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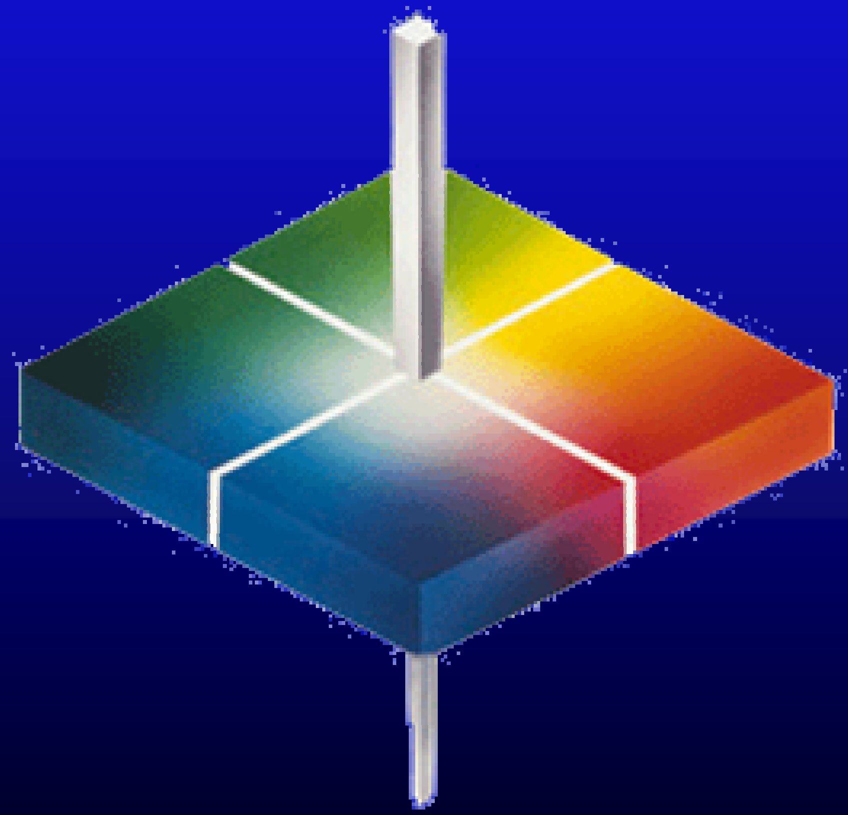
HunterLab Presents

The Basics Of Color Perception and Measurement



Version 1.4

The Basics Of Color Perception and Measurement

This is a tutorial about color perception and measurement. It is a self teaching tool that you can read at your own pace.

When a slide has all information displayed, the following symbols will appear on the lower left side of the screen –

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Contents

There are five sections to this presentation:

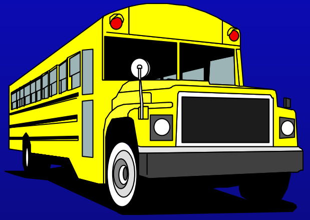
If you wish to jump to a specific section click above on the appropriate name or click below to advance to the next slide.

Color Perception

Things Required To See Color

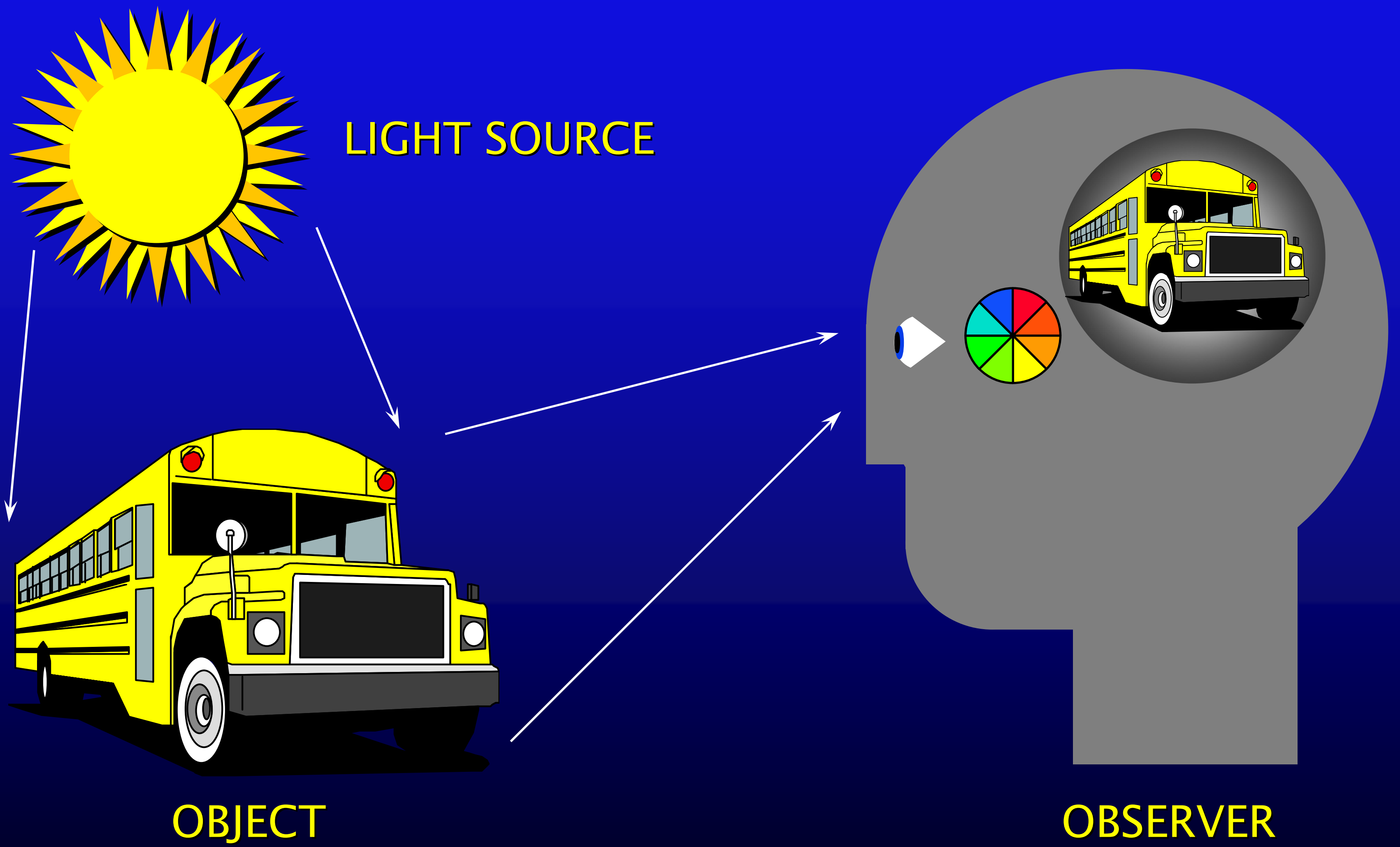
- A Light Source

- An Object



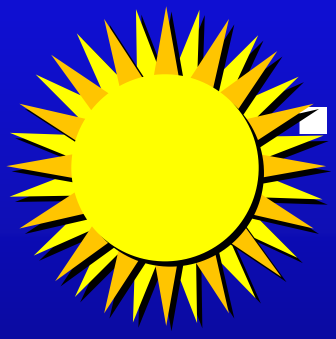
- An Observer

Visual Observing Situation



Visual Observing Situation

- The visual observing model shows the three items
  that are necessary to perceive color.
- In order to build an instrument that will quantify human color perception, each item in the visual observing situation must be represented as a table of numbers.

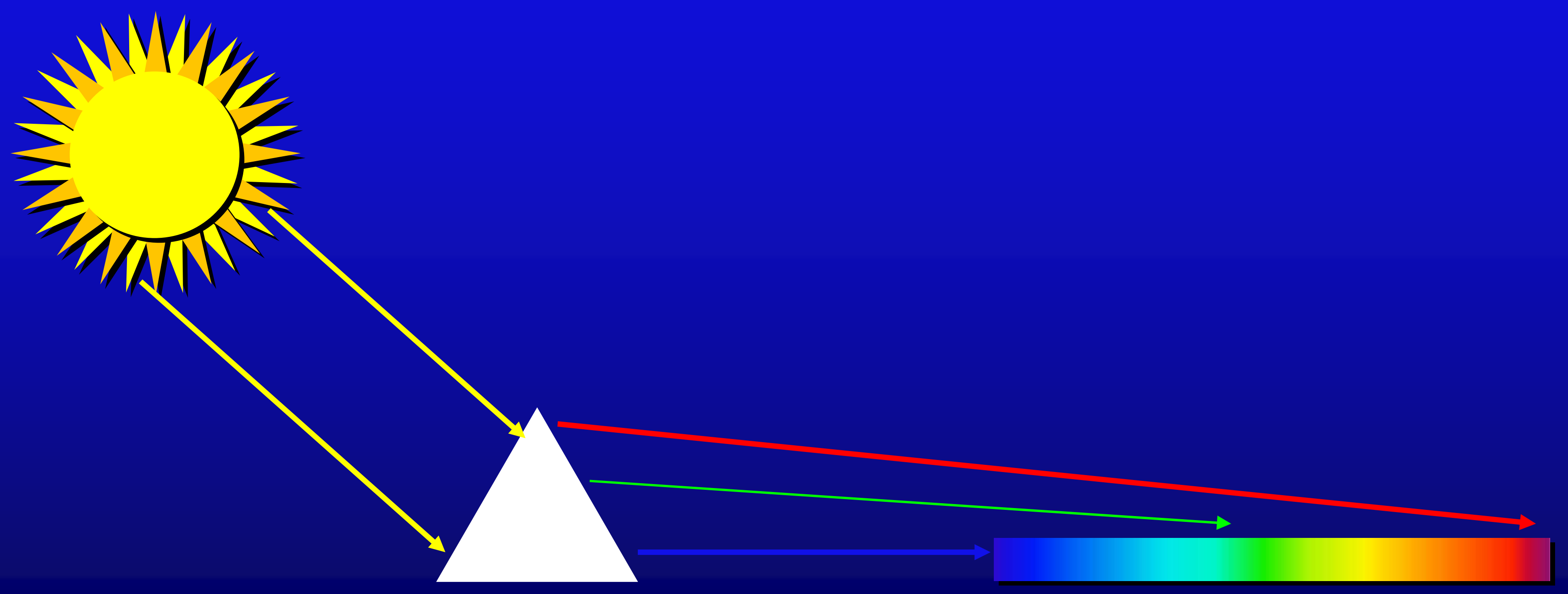


Light Source

Light Source

- A light source normally emits light that appears
  to be white.
- When the light is dispersed by a prism it is seen to be made up of all visible wavelengths.

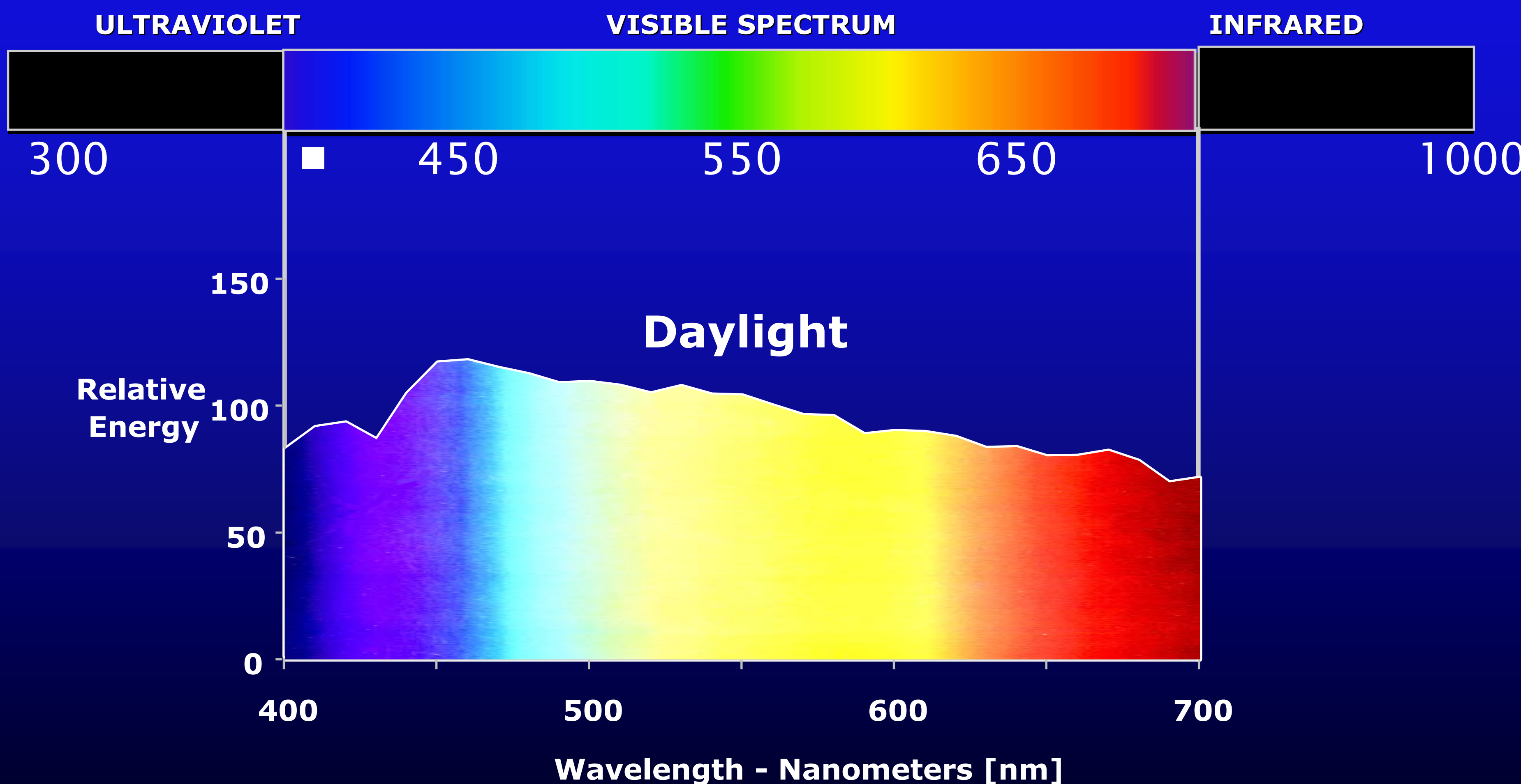
Sunlight Spectrum



Light Source

- Visible light is a small part of the electromagnetic spectrum.
- The wavelength of light is measured in nanometers (nm). One nanometer is one-billionth of a meter.
- The wavelength range of the visible spectrum is from approximately 400 to 700 nm.
- A plot of the relative energy of light at each wavelength creates a power distribution curve quantifying the spectral characteristics of the light source.

Spectral Power Distribution of Sunlight



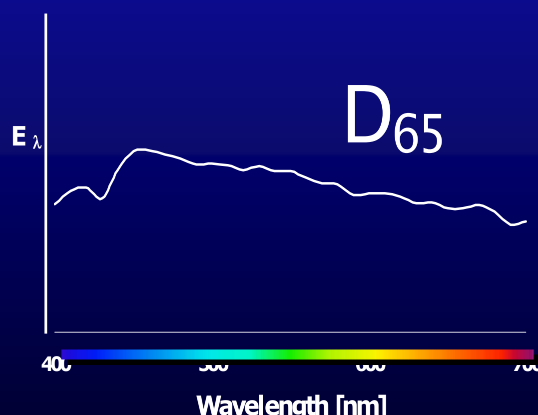
Light Source versus Illuminant

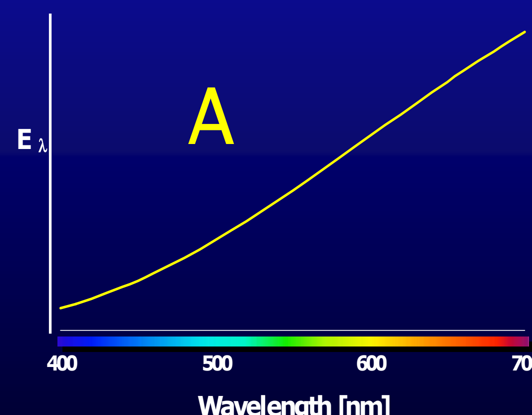
- A **light source** is a real physical source of light.
- An **illuminant** is a plot, or table, of relative energy versus wavelength that represents the spectral characteristics of different types of light sources.

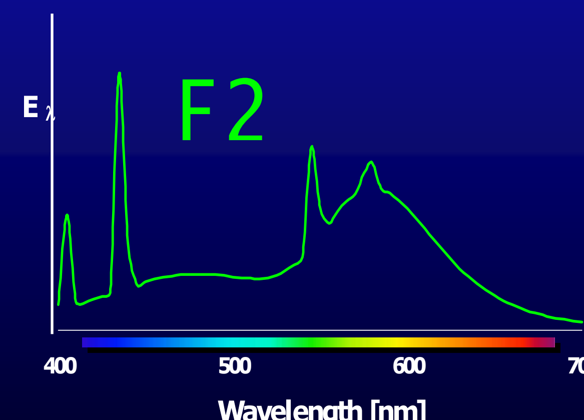
Light Source versus Illuminant

Source

Illuminant





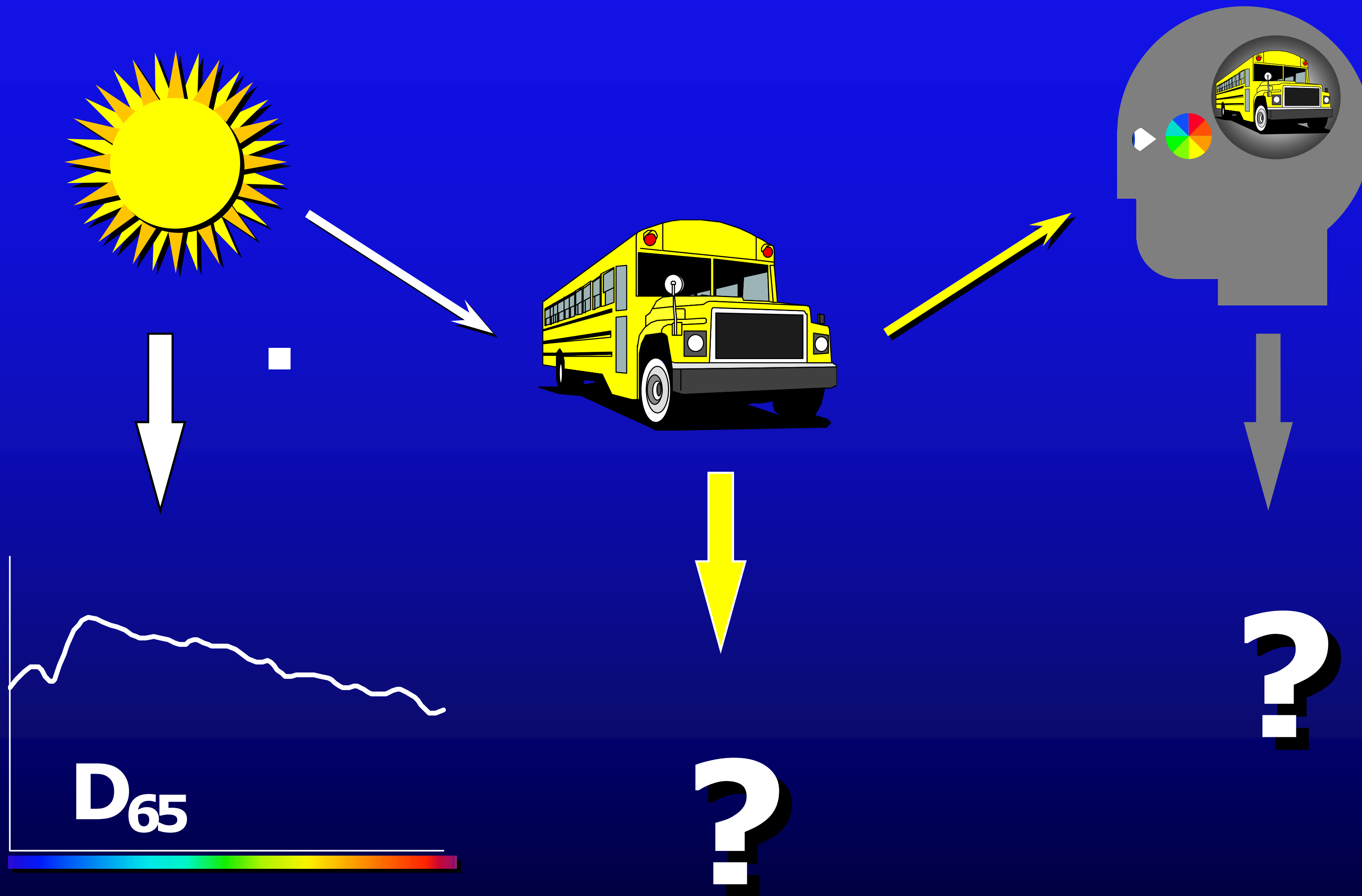


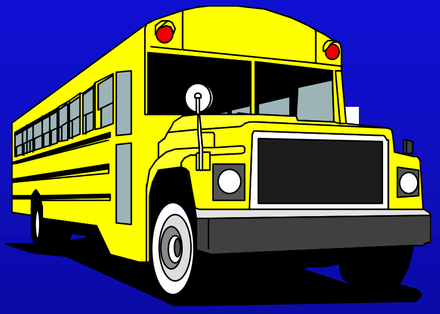
Some Common Illuminants

A	Incandescent
C	Average Daylight
D_{65}	Noon Daylight
F2	Cool White Fluorescent
U30	Ultralume

Light Source versus Illuminant

- By representing a light source as an illuminant, the spectral characteristics of the first element of the Visual Observing Situation have been **quantified** and **standardized.**


D65
?
?

