatches.
- Colour Difference Analysis : Standard:** Displays 'LDR Clamp' sliders and 'Delta E' values for each angle: dE -15° (21.191), dE 15° (34.339), dE 25° (20.431), dE 45° (12.761), dE 75° (12.626), and dE 110° (16.137). A 'Delta E Total (15°, 25°, 45°, 75° & 110°)' is shown as 20.877. The 'Delta E Formula' is set to 'DIN 6175-2 (production)'.
- HDR Extrapolation - Illuminant Power Override:** Includes 'Calibration Inputs' for 'Flakes (specular layer)' with 'FlakeAmount' and 'FlakeGloss' sliders.
- Paint colour (diffuse):** Shows RGB sliders for R (36), G (44), and B (132).
- Flake Colour (specular):** Shows RGB sliders for R, G, and B.
- Clear Coat:** Includes a 'Satin Finish' checkbox.
- Advanced Options:** Includes 'Forza Materials' and 'About' sections.

On the right side of the interface, there is a 3D preview area showing a series of blue rectangular panels with circular cutouts, arranged in a row. Below this are four graphs showing the color difference analysis results for 'Lightness', 'R', 'G', and 'B' channels. Each graph plots the color difference (Delta E) for the six angles, with lines radiating from the center to the data points. The 'Lightness' graph shows values ranging from approximately 10 to 15. The 'R', 'G', and 'B' graphs show values ranging from approximately 10 to 15. A callout box points to the 'Delta E Total' value of 20.877.

Old $\Delta E_{Total} = 20.9$
***Graphic arts industry tolerance: 6 units**

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Manufacturer Paint - "Estoril Blue Metallic"

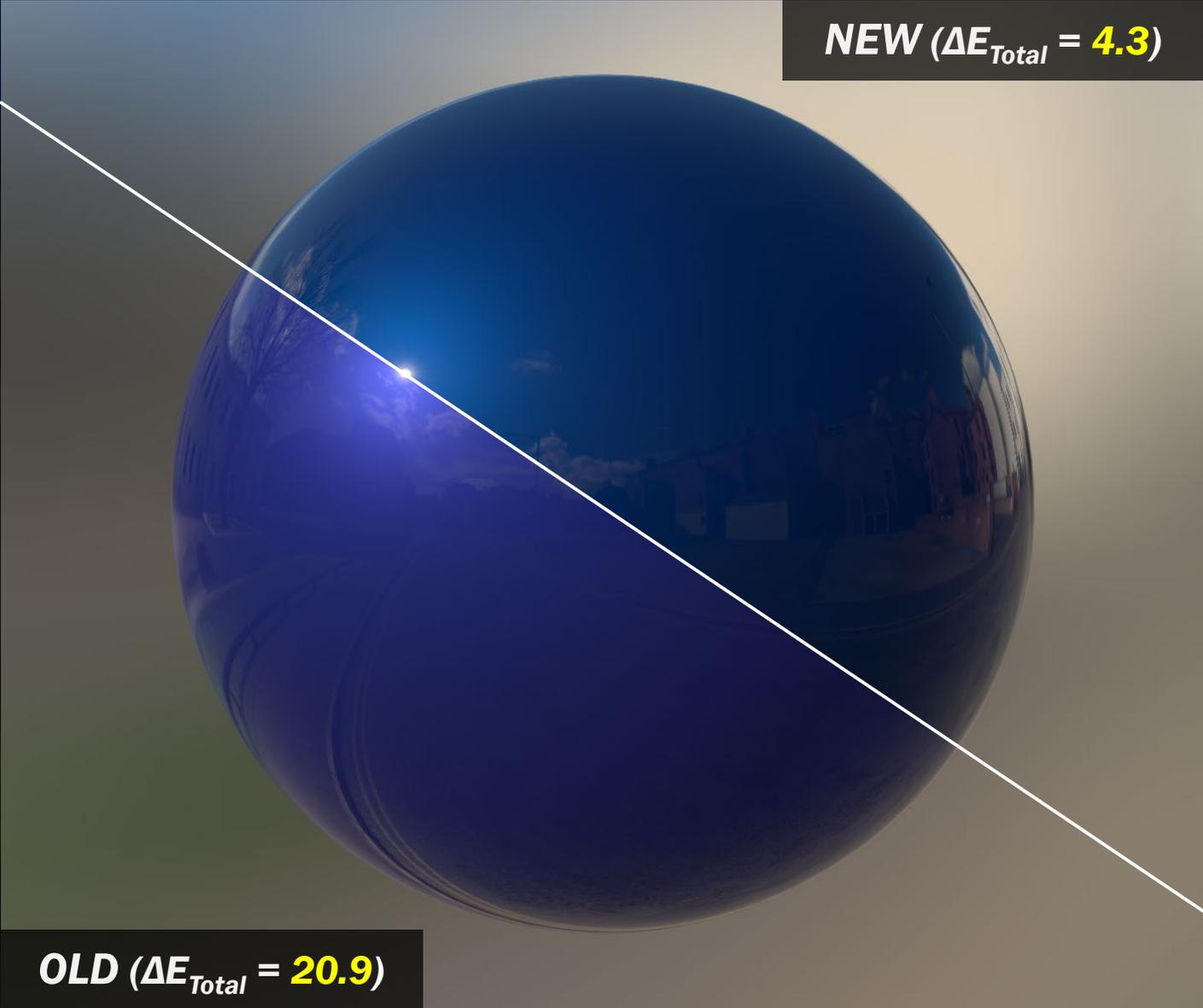
The screenshot displays the 'Car Paint Physical Calibration Tool' interface. The left sidebar contains several sections: 'Digital Masters' with a file path and paint name; 'Advanced Colour Data'; 'Overview' with angle selectors and color swatches; 'Colour Difference Analysis: Standard' with Delta E values for various angles and a total Delta E of 4.303; 'HDR Extrapolation - Illuminant Power Override'; 'Calibration Inputs' with sliders for 'FlakeAmount' and 'FlakeGloss', and 'Flake Colour' sliders for R, G, and B; and 'Advanced Options'.

