Life of a Color – The Management of a Color

Max Derhak (PhD)

Principal Scientist – ONYX Graphics Inc.

Co-Chair – International Color Consortium (ICC)

What is Color Management?

- **Color Management is related to asking and answering various questions about color**
  - What is it?
  - How is it formulated, controlled, or made?
  - What does it look like?
  - How does it relate to or interact with light?

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  - —Formulating the questions
  - —Finding and providing the answers
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- **Systems for Color Management define how these key components are implemented**

Example: Basic Color Reproduction

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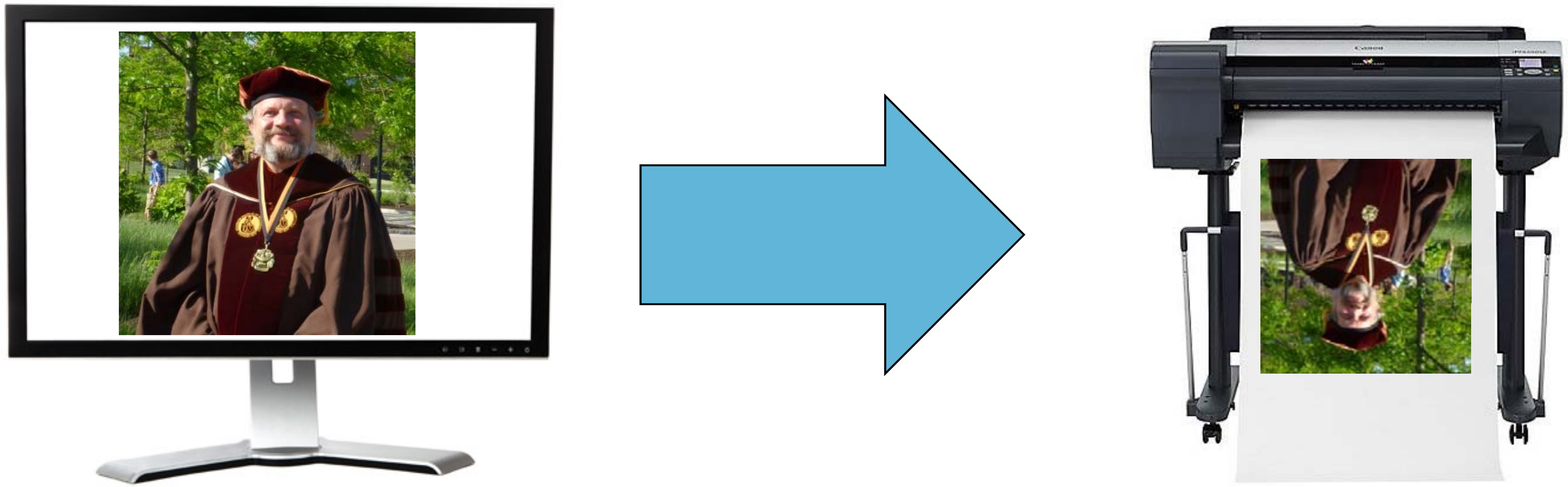

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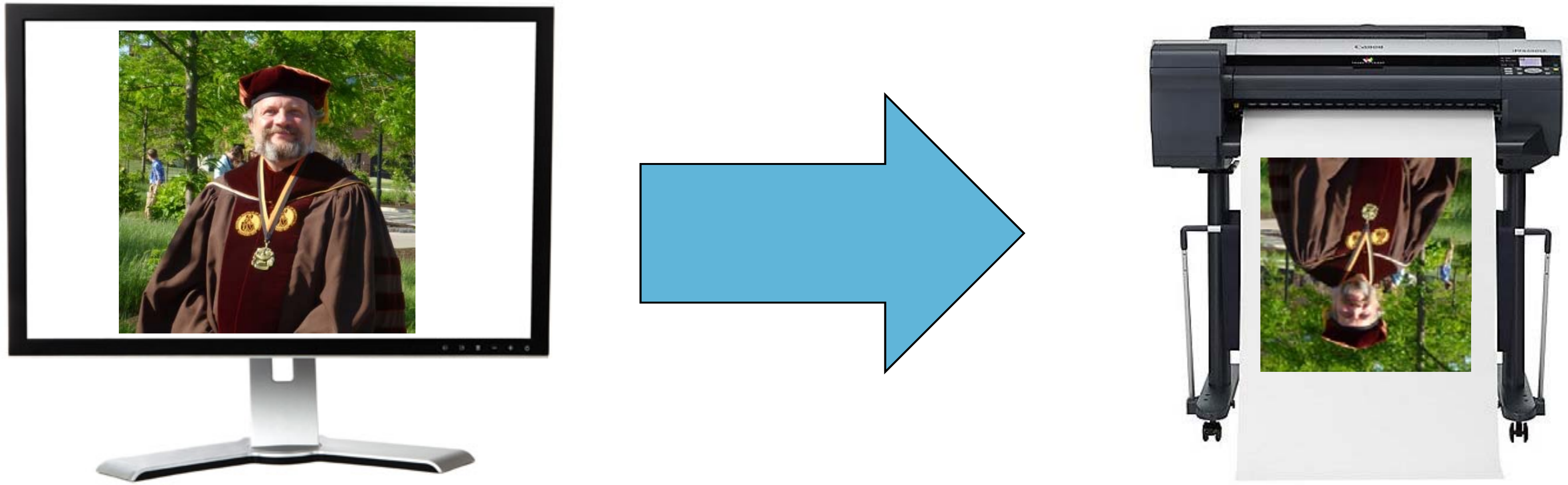