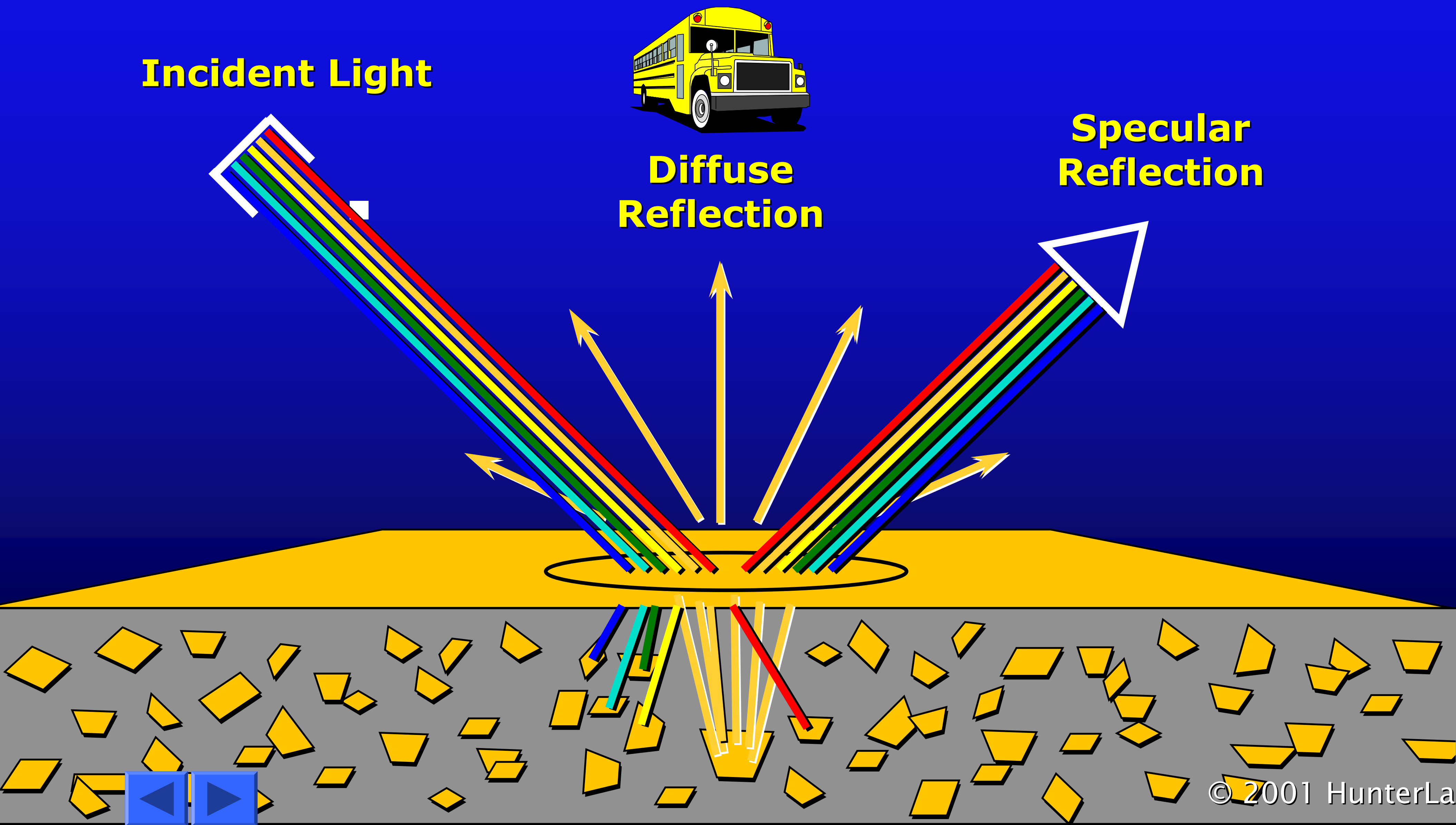


Object

Object

- Objects modify light. Colorants such as pigments or dyes, in the object, selectively absorb some wavelengths of the incident light while reflecting or transmitting others.

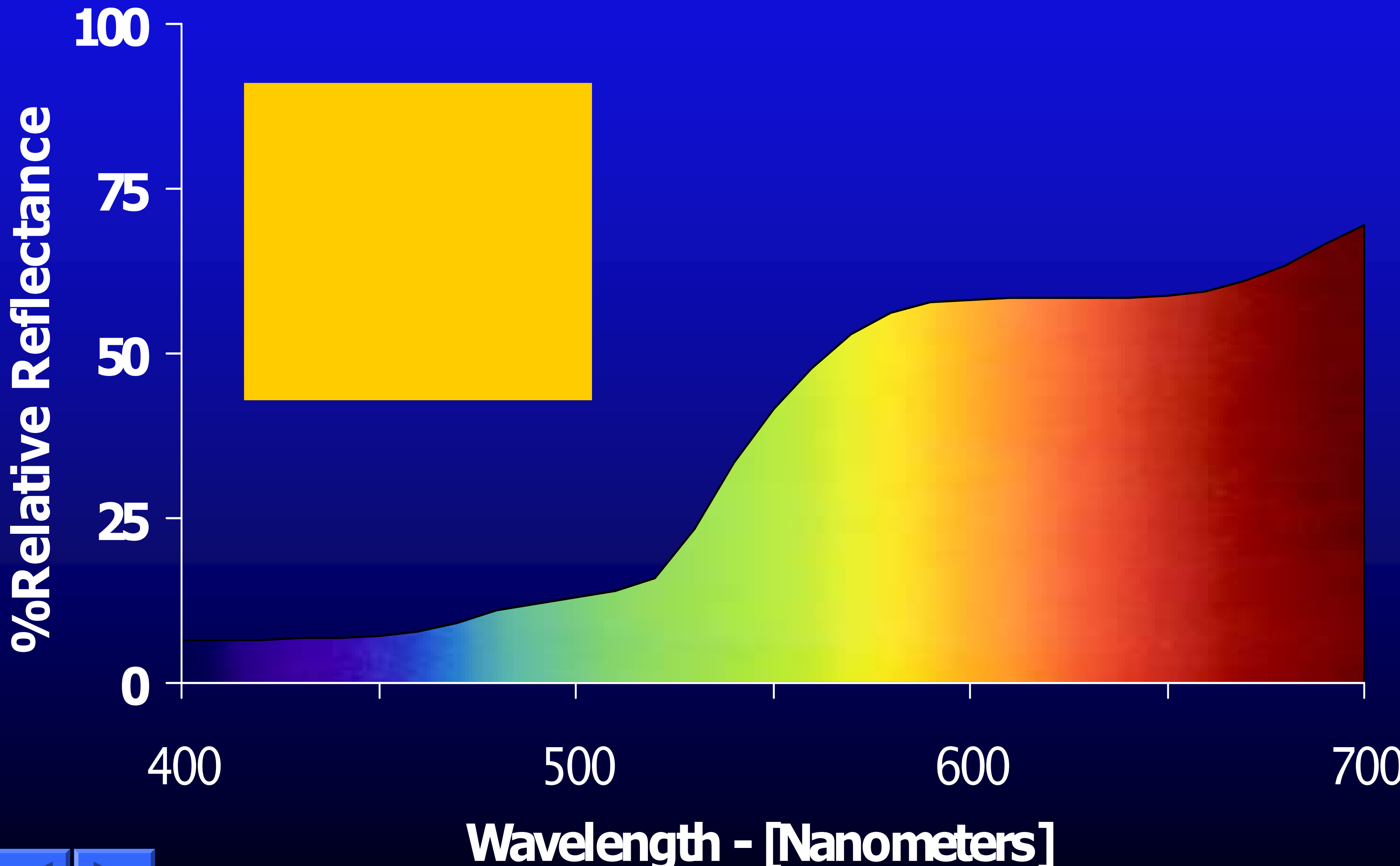
Light Interaction with School Bus Paint



Object

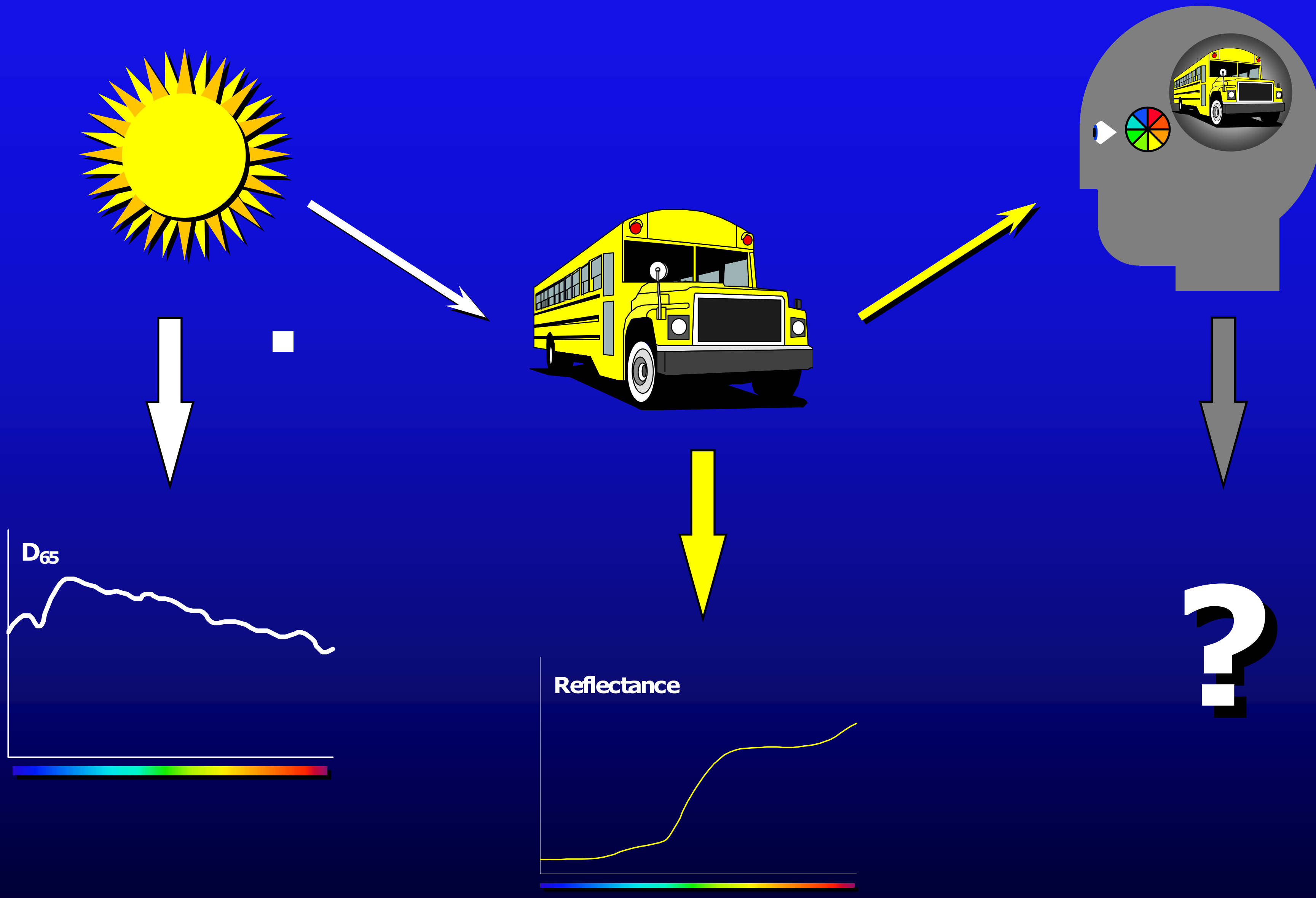
- The amount of reflected or transmitted light at each wavelength can be quantified. This is a spectral curve of the object's color characteristics.

Spectrophotometric Curve for "School Bus Yellow"



Object

- By measuring the relative reflectance or transmission characteristics of an object, the second element of the Visual Observing Situation has been quantified.

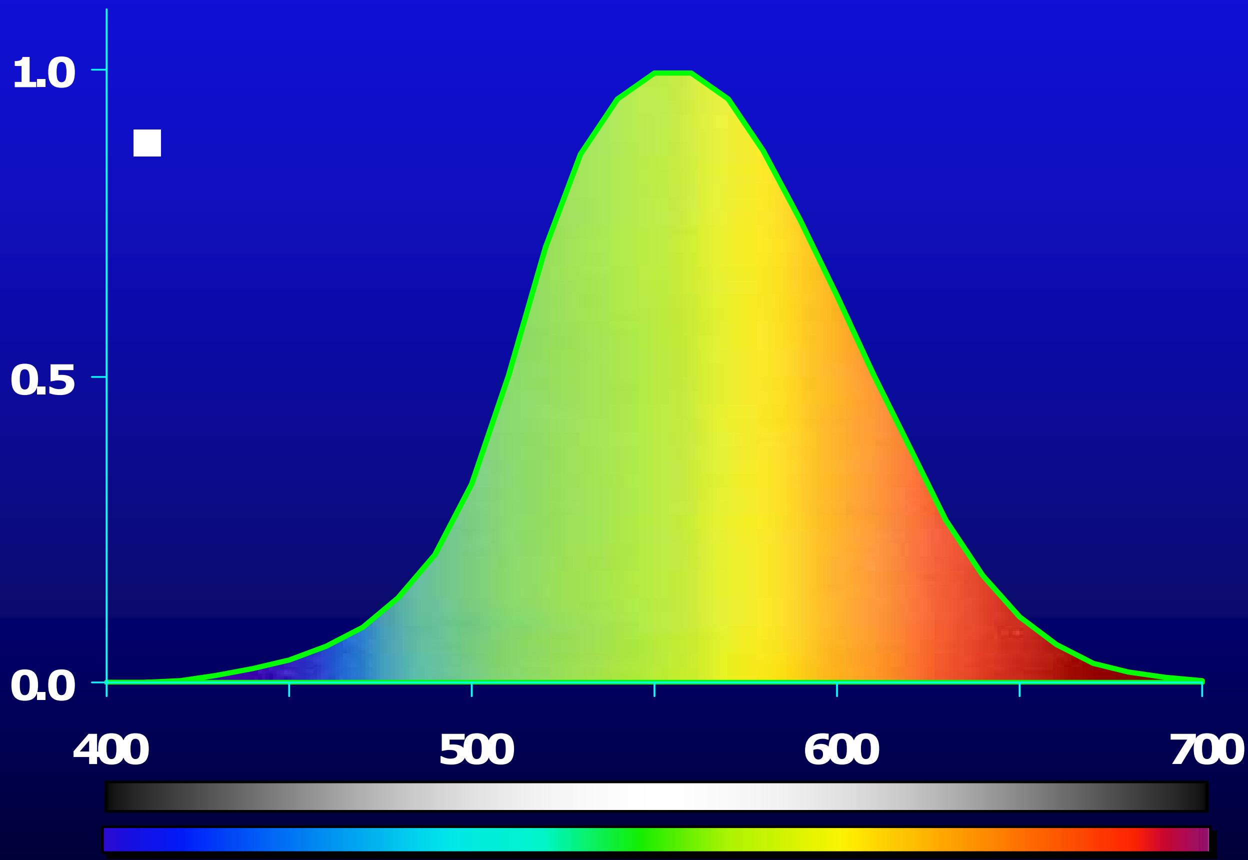

D65
Reflectance
?

Observer

Observer

- Luminosity is the relative sensitivity of the human eye to various wavelengths of light. ■

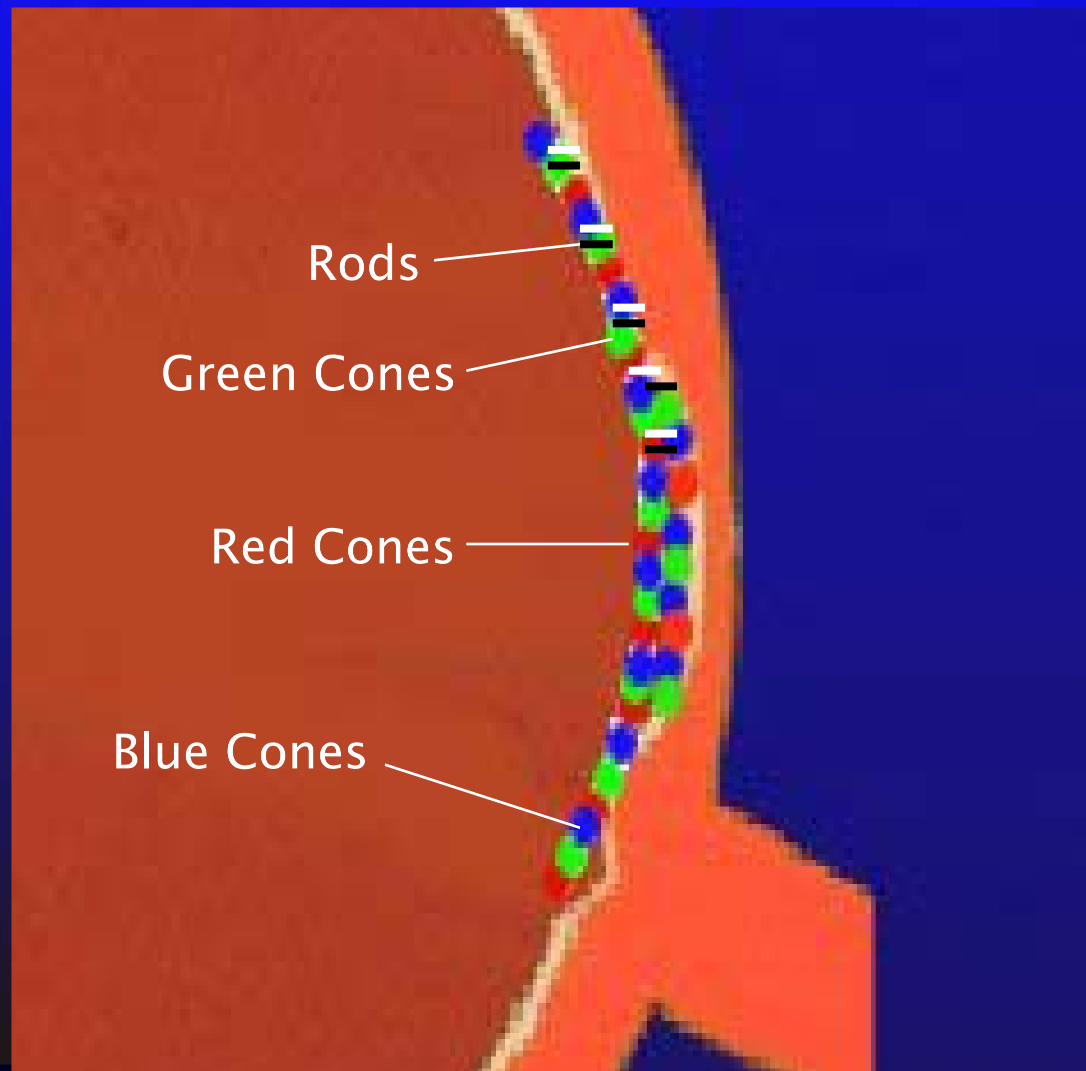
Human Eye Sensitivity to Spectral Colors



Observer

- **Rod** shaped receptors in the eye are responsible for night vision.
- **Cone** shaped receptors are responsible for daylight and color vision.
- There are three types of cone shaped receptors sensitive to **red**, **green** and **blue**.