The main workspace shows a 3D visualization of the paint's appearance at various viewing angles (-15°, 15°, 25°, 45°, 75°, 110°). The visualization is divided into four quadrants: 'Lightness' (top-left), 'R' (top-right), 'G' (bottom-left), and 'B' (bottom-right). Each quadrant shows a fan of lines representing the viewing angles, with a corresponding color bar at the bottom. The 'Lightness' bar is white, 'R' is red, 'G' is green, and 'B' is blue.

A callout box highlights the new Delta E Total value: **New $\Delta E_{Total} = 4.3$** . Below this, it states: ***Graphic arts industry tolerance: 6 units**.

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Manufacturer Paint - "Estoril Blue Metallic"





OLD

NEW

"Estoril Blue Metallic" – Jaguar Land Rover™



OLD



NEW

"Estoril Blue Metallic" – Jaguar Land Rover™



'Shading' Was Also Improved

OLD



NEW

"Estoril Blue Metallic" - Jaguar Land Rover™



OLD

NEW

“Viridian Green Metallic” – Aston Martin™



OLD

NEW

“Moonstone Metallic” – BMW™



OLD

NEW

“Grey Bull” – Aston Martin™

Sourcing for Production



Ferrari Dealership Visit
Swindon, UK









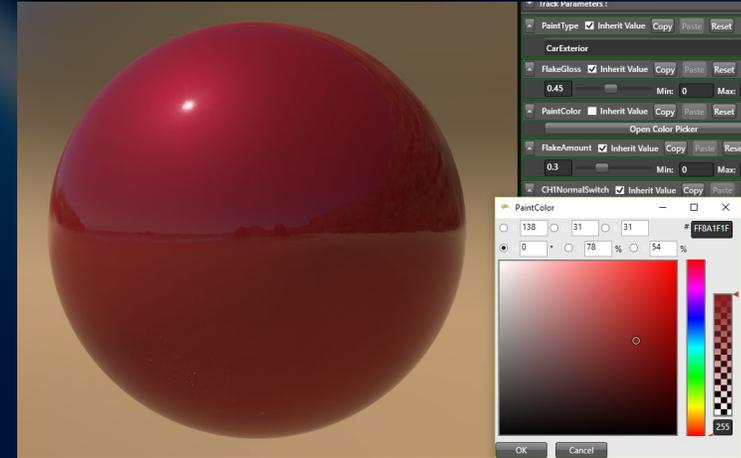
Production Summary

REFERENCE



- **Photographs Only**
- **Unknown/Uncontrolled Factors**
 - Lighting Conditions
 - Reflected Environment
 - Camera Settings
 - Image Editing