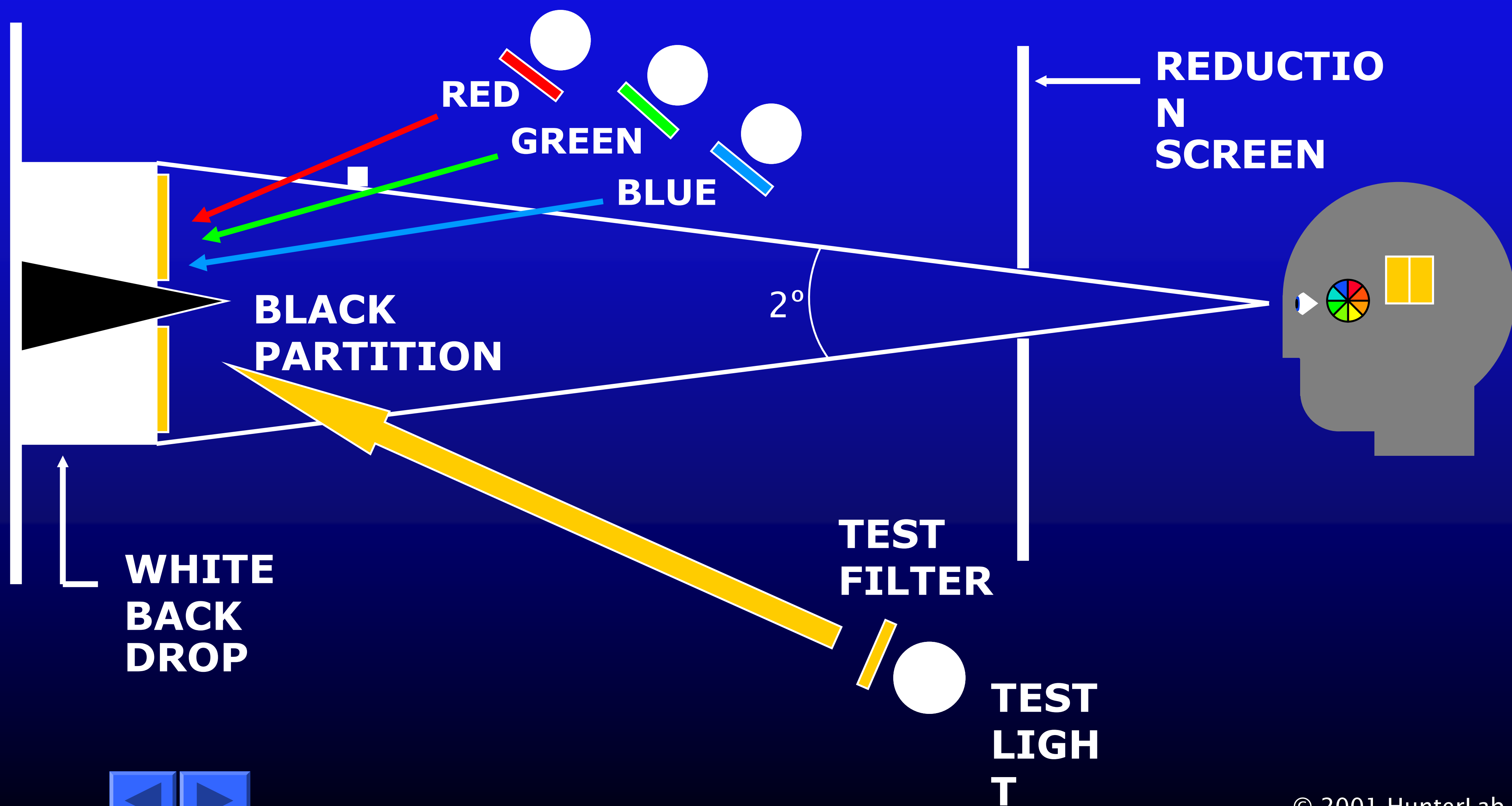
The Human Eye



Observer

- Experiments were conducted to quantify the ability of the human eye to perceive color. An observer looked at a white screen through an aperture having a 2 degree field of view. Half of a screen was illuminated by a test light. The observer adjusted the intensity of three primary colored lights that mixed together on the other half of the screen until they matched the color of the test light. This process was repeated for test colors covering the entire visible spectrum.

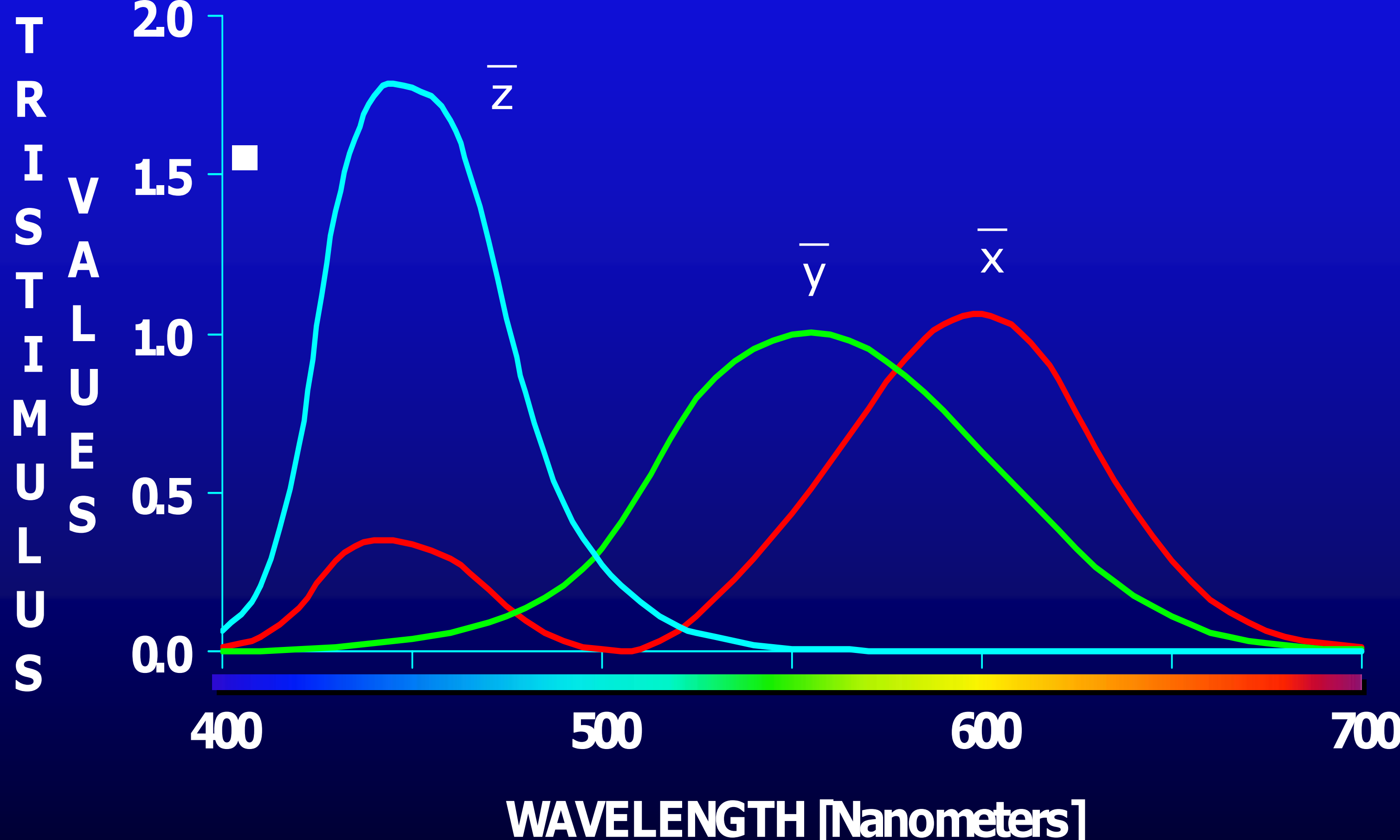
Determination of Standard Colorimetric Observer



Observer

- The experimentally derived $\bar{x}$, $\bar{y}$, and $\bar{z}$ functions became the CIE 1931 2° Standard Observer. These functions quantify the red, green and blue cone sensitivity of the average human observer.

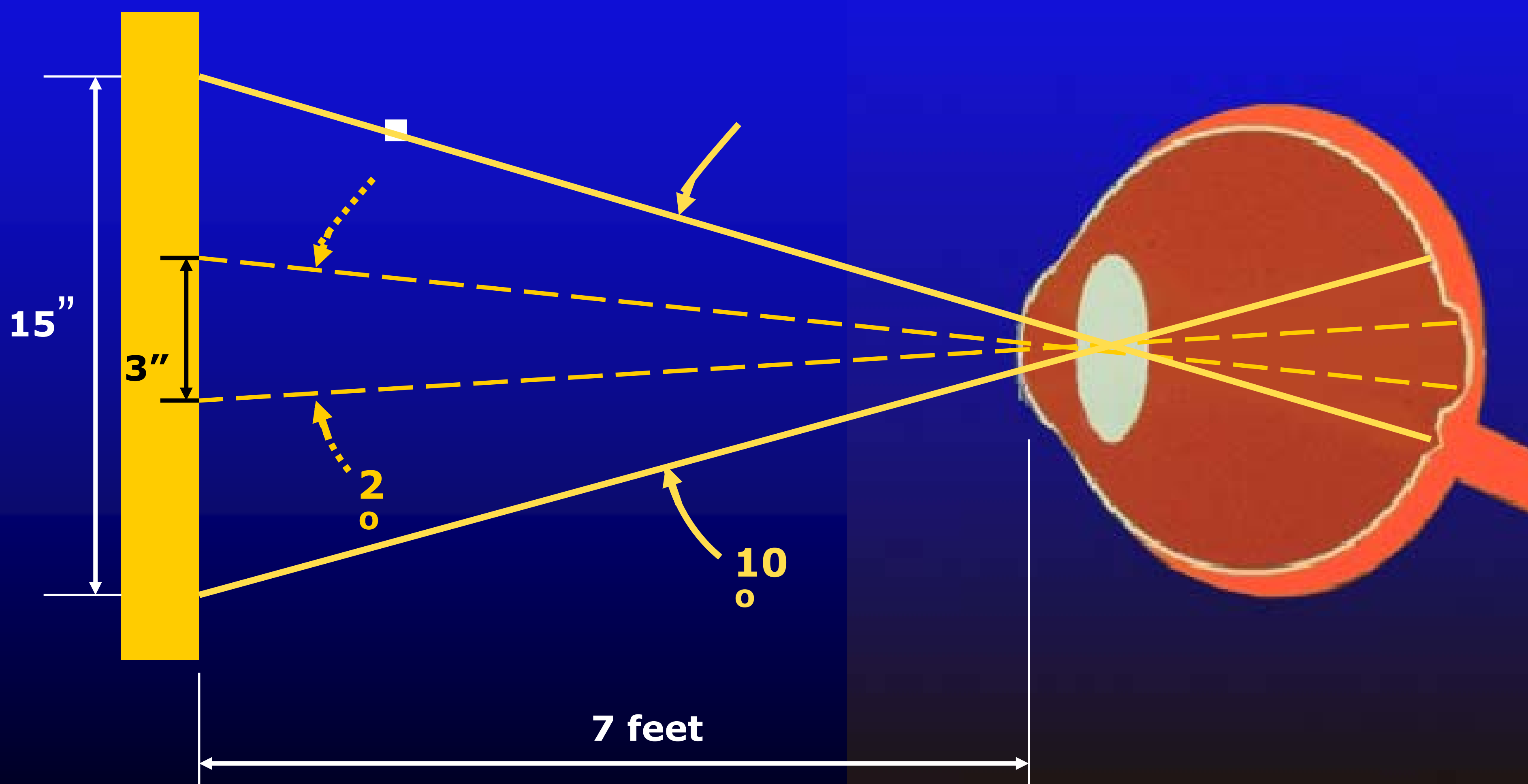
CIE 2° Standard Colorimetric Observer



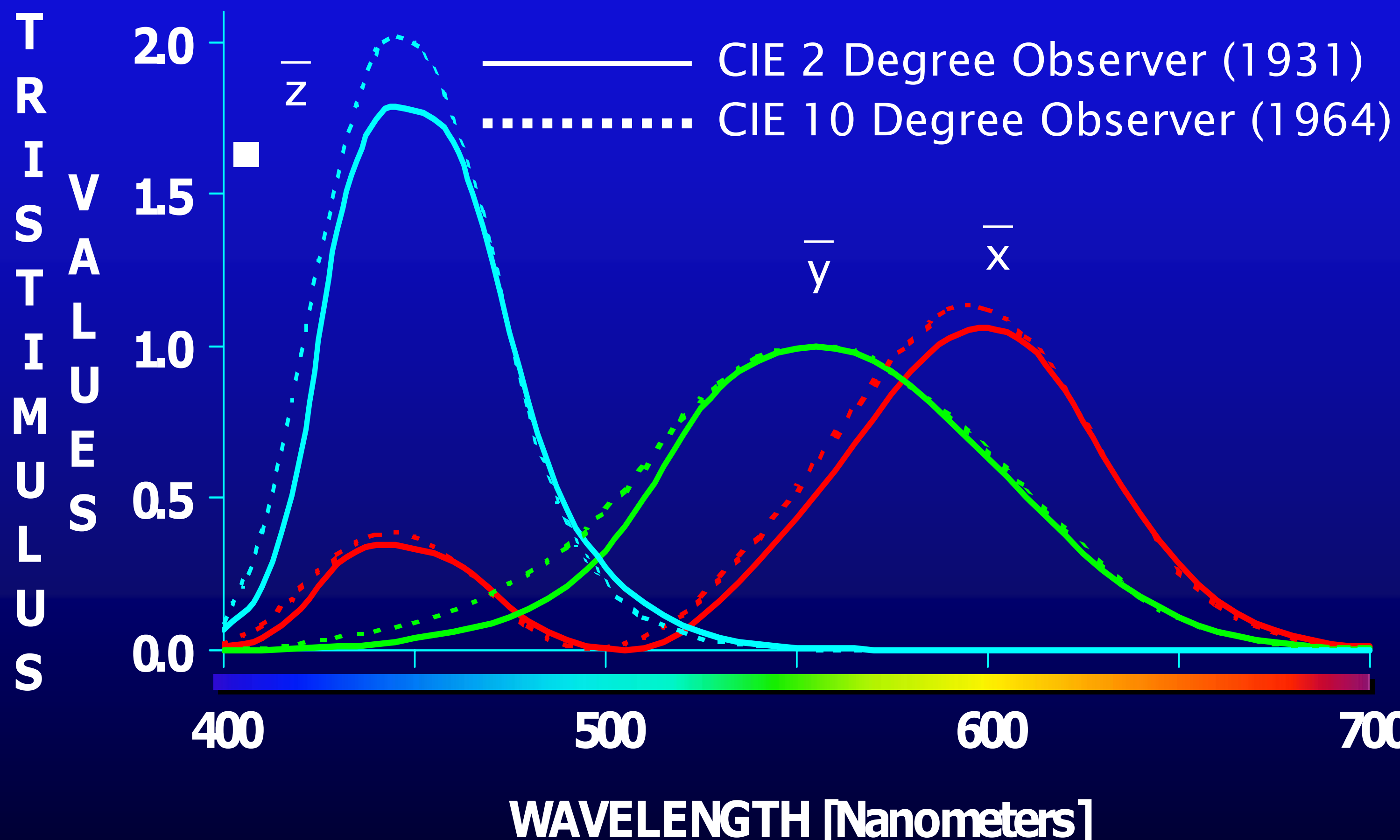
Observer

- At the time the 1931 2° Standard Observer experiments were conducted it was thought that the cone concentration was in the foveal region. Later it was determined that the cones were spread beyond the fovea. The experiments were re-done in 1964, resulting in the 1964 10° Standard Observer.

2° and 10° Observer



2 versus 10 Degree Standard Observer

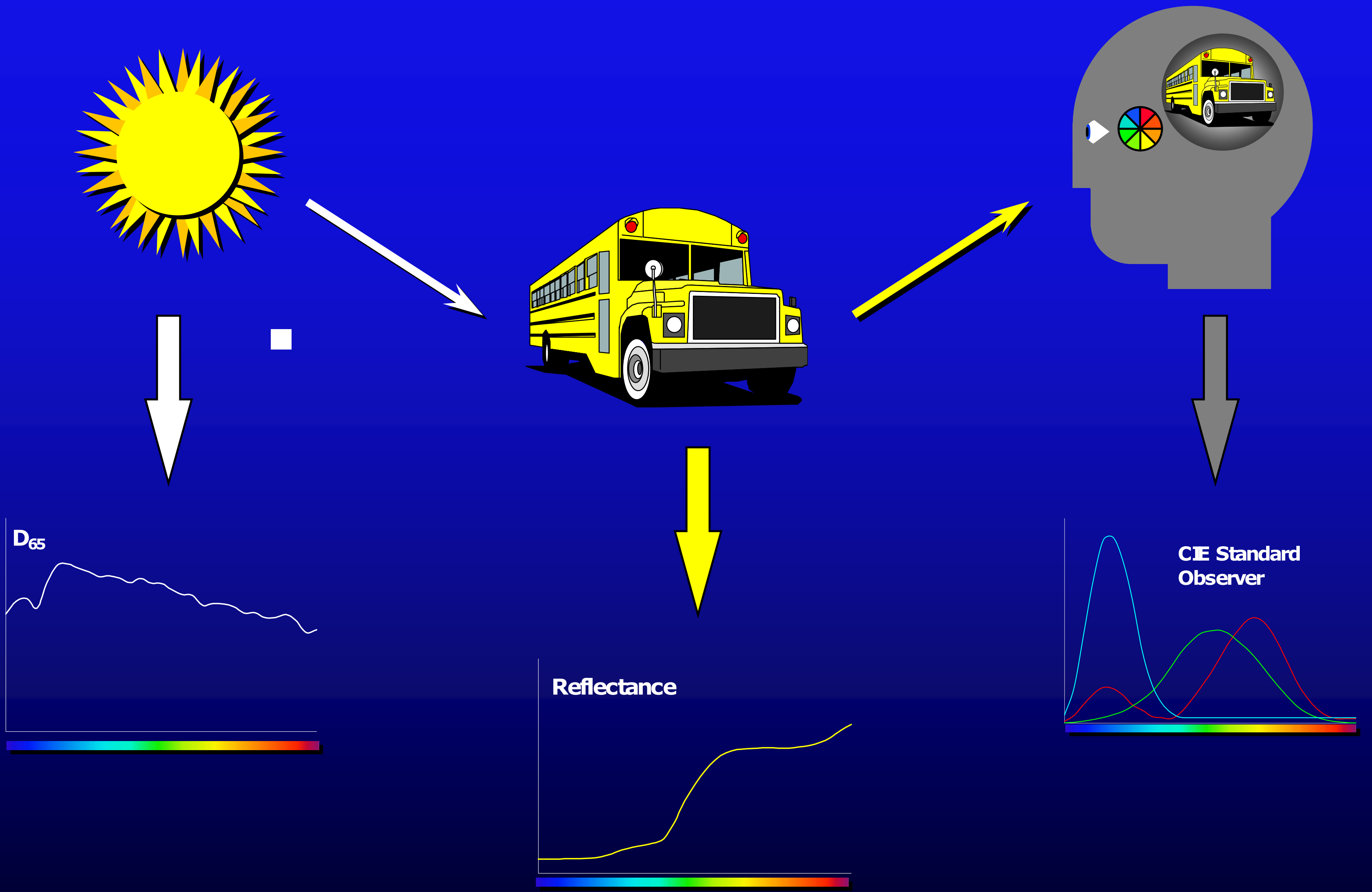


Observer

- Of the two sets of observer functions, the 10° Standard Observer is recommended for better correlation with average visual assessments made with large fields of view that is typical of most commercial applications.

Observer

- The three elements of the Visual Observing Situation have now been modeled as tables of numbers.
  - The **Source** is quantified as a user selected illuminant
  - The **Object** is quantified by measuring the reflectance or transmission curve
  - The **Observer** is quantified by the selected CIE Standard Observer Functions

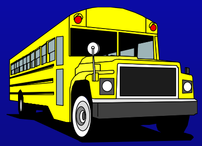

D65
Reflectance
CIE Standard
Observer

Color Measurement

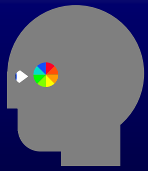
Things Required:

To See Color

Light Source

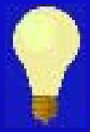


Object



Observer

To Measure Color



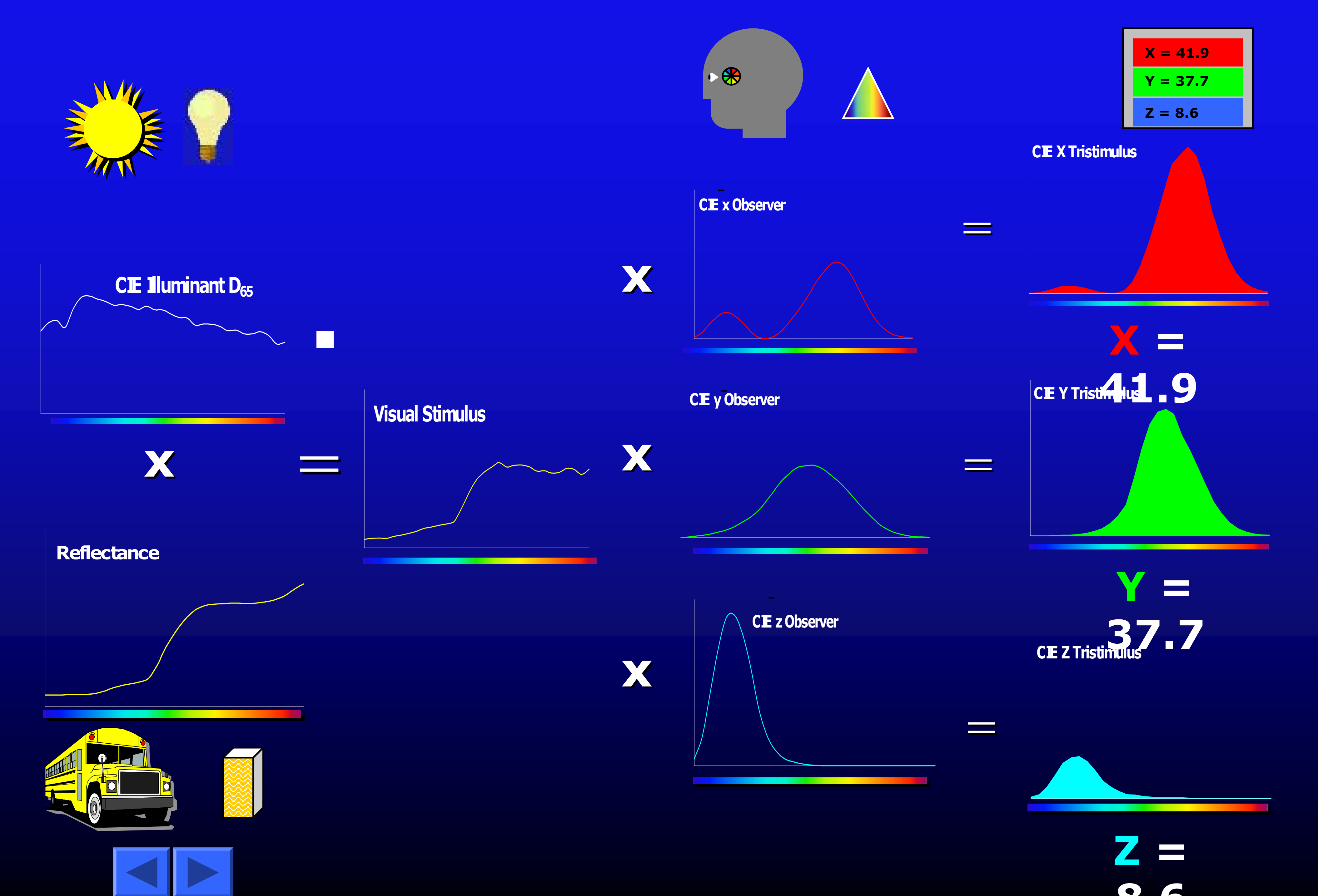
Light Source

Specimen

Spectrometer

Color Measurement

- The **CIE Tristimulus color values X, Y, Z** of any color are obtained by multiplying together the data values for the illuminant, the reflectance or transmittance of the object, and the standard observer functions. The product is then summed for the wavelengths in the visible spectrum to give the resulting X, Y, Z tristimulus values.

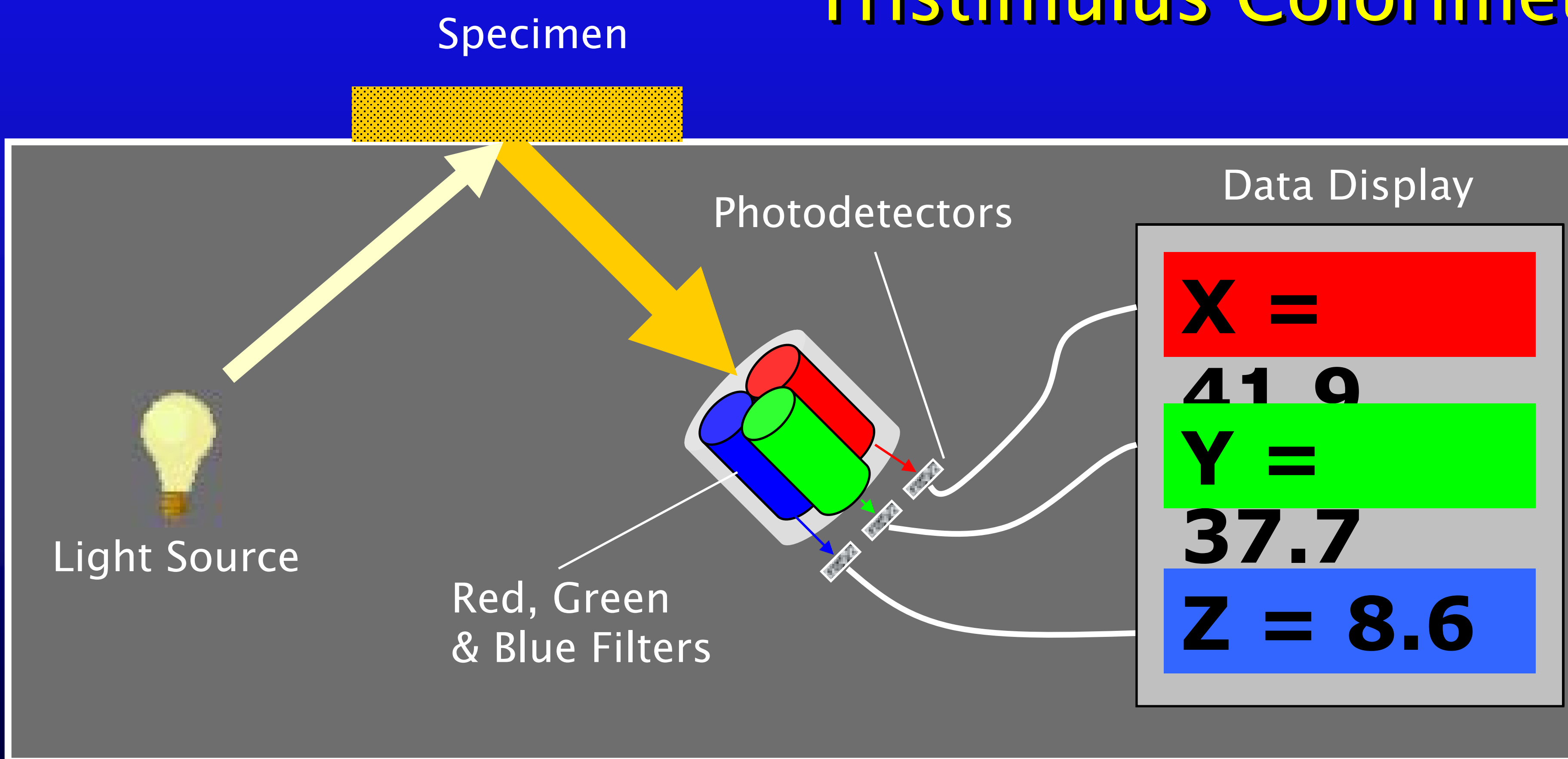

X = 41.9
Y = 37.7
Z = 8.6
CIE X Tristimulus
CIE x Observer
CIE Illuminant D65
Visual Stimulus
CIE y Observer
CIE Y Tristimulus
Reflectance
CIE z Observer
CIE Z Tristimulus
X = 41.9
Y = 37.7
Z =

Measuring Color

- A **Tristimulus Colorimeter** or **Colorimeter** uses a light source to light the specimen being measured. The light reflected off of the object then passes through a red, green and blue glass filter to simulate the standard observer functions for a particular illuminant (typically C). A photodetector beyond each filter then detects the amount of light passing through the filters. These signals are then displayed as X, Y and Z values.

Measuring Color

Tristimulus Colorimeter



Some Colorimeter Systems

- 

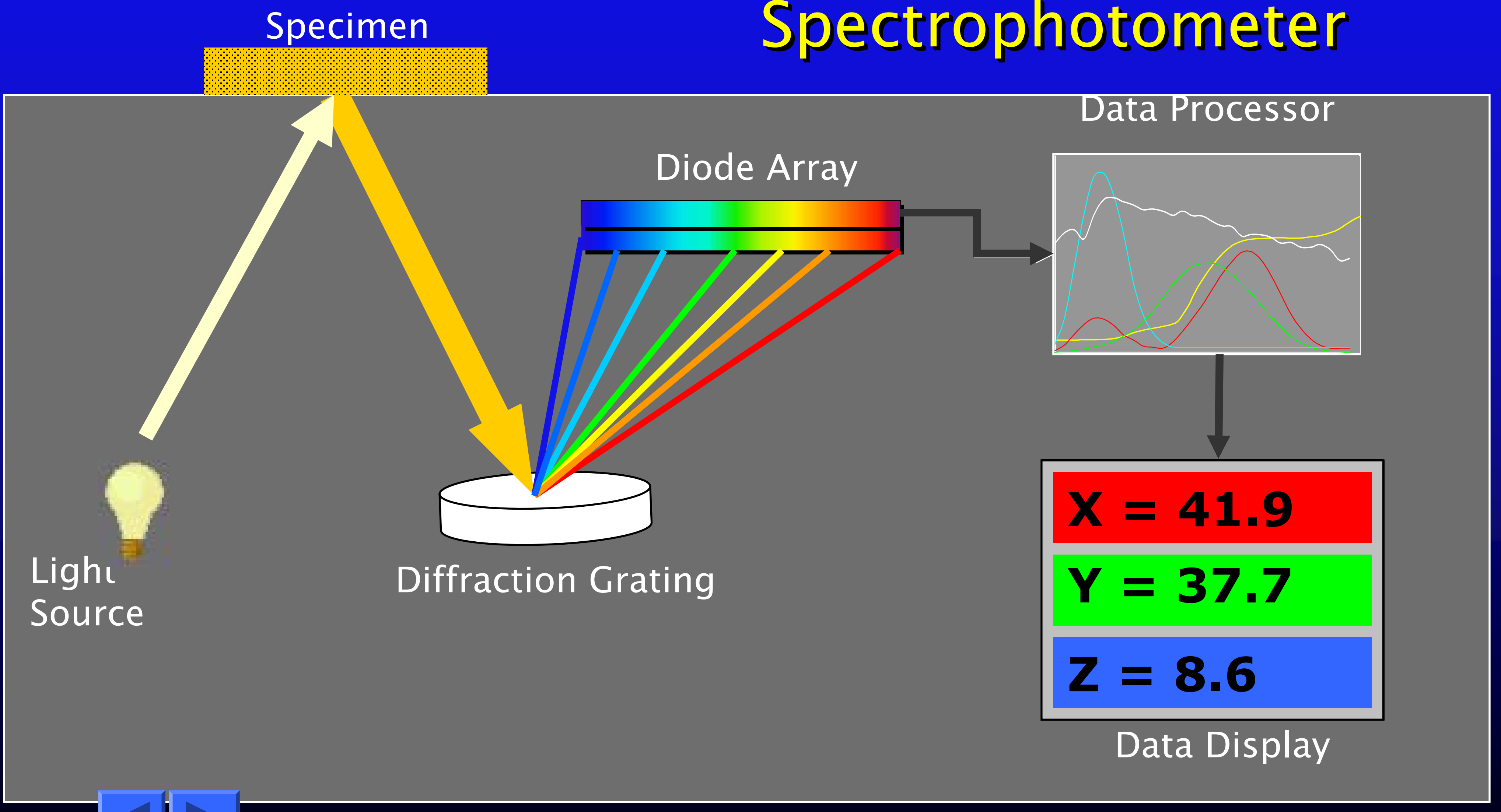
D25-9000 Colorimeters

Measuring Color

- A **Colorimetric Spectrophotometer** or **Spectrophotometer** uses a light source to light the specimen being measured. The light reflected by the object then passes to a grating which breaks it into the spectrum. The spectrum falls onto a diode array which measures the amount of light at each wavelength. This spectral data is then sent to the processor where it is multiplied together with data table values for the selected CIE illuminant and the 2° or 10° standard observer functions to obtain the X, Y, Z values.

Measuring Color

Spectrophotometer



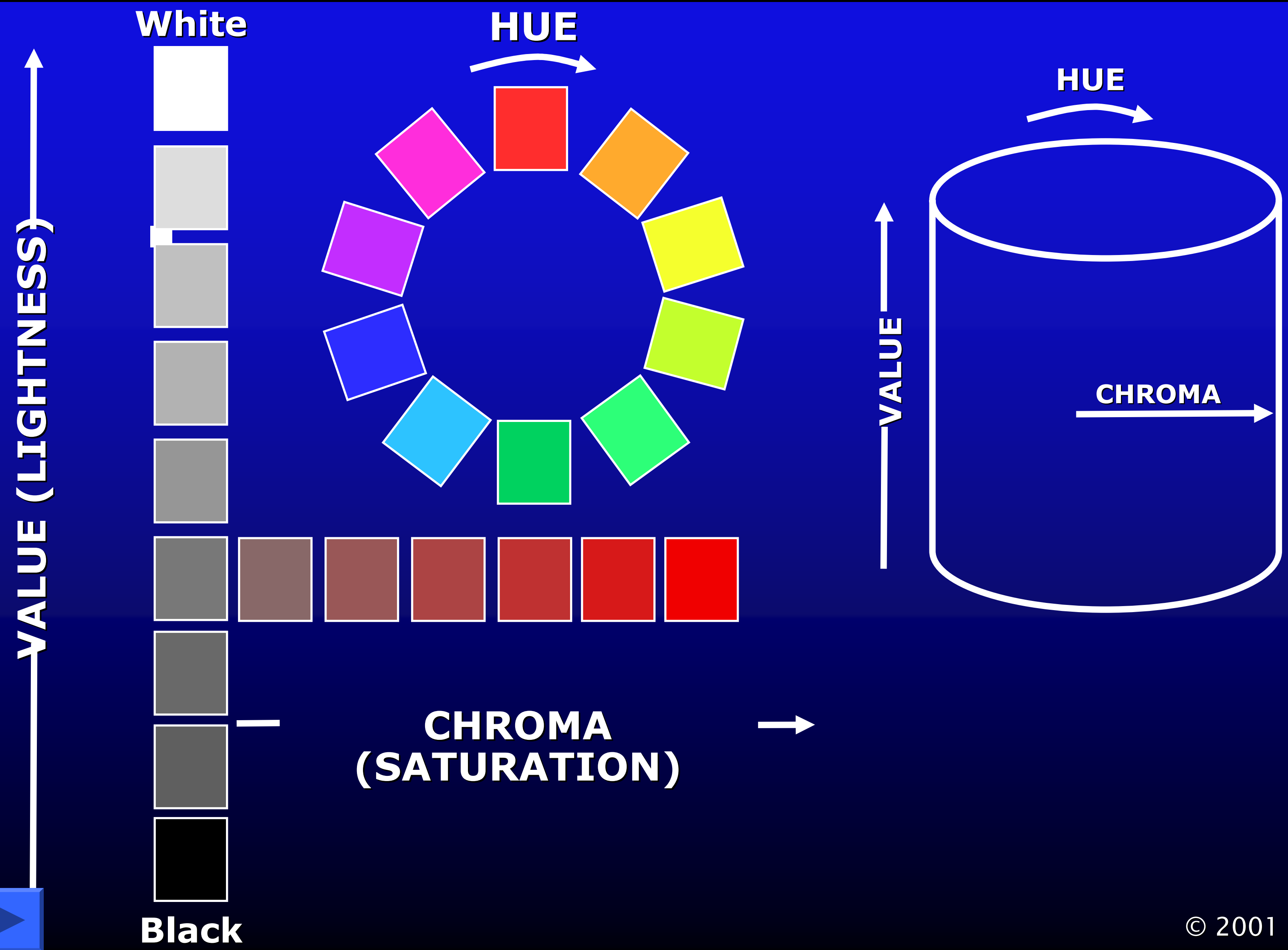
Some Spectrophotometer Systems

- Color Scales

Visual Organization of Color

- Color has a degree of **Lightness** or **Value**
- **Hue** is the color from the rainbow or spectrum of colors.
- Colorant can be added to increase the amount of **Chroma** or **Saturation**.

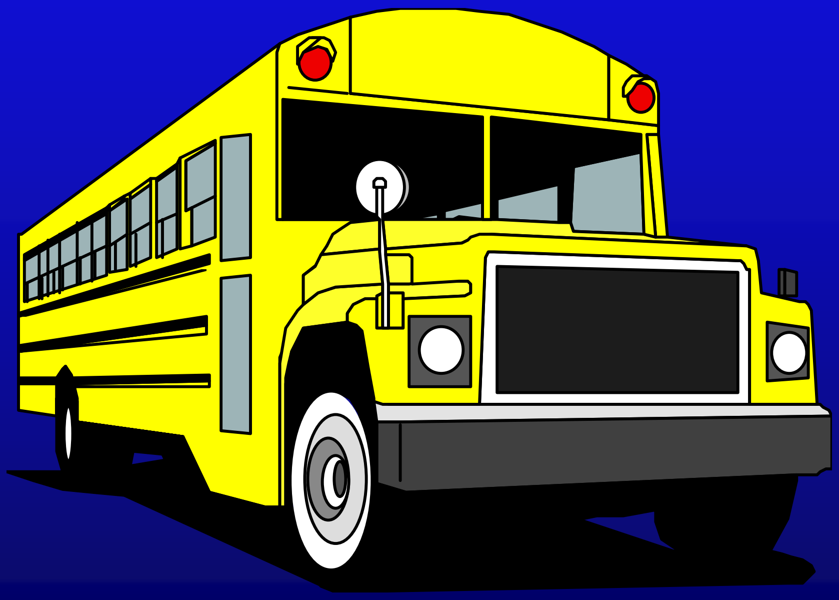
Visual Organization of Color



Measured Color Values

- Visual methods of specifying color are **subjective**.
- Measuring color using an instrument gives **objective** results.