TUNING



- **Based on 'Feelings'**
- **Difficult to Match Scientifically**
 - Monitor Conditions
 - Reflected Environment
 - Rendering Configurations
 - Viewing Conditions

Production Summary

REFERENCE



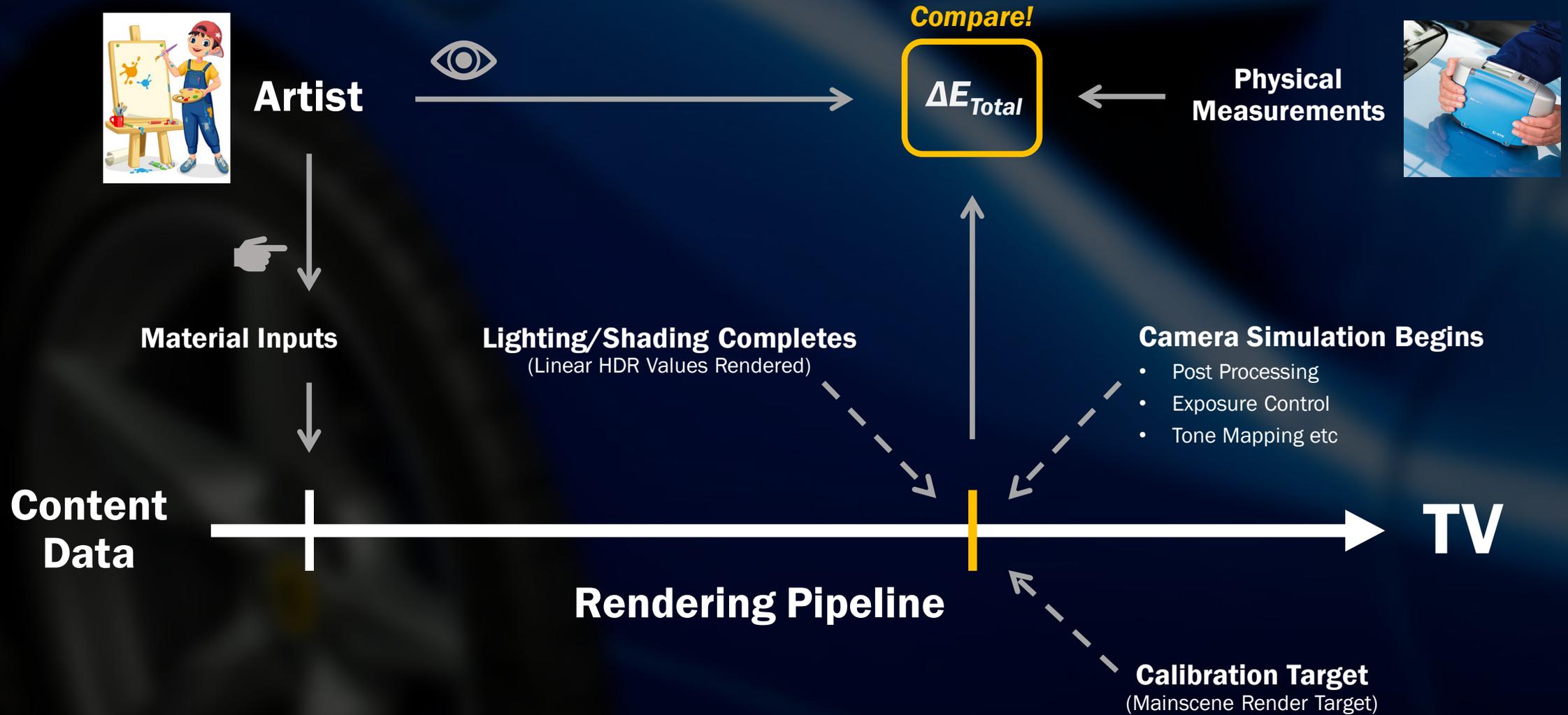
Spectrophotometric Data

TUNING

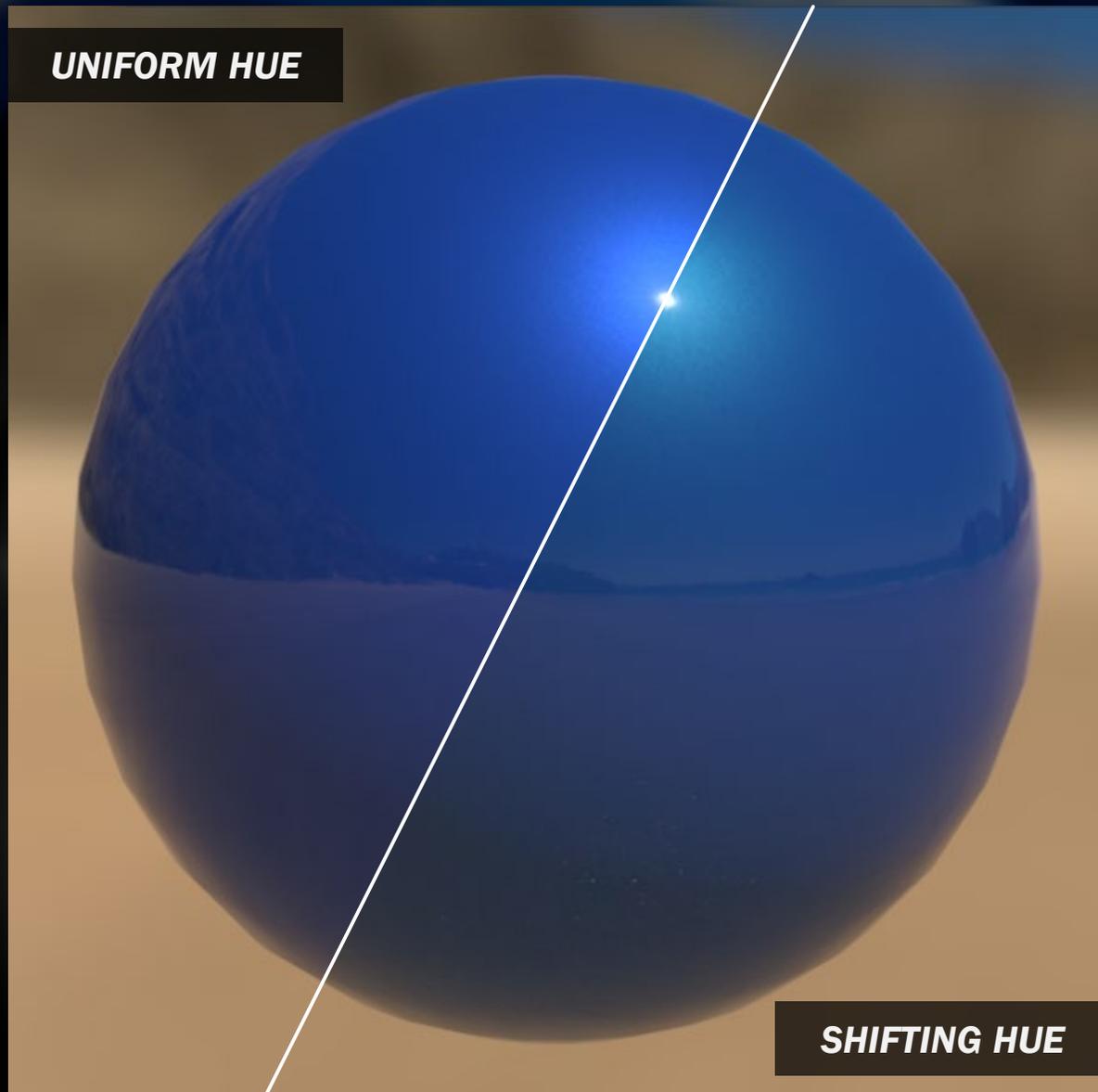


Quantitative Calibration

Calibration Summary

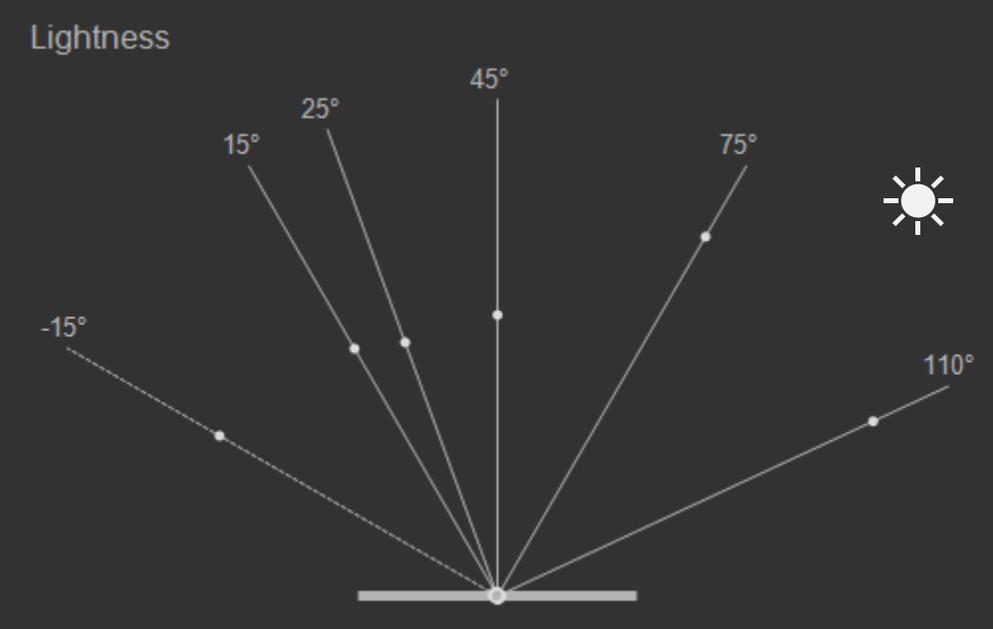


Happy Accidents



- Hue Shift Phenomenon
- 'PBR Guide' does not always apply
- Facing visual issues, there's extra confidence to blame lighting 😊