Measured Value of School Bus Yellow



X = 41.9
Y = 37.7
Z = 8.6

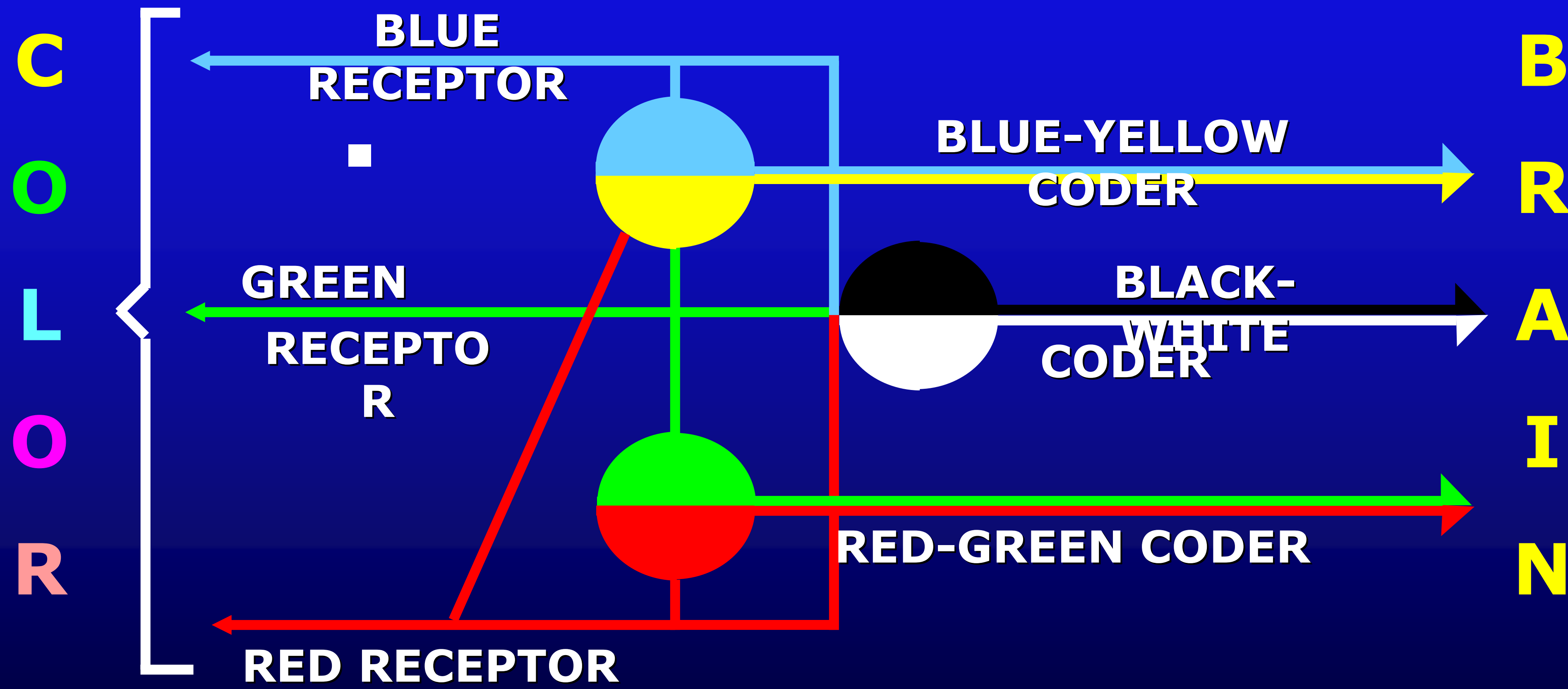
Color Scales

- Because XYZ values are not easily understood in terms of object color, other color scales have been developed to:
  - Relate better to how we perceive color
  - Simplify understanding
  - Improve communication of color differences
  - Be more linear throughout color space

Opponent–Colors Theory

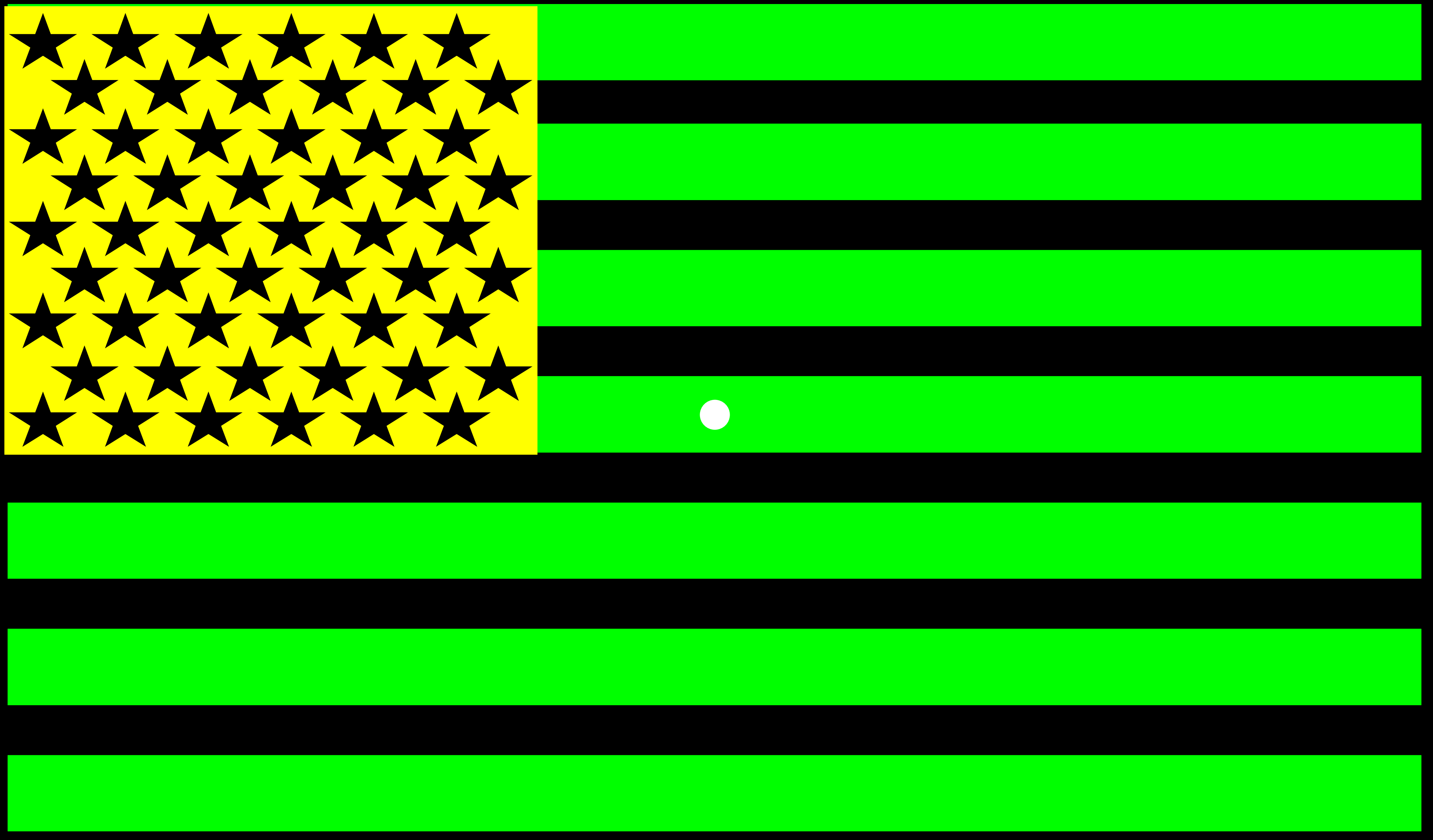
- **Opponent-Colors Theory** states that the red, green and blue cone responses are re–mixed into opponent coders as they move up the optic nerve to the brain.

Opponent-Colors Theory



Opponent-Colors Theory

- When the next slide appears, stare at the white dot in the center of the flag until the slide automatically changes to the white screen (after about 20 seconds). When the white screen appears blink a few times while staring at it.



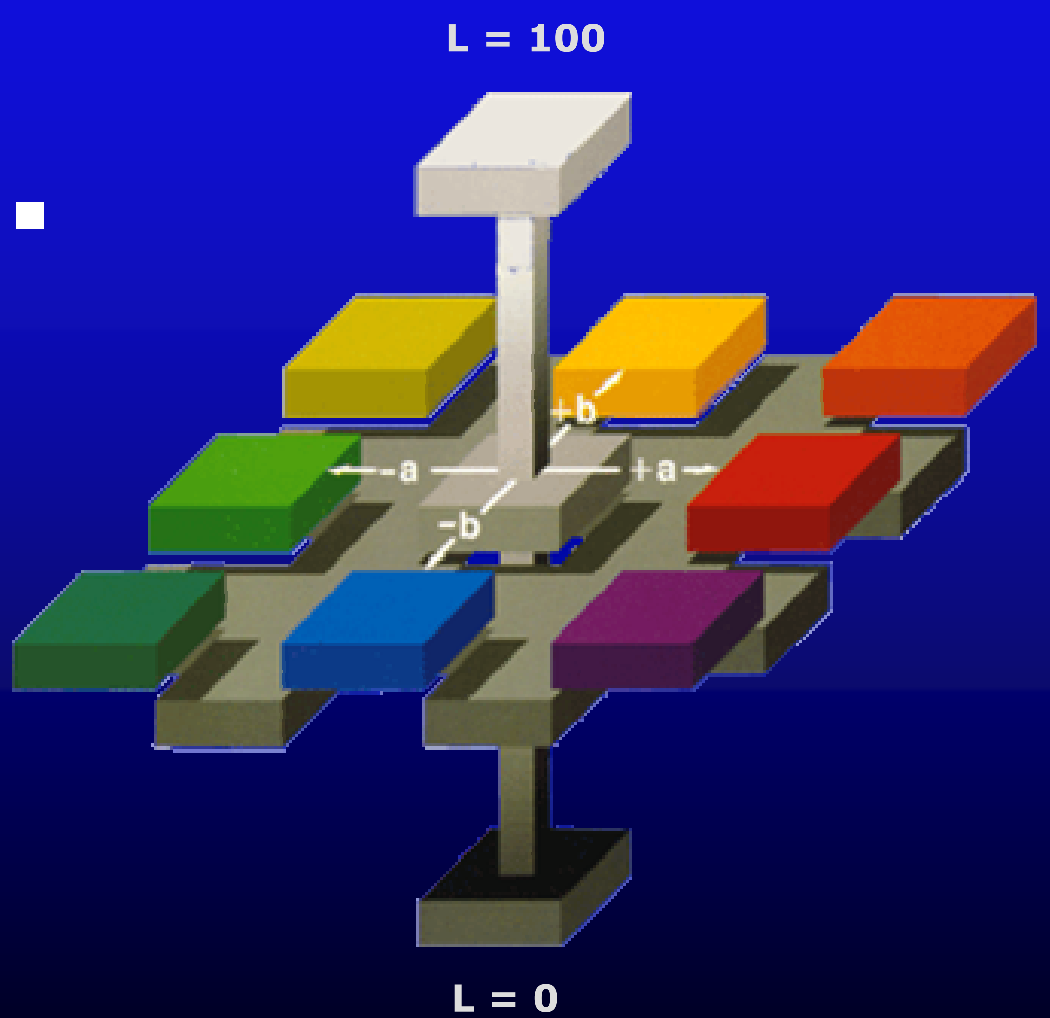
Opponent-Colors Theory

- Did you see the flag as red, white and blue?
- This happens because by staring at the green, black and yellow flag you over-saturate the green portion of the red-green coder, the black portion of the black-white coder and the yellow portion blue-yellow coder. When you look at the white screen your vision tries to return to balance and you see the red, white and blue after-image.
- This demonstration adds credence to the

Hunter L,a,b Color Space

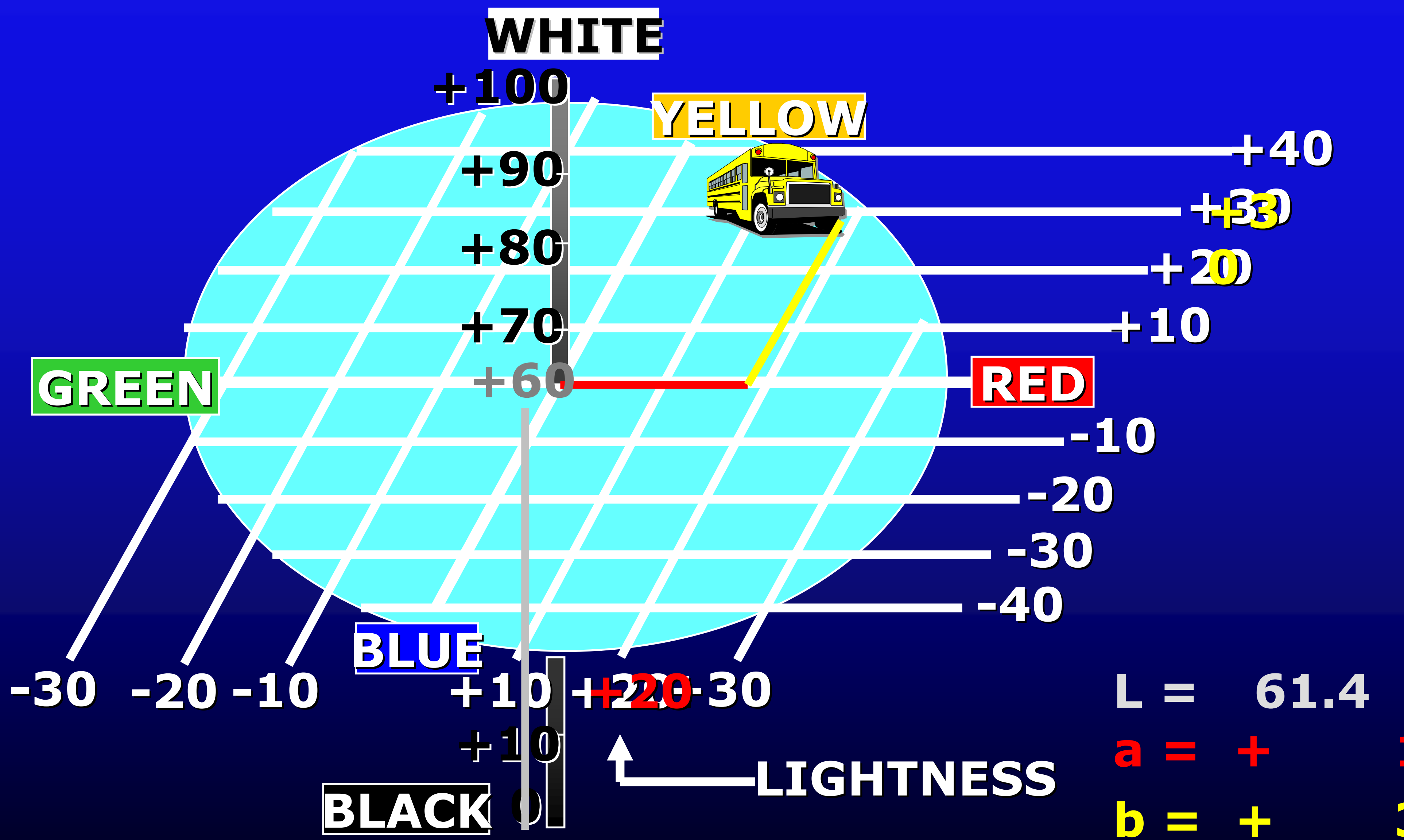
- The Hunter L,a,b color space is a 3-dimensional **rectangular** color space based on the opponent-colors theory.
  - **L** (lightness) axis – 0 is black, 100 is white
  - **a** (red-green) axis – positive values are red; negative values are green and 0 is neutral
  - **b** (blue-yellow) axis – positive values are yellow; negative values are blue and 0 is neutral

Hunter L,a,b Color Space

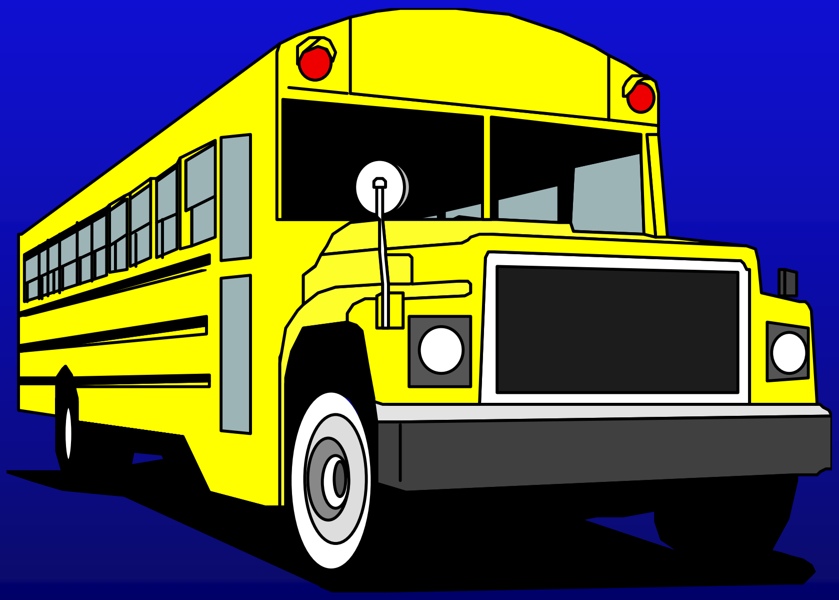


Hunter L,a,b Color Space

- All colors that can be visually perceived can be plotted in this L,a,b rectangular color space.
- The following slide shows where the “school bus yellow” falls in Hunter L,a,b color space.


WHITE
+100
+90
+80
+70
+60
YELLOW
+40
+30
+20
+10
GREEN
RED
-10
-20
-30
-40
BLUE
-30
-20
-10
+10
+20
+30
+10
BLACK
0
LIGHTNESS
L = 61.4
a = +
b = +

Hunter L,a,b Values for School Bus Yellow



$L = 61.4$

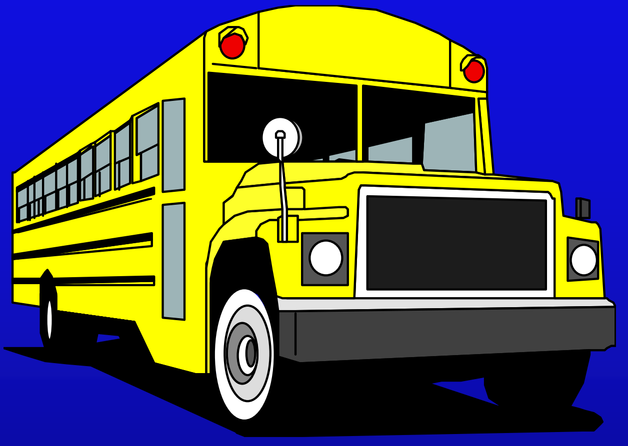
$a = +18.1$

$b = +32.2$

L,a,b Color Scales

- There are two popular L,a,b color scales in use today – **Hunter L,a,b** and **CIE L*,a*,b***.
- While similar in organization, a color will have different numerical values in these two color spaces.

Hunter L,a,b (1958) versus CIE L*,a*,b* (1976)



Hunter L,a,b	CIE L*,a*,b*
L = 61.42	L* = 67.81
a = +18.11	a* = +19.56
b = +32.23	b* = +58.16

L,a,b Color Scales

- Hunter and CIE L*,a*,b* scales are both mathematically derived from the X, Y, Z values
- Neither scale is visually uniform, Hunter L,a,b is over expanded in the blue region of color space and CIE L*,a*,b* is over expanded in the yellow region.
- The current CIE recommendation is to use CIE L*,a*,b*.

Calculation of Color Formulas

Hunter L,a,b

$$L = 100\,(Y/Y_n)^{1/2}$$

$$a = Ka\,\frac{(X/X_n - Y/Y_n)}{(Y/Y_n)^{1/2}}$$

$$b = Kb\,\frac{(Y/Y_n - Z/Z_n)}{(Y/Y_n)^{1/2}}$$

CIE L*,a*,b*

$$L^* = 116\,(Y/Y_n)^{1/3} - 16$$

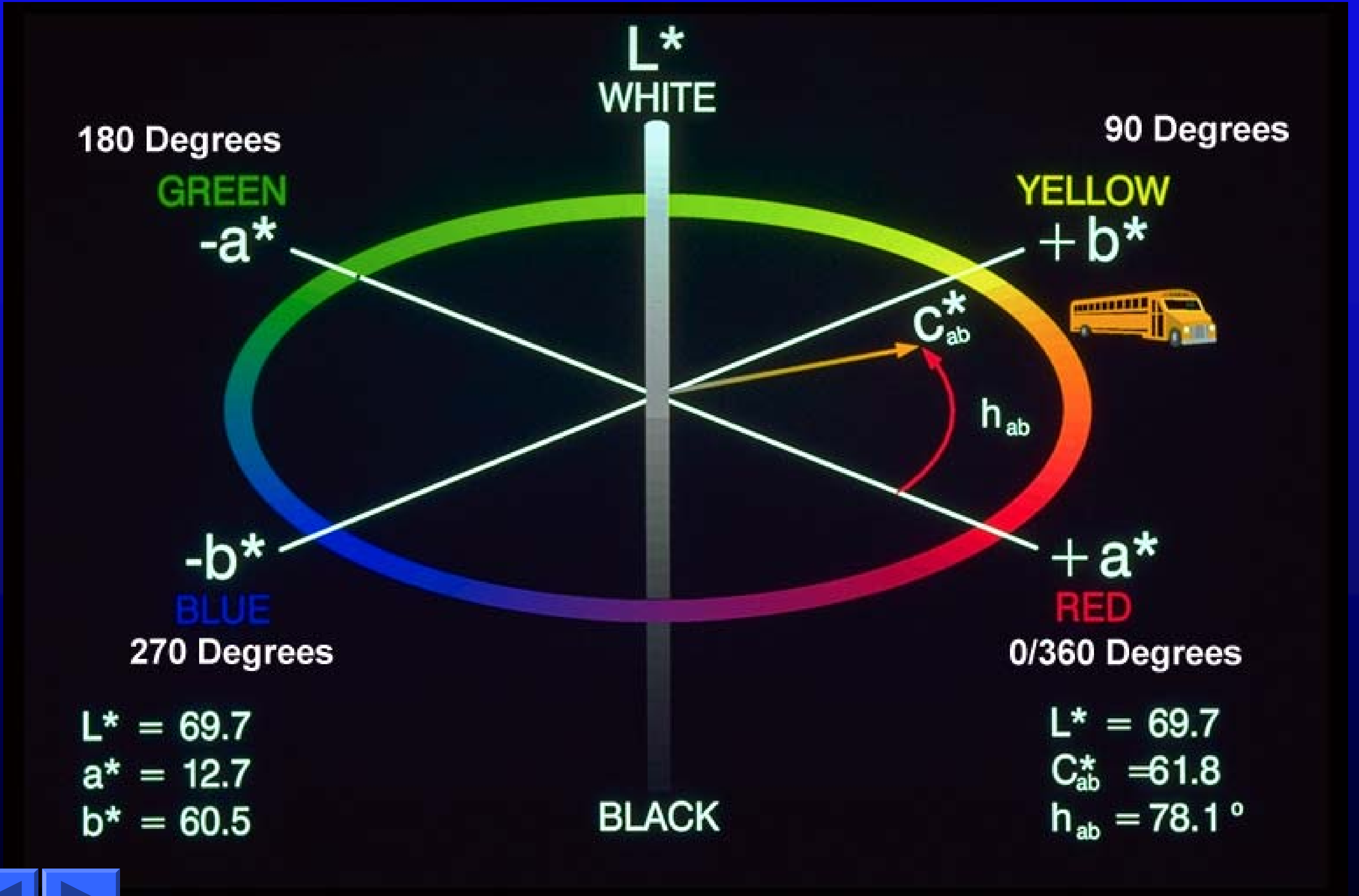
$$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

Polar CIE L*,C*,h

- CIE **L*,C*,h** is a **polar** representation of the CIE L*,a*,b* rectangular coordinate system.
- Numerically CIE L*,C*,h describes color in the same way that we verbally communicate color in terms of lightness, chroma (saturation) and hue.
- Derived mathematically from CIE L*,a*,b*, its visual uniformity is no better than CIE L*,a*,b*.
- It is not as easy to understand as the L,a,b ales

Polar CIE L*,C*,h



What is an Acceptable Color Difference?

Maximum Acceptable

↑

Minimum Perceptible

What is an Acceptable Color Difference?

- What is an acceptable color difference varies with the application. For example:
  - What is acceptable for color matching of automotive paint is close to being a **minimum perceptible** limit.
  - What is acceptable for the snack foods is a greater limit and the **maximum acceptable limit** defines the tolerance of acceptance for the product.

Rectangular $\Delta L^*, \Delta a^*, \Delta b^*$ Color Differences

- Color Differences are always calculated as SAMPLE – STANDARD values.
  - If **delta L*** is **positive**, than the sample is **lighter** than the standard. If **negative**, it would be **darker** than the standard.
  - If **delta a*** is **positive**, than the sample is **more red** (or **less green**) than the standard. If **negative**, it would be **more green** (or **less red**).
  - If **delta b*** is **positive**, then the sample is **more yellow** (or **less blue**) than the standard. If **negative**, it would be **more blue** (or **less yellow**).

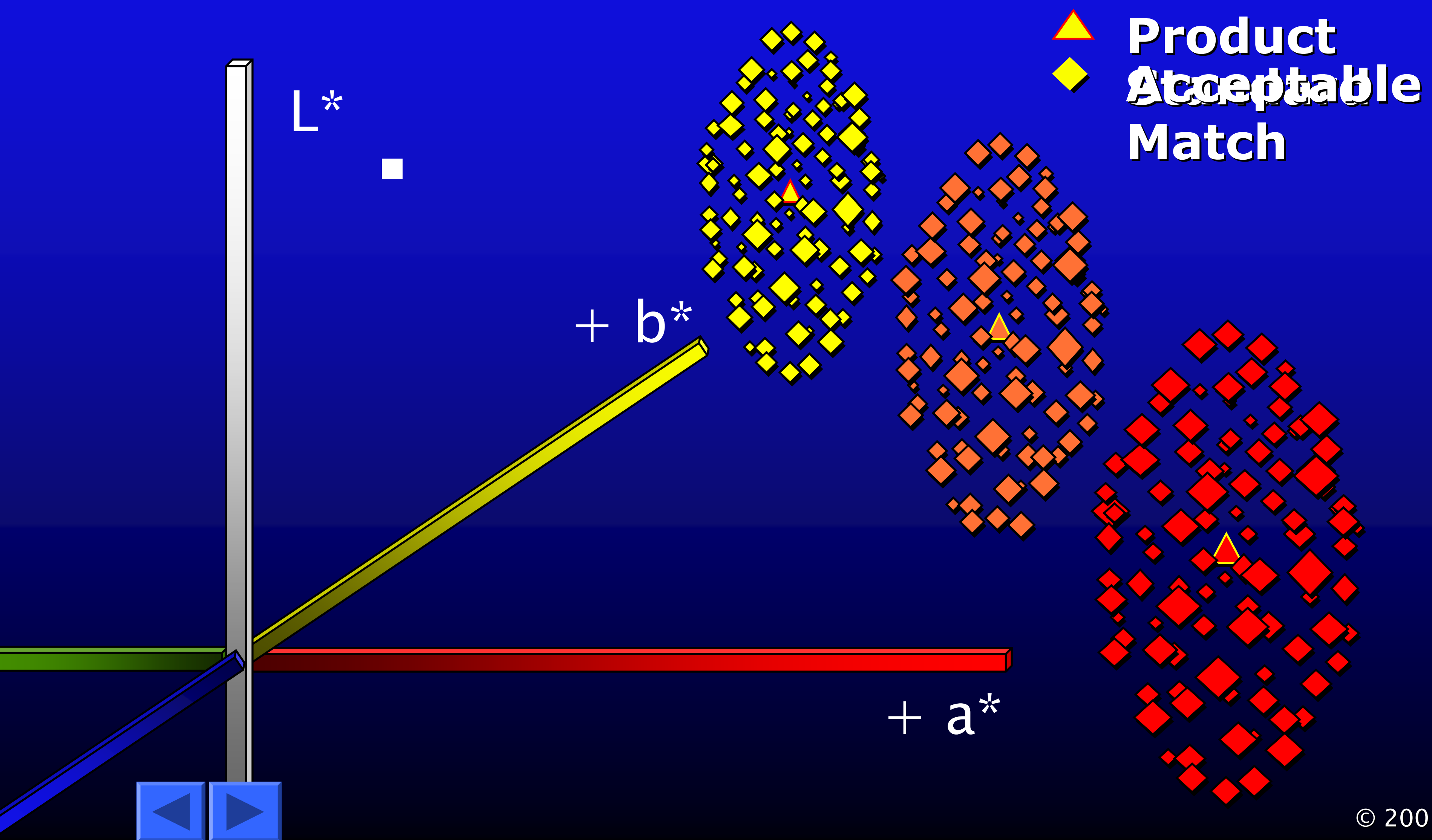
Rectangular ΔL^*, Δa^*, Δb^* Color Differences

SAMPLE		STANDARD		COLOR DIFFERENCES
$L^* = 71.9$	–	$L^* = 69.7$	=	$\Delta L^* = +2.2$
$a^* = +10.2$		$a^* = +12.7$		$\Delta a^* = -2.5$
$b^* = +58.1$		$b^* = +60.5$		$\Delta b^* = -2.4$

Shape of Acceptable Color Matches

- For products requiring tight tolerances, what is acceptable is elliptical in shape.
- We find some color difference attributes more objectionable than others. Hue differences are most objectionable. Chroma differences are less objectionable than hue differences and lightness differences are the least objectionable.

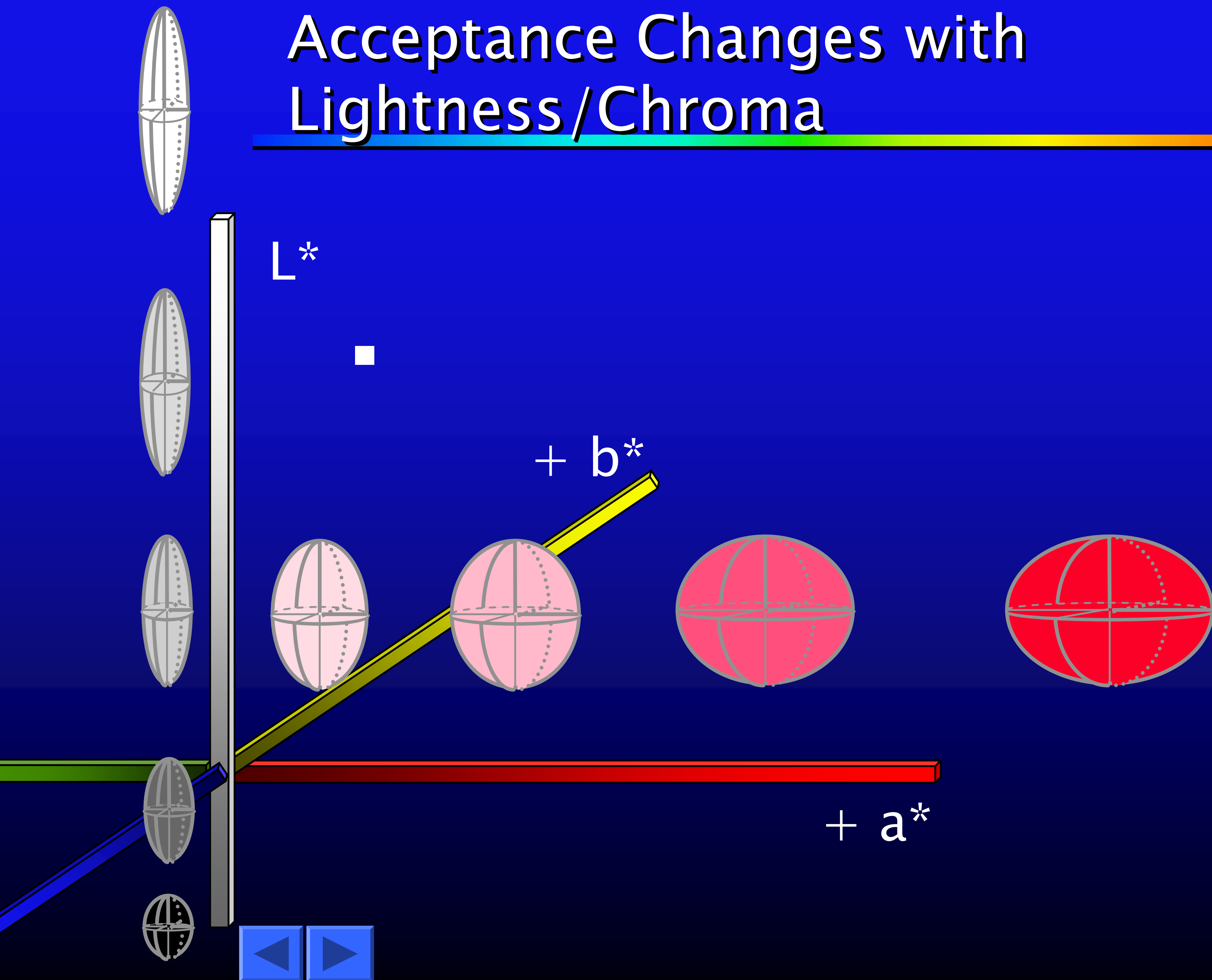
Shape of Acceptable Color Matches



Acceptance Changes with Lightness/Chroma

- Due to the non-uniformity of color space, the lighter the color the larger the L* tolerance and frequently the smaller the a* and b* tolerance.
- The more chromatic (saturated) the color, the larger the a* and b* tolerance.

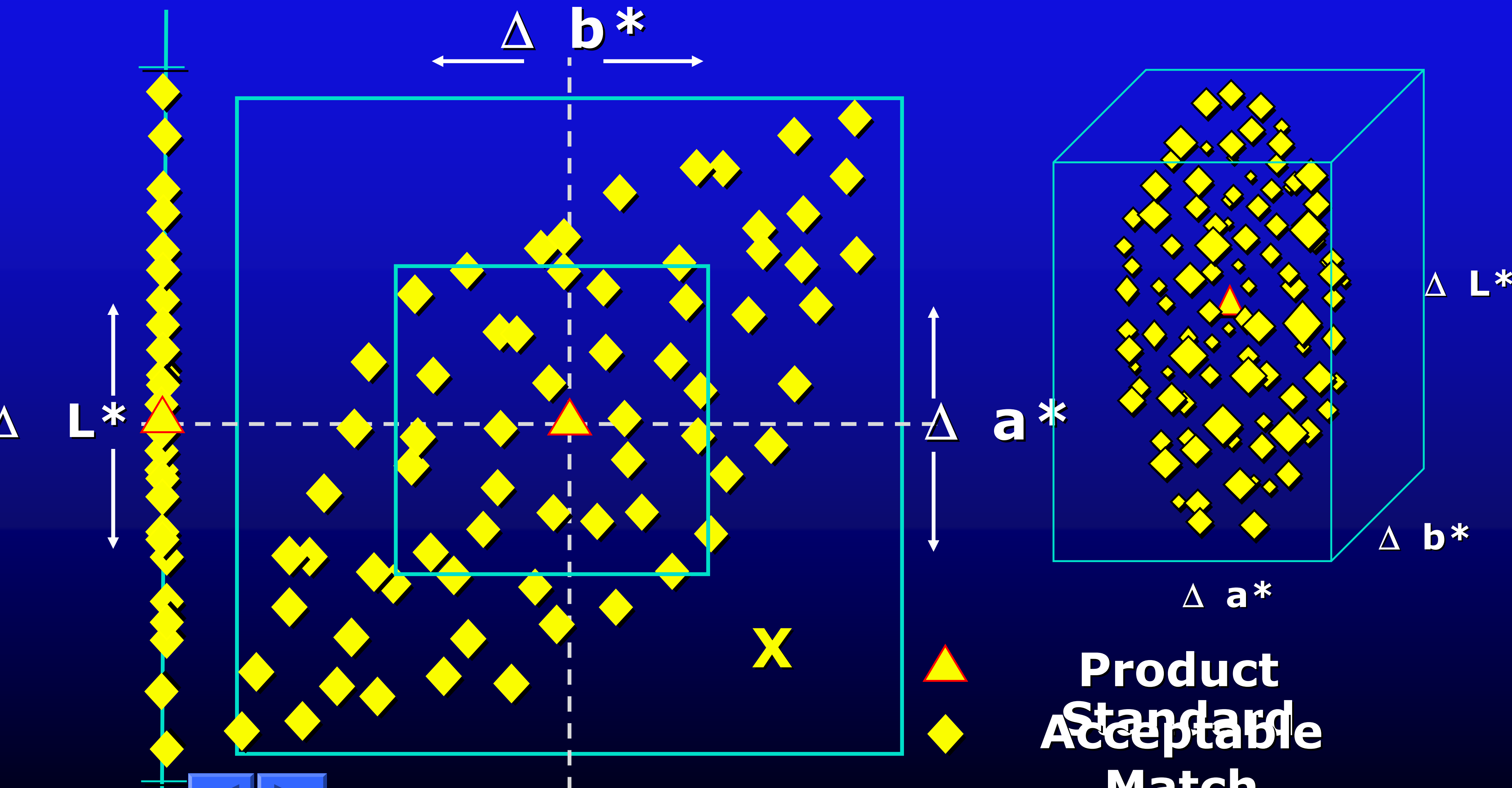
Acceptance Changes with Lightness/Chroma



Rectangular ΔL^*, Δa^*, Δb^* Space

- When Hunter L,a,b or CIE L*,a*,b* rectangular coordinates are used as a 3-dimensional color difference space, the result is fitting of acceptable samples in a box.

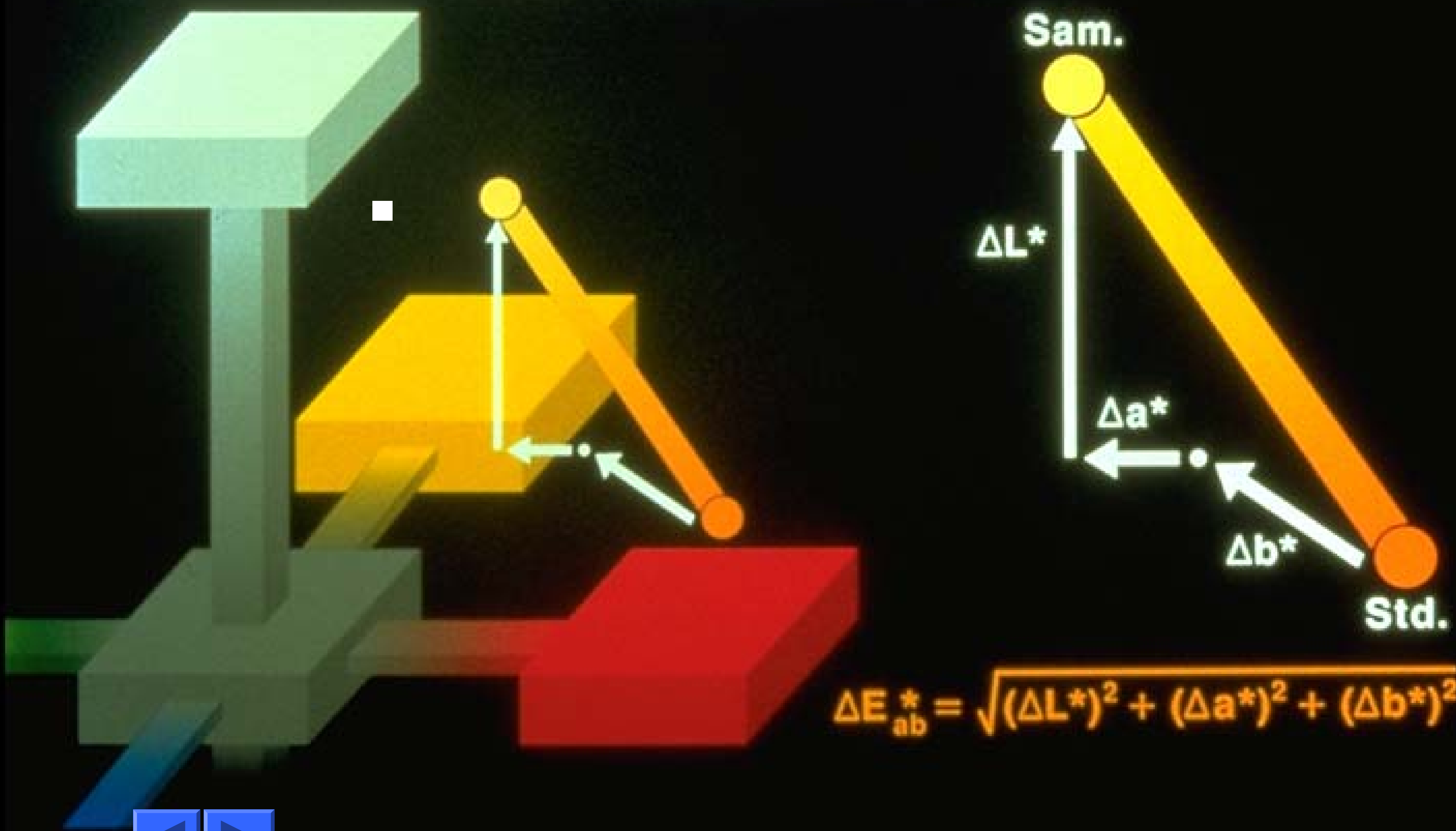
Rectangular Δ L *, Δ a *, Δ b * Space



Δ E*

- Delta E* (Total Color Difference) is based on L*,a*,b* color differences and was intended to be a single number metric for PASS/FAIL decisions.