Happy Accidents



Performance and Limitations

Performance:

- **Zero** performance cost at runtime 😊
- Sample acquisition: **6** sec per scan
- Artist calibration time: **~5** mins per material (close to **900** materials calibrated in FH4)
- Most PBC materials: $\Delta E_{Total} < 5.0$

Limitations:

- Data availability
- Instrument cost
- Lack of texture information
- Calibrated with directional light only (loophole)

Future Work



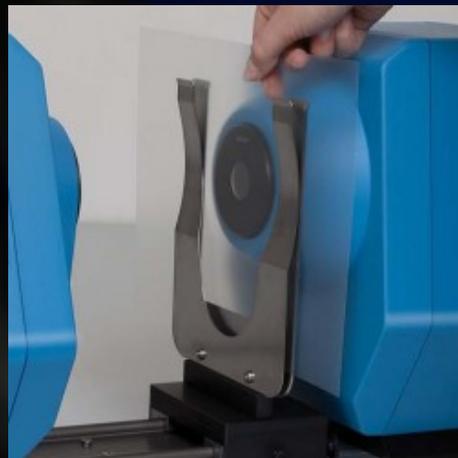
Gloss Meter



Haze Meter



Orange Peel Meter



Transparency Meter

- Feasibility on non-paint materials
- Wide gamut pipeline
- Solutions for capturing textures
- Spectrophotometer is just the tip of an ice berg
- Much to learn from the appearance industry

Special Thanks



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Neil Massam

Sally Upex

Simon Gibson



Michael Bishop

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*There are no real colours,
only real **Optical Properties***



There's more to the world than meets the eye



QUESTIONS?