TOTAL COLOR DIFFERENCE IN RECTANGULAR COORDINATES



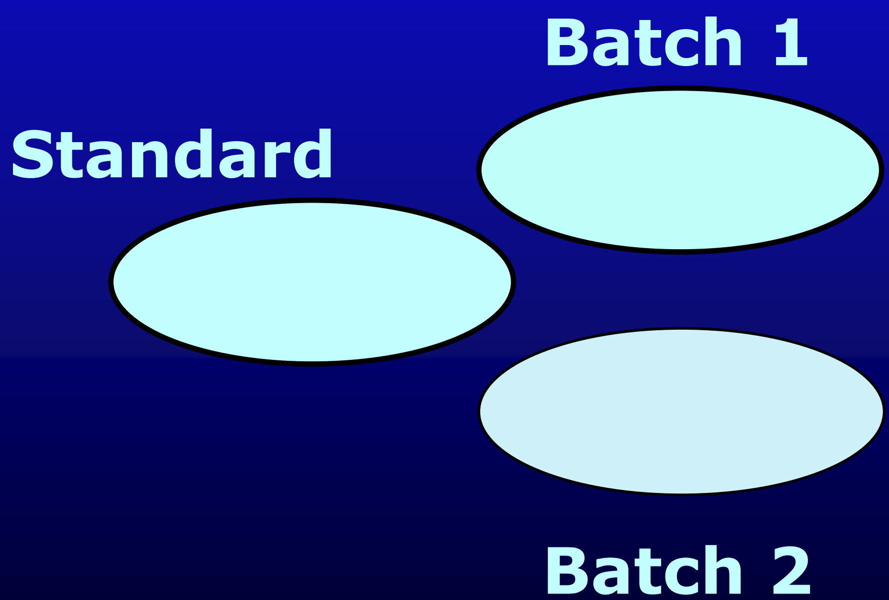
$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Non-Uniformity of ΔE^* in Color Space

- Delta E* is not always reliable by itself. In the following example Batch 1 is visually a good match to the standard. Batch 2 is not. However they both have the same delta E* value. For Batch 2 all of the difference is in the "a" value (less green) and is visually unsuitable.

Non-Uniformity of ΔE^* in Color Space

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



$$\Delta E^* = \sqrt{(0.57)^2 + (0.57)^2 + (0.57)^2} = 1$$

$$\Delta E^* = \sqrt{(0.0)^2 + (1.0)^2 + (0.0)^2} = 1$$

Polar ΔL^*, ΔC^*, ΔH^* Color Differences

- Delta H* is calculated as follows:

$$\Delta H = [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2}$$

  - If **delta L*** is **positive**, than the sample is **lighter** than the standard. If **negative**, it would be **darker** than the standard.
  - If **delta C*** is **positive**, then the sample is **more saturated** than the standard. If **delta C*** is **negative** then the sample is **less saturated**.
  - **Delta H*** indicates the magnitude of a change in **hue**.

Polar ΔL^*, ΔC^*, ΔH^* Color Differences

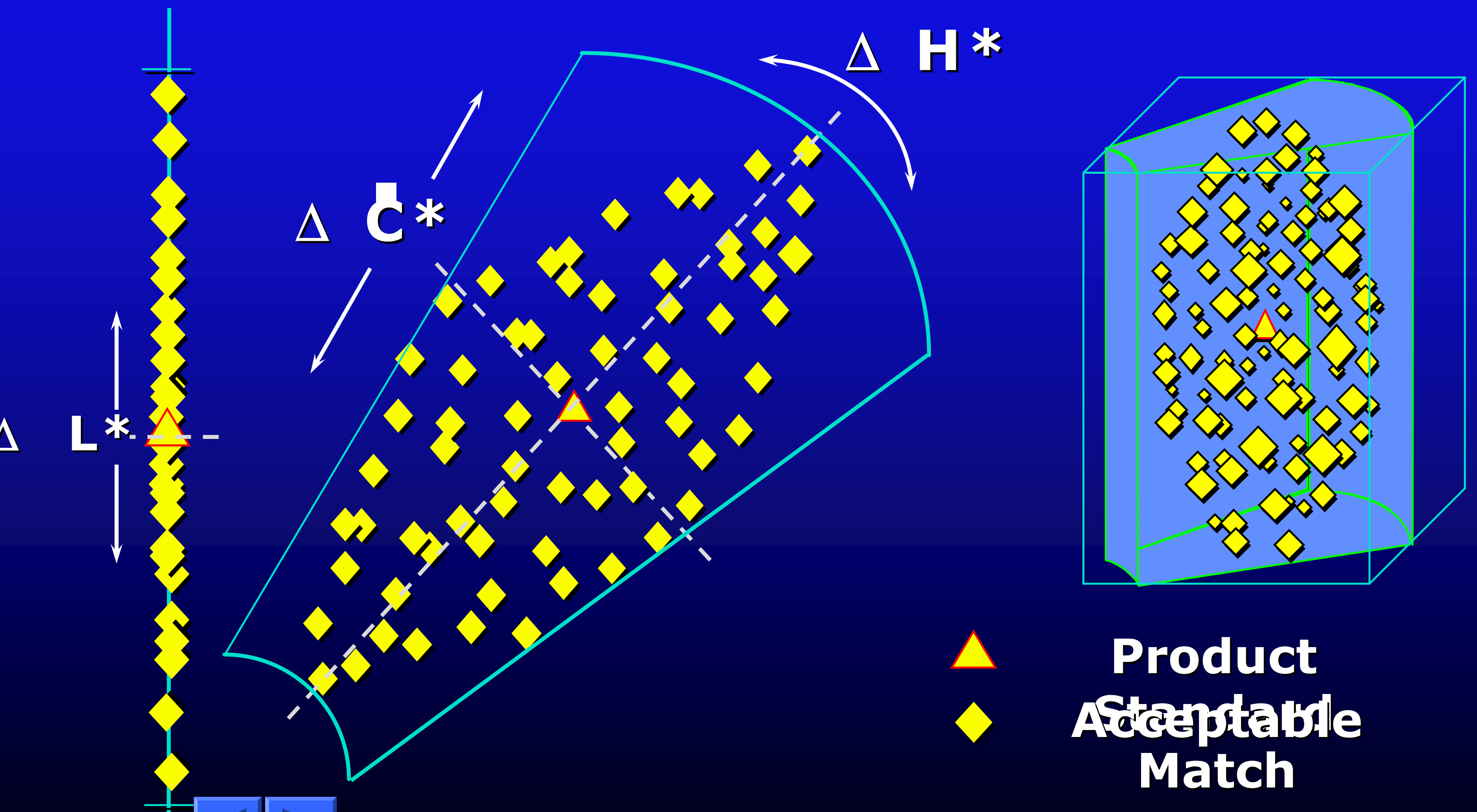
SAMPLE − **STANDARD** = **COLOR DIFFERENCES**

SAMPLE	STANDARD	COLOR DIFFERENCES
$L^* = 71.9$	$L^* = 69.7$	$\Delta L^* = +2.2$
$C^* = 58.9$	$C^* = 61.8$	$\Delta C^* = -2.8$
$h = 80.0°$	$h = 78.5°$	$\Delta H^* = +2.0$

Polar $\Delta L^*, \Delta C^*, \Delta H^*$ Color Space

- When ΔL^*, ΔC^*, ΔH^* coordinates are used as a 3-dimensional color difference space, the result is fitting of acceptable samples in the shape of a flat-topped pie.

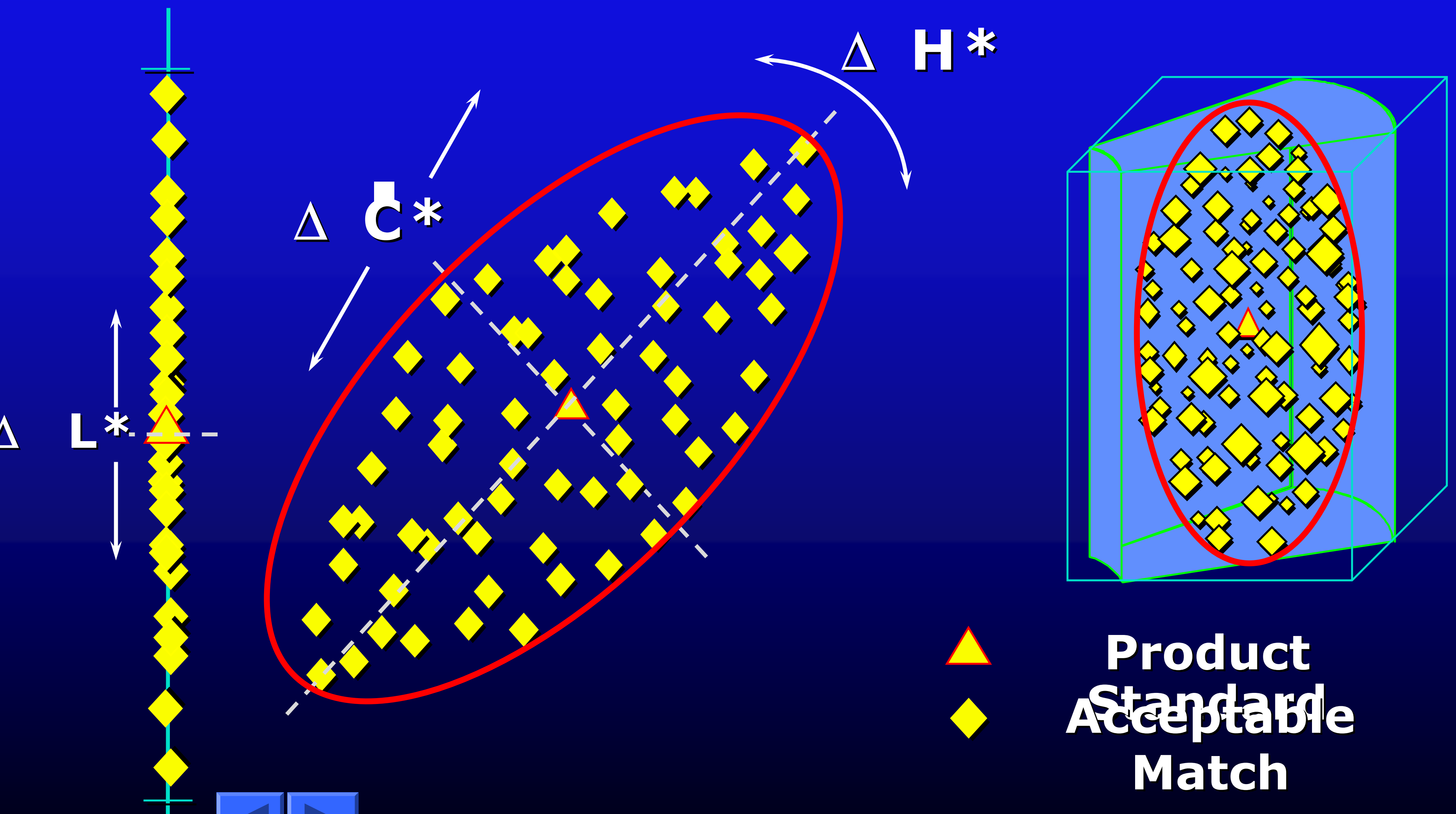
Polar Δ L *, Δ C *, Δ H* Color Space



Elliptical ΔE cmc Color Space

- Delta Ecmc is a single number measurement that defines an elliptical color difference space around the product standard.

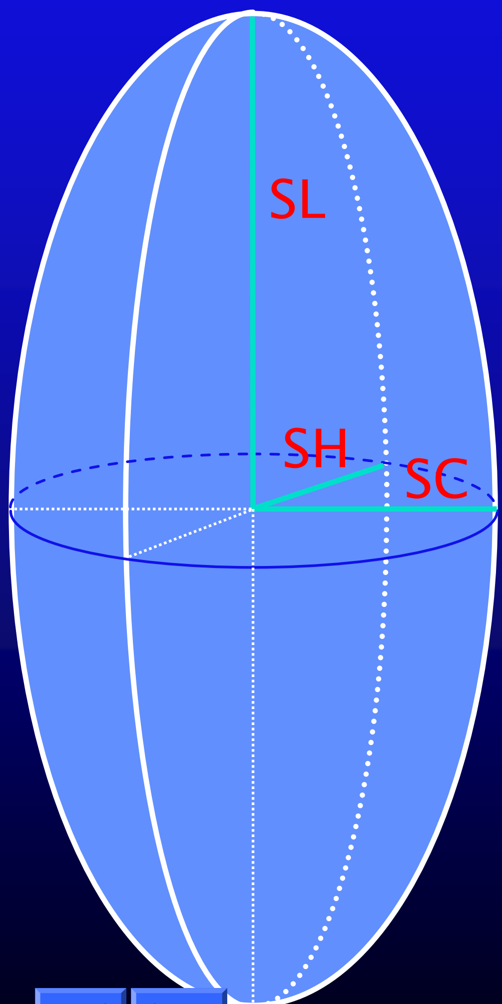
Elliptical ΔE cmc Color Space



Elliptical Δ E cmc Color Space

- Delta Ecmc is a single number PASS/FAIL measurement that defines a 3-dimensional tolerancing space. An ellipsoid is centered around the product standard. The shape of the ellipsoid can be adjusted to industry parameters by adjusting the lightness-to-chroma (l:c) ratio. A ratio of 1:1 would be shaped like a round ball. A ratio of 3:1 would be an elongated sphere. Typically an l:c ratio of 2:1 is a good starting point. The size of the ellipsoid can be adjusted to the maximum acceptable limit by adjusting the commercial factor (cf). A cf of 1 is a good starting point.

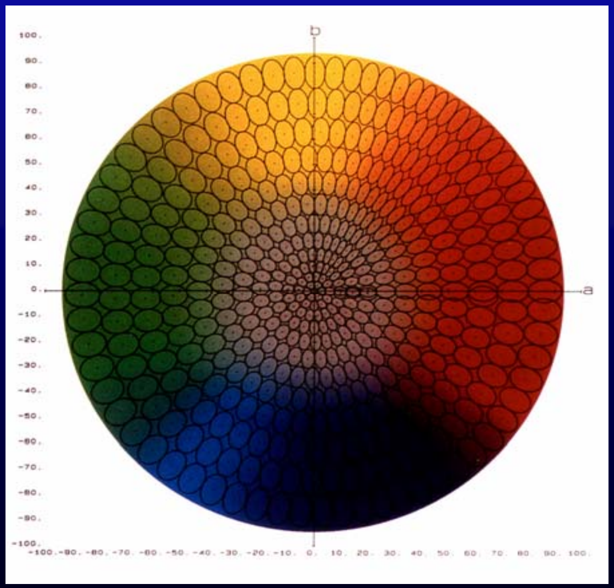
ΔE cmc Color Difference Equation



$$\Delta E_{cmc} = cf \sqrt{\left(\frac{\Delta L^*}{l\,SL}\right)^2 + \left(\frac{\Delta C^*}{c\,SC}\right)^2 + \left(\frac{\Delta H^*}{SH}\right)^2}$$

Where:

cf = commercial factor
l:c = lightness to chroma ratio

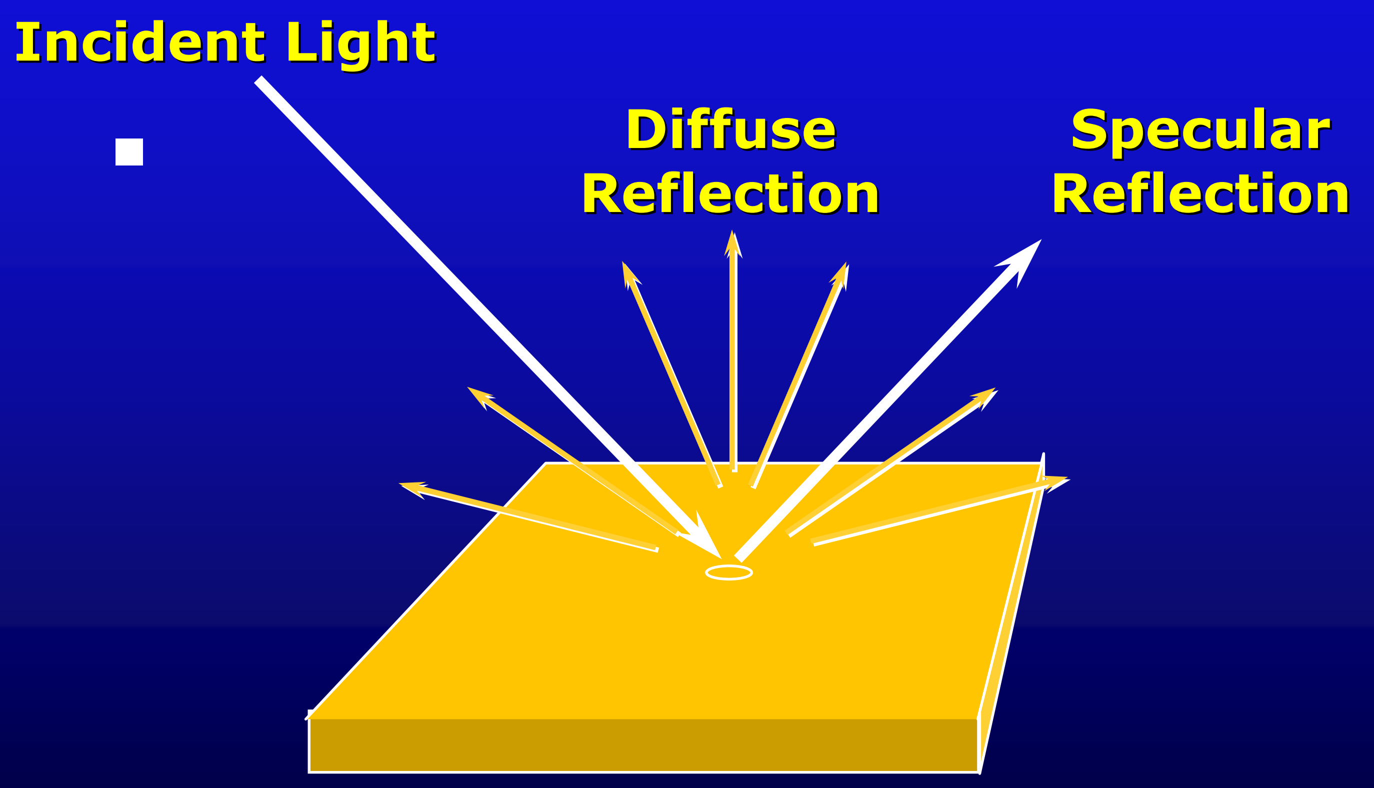


Surface Characteristics and Geometry

Reflectance of Light

- For opaque materials most of the incident light is reflected. Color is seen in the diffuse reflection and gloss is seen in the specular reflection. The reflection at the specular angle is generally the greatest amount of light reflected at any single angle. However specular reflection only represents less than 4% of the total reflected light. The remaining reflection is in the diffuse reflection.

Reflectance of Light



Effect of Surface Characteristic on Perceived Color

- When you look at samples that are exactly the same color, but have different surface characteristics, the apparent color you perceive is different for each. Glossy surfaces appear darker and more chromatic. Matte and textured surfaces appear lighter and less chromatic.

Effect of Surface Characteristic on Perceived Color

Glossy

Matte

Textured

Effect of Surface Characteristic on Perceived Color

- The effect of increased surface roughness is the dilution of the pigment color so that it appears lighter and less saturated. This is caused by the dilution of the diffuse reflectance (where we see pigment color) by the increased scatter of the specular reflectance (white). The rougher the surface, the greater the scatter of the specular reflectance.

Light Distribution From Different Surfaces

Instrument Geometry

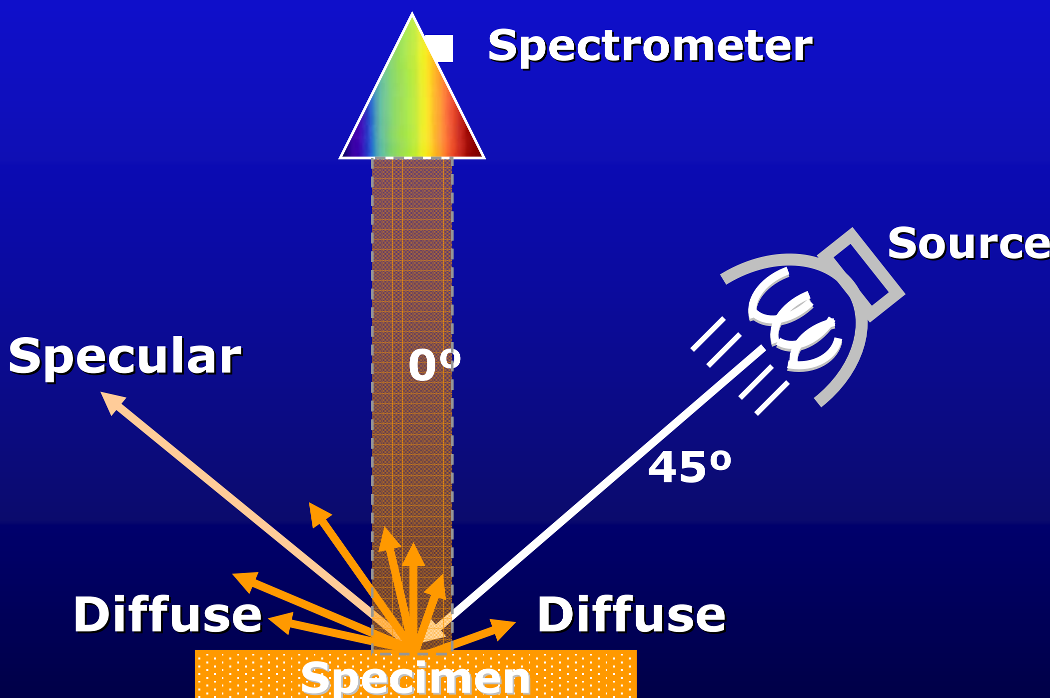
- The geometry of an instrument defines the arrangement of light source, sample plane and detector. There are two general categories of instrument geometries, **directional** (45°/0° or 0°/45°) and **diffuse** (sphere).

Directional Geometry

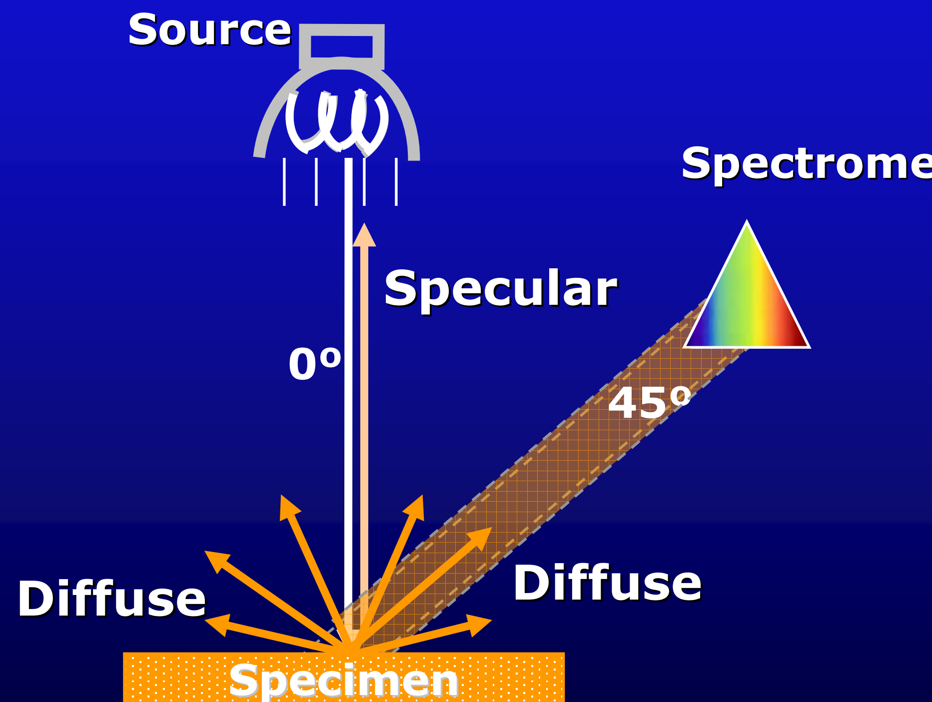
- Directional geometry typically has illumination at a 45° angle and a measurement angle of 0°. This is called **45°/0°** geometry. **0°/45°** geometry has illumination at 0° and measurement at 45°. Both **exclude** the specular reflection in the measurement (specular excluded). This provides measurements that correspond to visual changes in appearance of the sample due to both changes in pigment color and surface gloss or texture.

45°/0° and 0°/45° Specular Excluded Geometry

45º Illumination/0º Measure



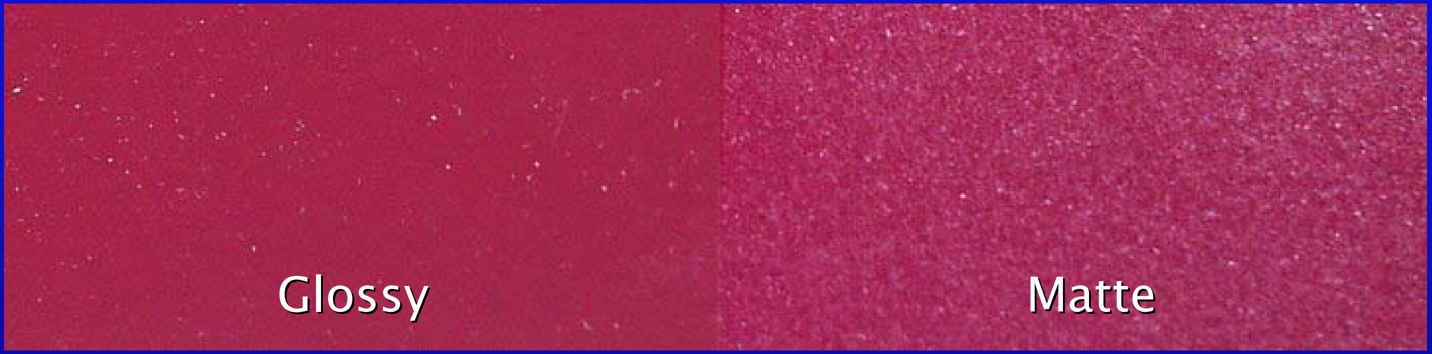
0º Illumination/45º Measure



Gloss Effect on Color Difference Measurement

- On the following slide the paint on the card is the same color across the entire card. The right side has a matte surface finish (read as the Sample) and the left side has high gloss (read as the Standard). Note that the color difference measurement made using a 0°/45° geometry (specular excluded) instrument indicates a color difference that agrees with what you see (the matte side is lighter and less red). That is because it is measuring both the effect of the pigment and the effect of the surface finish. 0°/45° instrument geometry is excellent for the quality control applications where agreement to what you see is important.

Gloss Effect on Color Difference Measurement



<u>0º/45º Geometry</u>

	ΔL^*	Δa^*	Δb^*
Specular Excluded	**1.4**	**-1.5**	**-1.2**

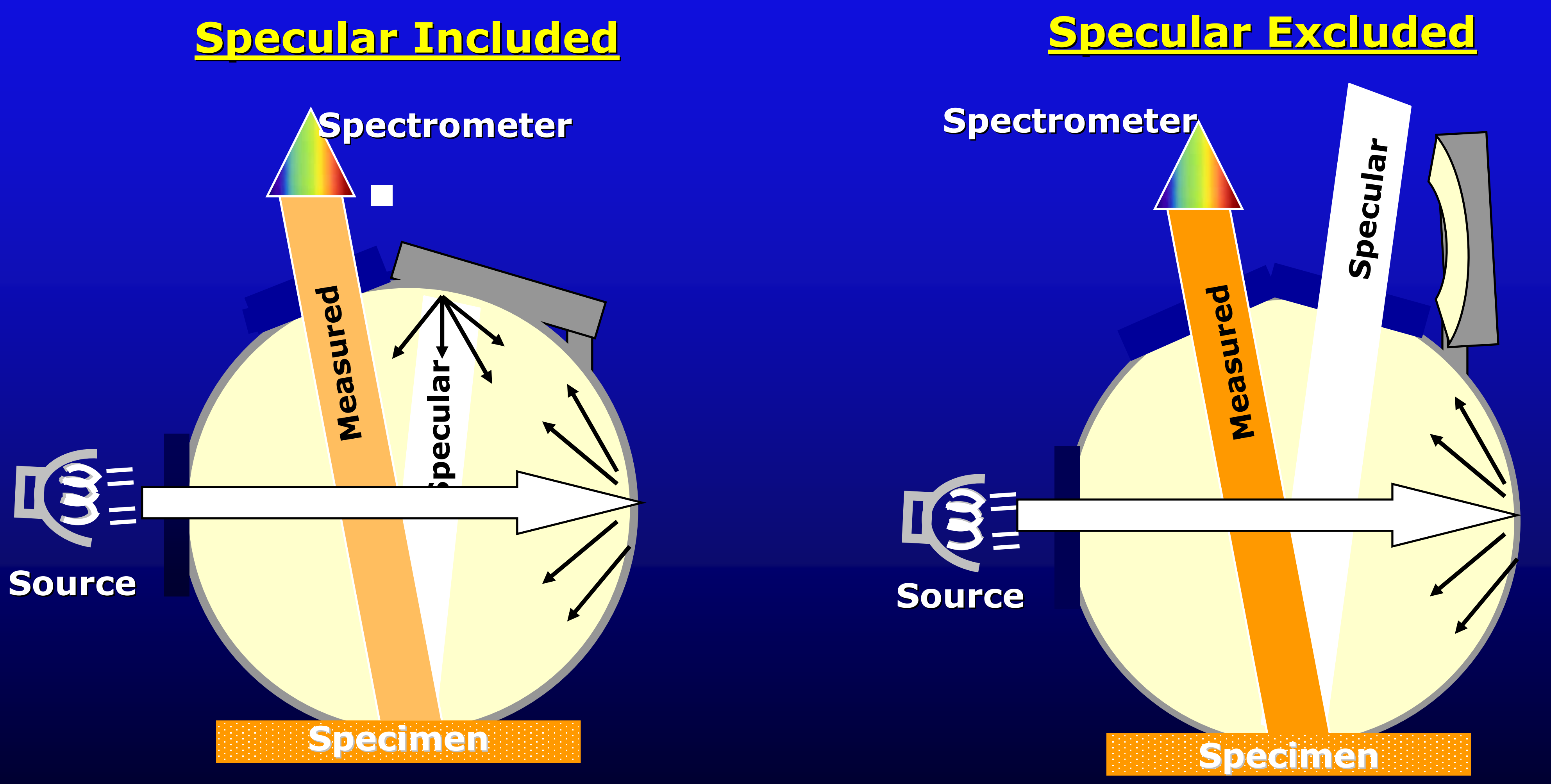
A 0°/45° Geometry Spectrophotometer

▪

Diffuse Geometry

- Diffuse (**sphere**) geometry instruments typically use a white coated sphere to diffusely illuminate the sample. The measurement is at an 8 º angle (**d/8 º**). Normally the specular reflection is **included** in the measurement. This negates differences due to surface differences and provides measurements that correspond to changes due only to pigment color. Sphere instruments also have the ability to exclude specular reflection, however they are not efficient at doing this.

Sphere Geometry d/8°



Gloss Effect on Color Difference Measurement

- On the next slide we see the same card that was previously measured, however this time the measurements are made using a d/8° sphere instrument. As you can see the specular included difference reading of the sphere instrument indicates no color difference. It sees only the effect of the pigment and not the surface gloss. This is useful for some color formulation applications.
- The sphere instrument can also measure the card in a specular excluded mode. For this flat, smooth, uniform card the readings are similar to those of the 0 °/45 ° instrument.

Gloss Effect on Color Difference Measurement

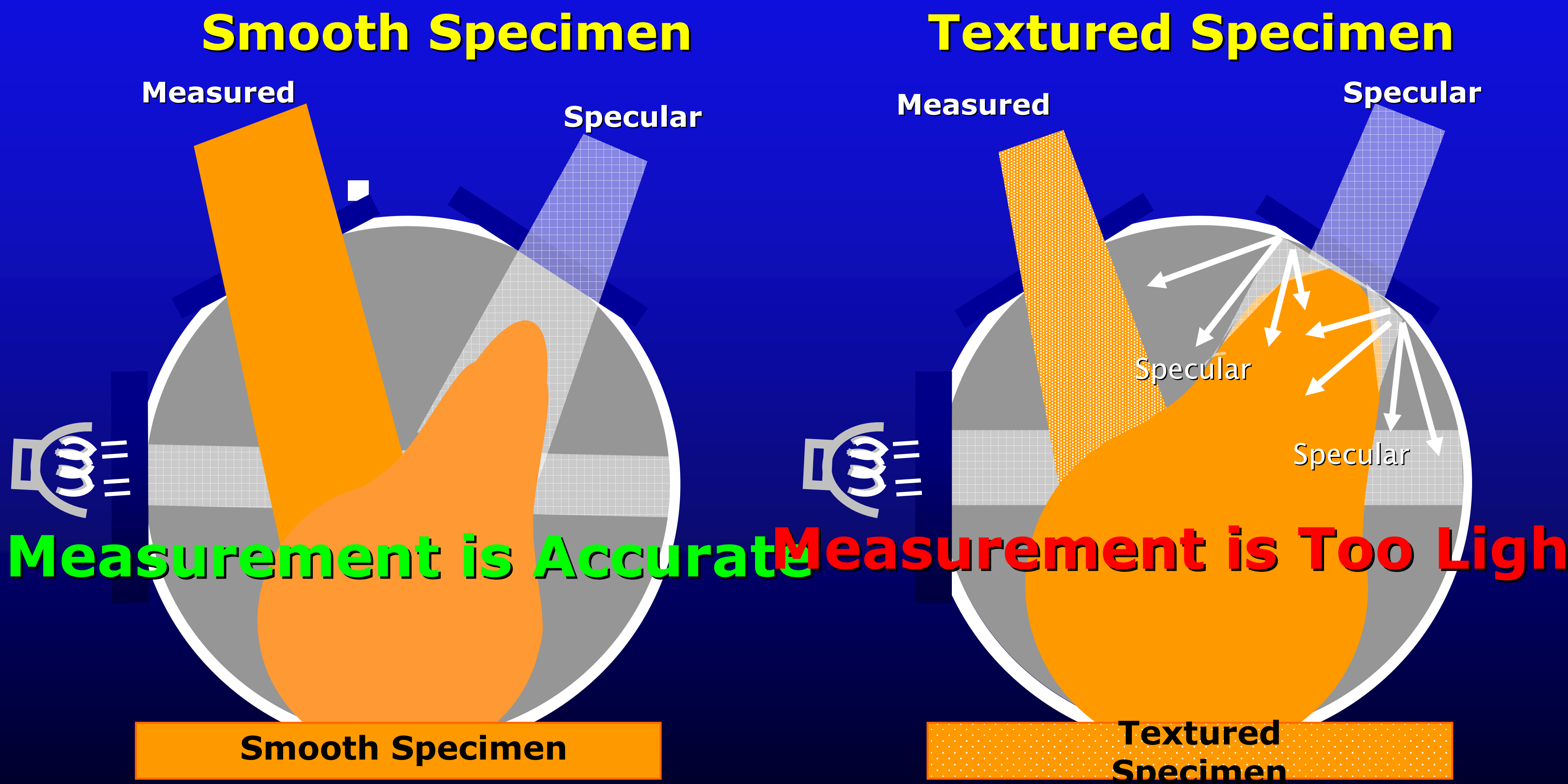
Sphere Geometry

	ΔL^*	Δa^*	Δb^*
Specular Included	0.0	0.1	-0.0
Specular Excluded	1.8	-1.6	0.9

Sphere Geometry Specular Exclusion

- A sphere instrument is excellent when specular included measurements are desired. However, because a sphere instrument is not efficient at excluding specular, measurements made in the specular excluded mode are frequently inaccurate. This is because any sample curvature or texture will cause the specular light to strike inside the sphere's specular exclusion port and some (often inconsistent) specular light to be erroneously included in the measurement.

Sphere Geometry Specular Exclusion



Texture Effect on Color Difference Measurement

- The following example is of two plastic sheets again with the only difference being the surface finish. Both are textured to some degree, one more than the other. Note that for the sphere geometry, specular included readings indicate virtually no color difference (as it should). However the sphere geometry color difference readings in the specular excluded mode are much lower than they should be. This is because, both the Light Texture reading and the Heavy Texture readings were higher than they should be, by differing amounts, thus the difference is reported to be <u>smaller</u> than it actually is.
- The 0 °/45 ° geometry instrument readings were much more accurate and agree well with visual assessment.

Texture Effect on Color Difference Measurement

Sphere Geometry

	ΔL^*	Δa^*	Δb^*
Specular Included	**0.1**	**-0.1**	**0.1**
Specular Excluded	**2.0**	**0.5**	**1.0**

0º/45º Geometry

	ΔL^*	Δa^*	Δb^*
Specular Excluded	**5.2**	**1.8**	**2.5**

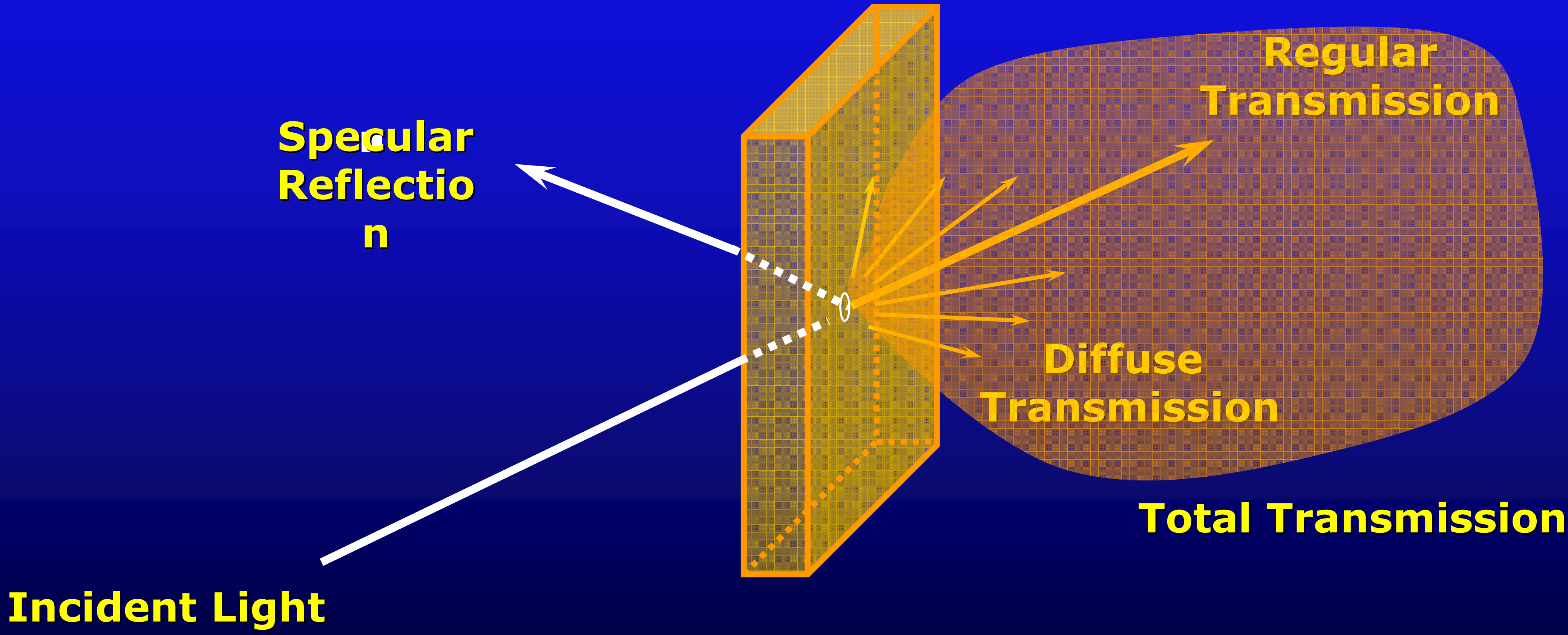
Sphere Geometry

Sphere Geometry Instruments Also Have the Ability To Measure The Color of Transmitted Light

Transmission of Light

- Transparent materials can be solids or liquids. The gloss is seen as specular reflection. Color is seen primarily in the **regular transmission** that transmits straight through the material. Surface texture or internal scattering within the material can cause the light to scatter or diffuse. This **diffuse transmission** also contains color of the material and is responsible for haze. **Total transmission** is a combination of regular plus diffuse transmission.

Transmission of Light



A Sphere Geometry Spectrophotometer

ColorQuest XE

Sample Preparation and Presentation

Ideal Sample For Color Measurement

- Flat
- Smooth
- Uniform
- Non-directional
- Opaque or transparent

Sample Preparation and Presentation

- Choose samples that are representative of the product.
- Prepare the sample in a way to best approximate the ideal sample characteristics.
- Prepare samples in the same way each time.
- Present the samples to the instrument in a repeatable manner.
- Make multiple preparations of the sample and average measurements.

Some Examples of Preparation and Presentation

Thank You For Your Attention

If you are connected to the internet click

For more information about sample preparation and presentation

For product information

OR

Contact us at 703-471-6870,

info@hunterlab.com, or visit our website at

www.hunterlab.com