Questions:

- **How much ink is needed to match pixels on screen?**

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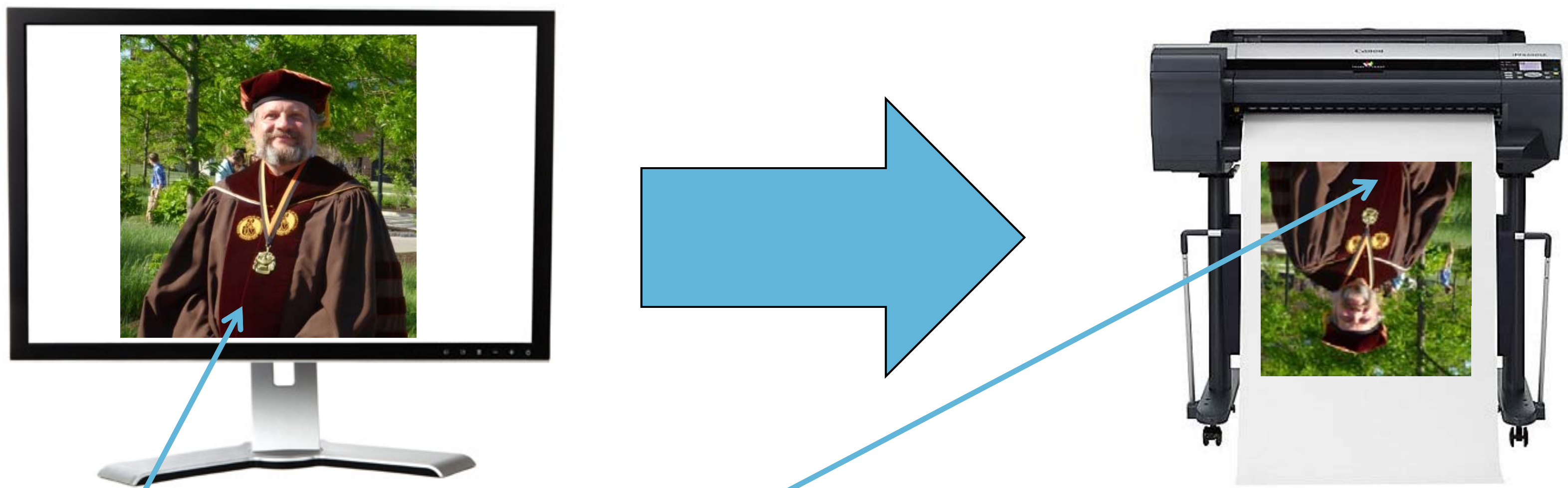

Questions:

- **How much ink is needed to match pixels on screen?**

or

- **What does this (RGB) pixel "look" like?**
- **How much (CMYK) ink is needed to get the same "look"?**

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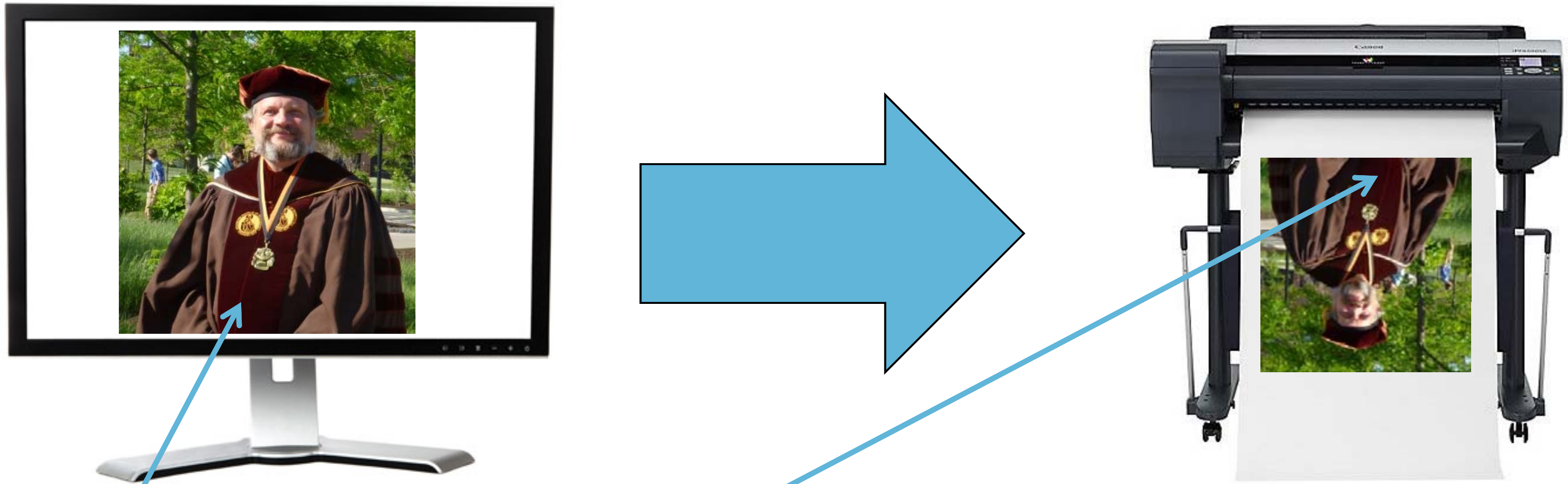

Questions:

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Color Perception

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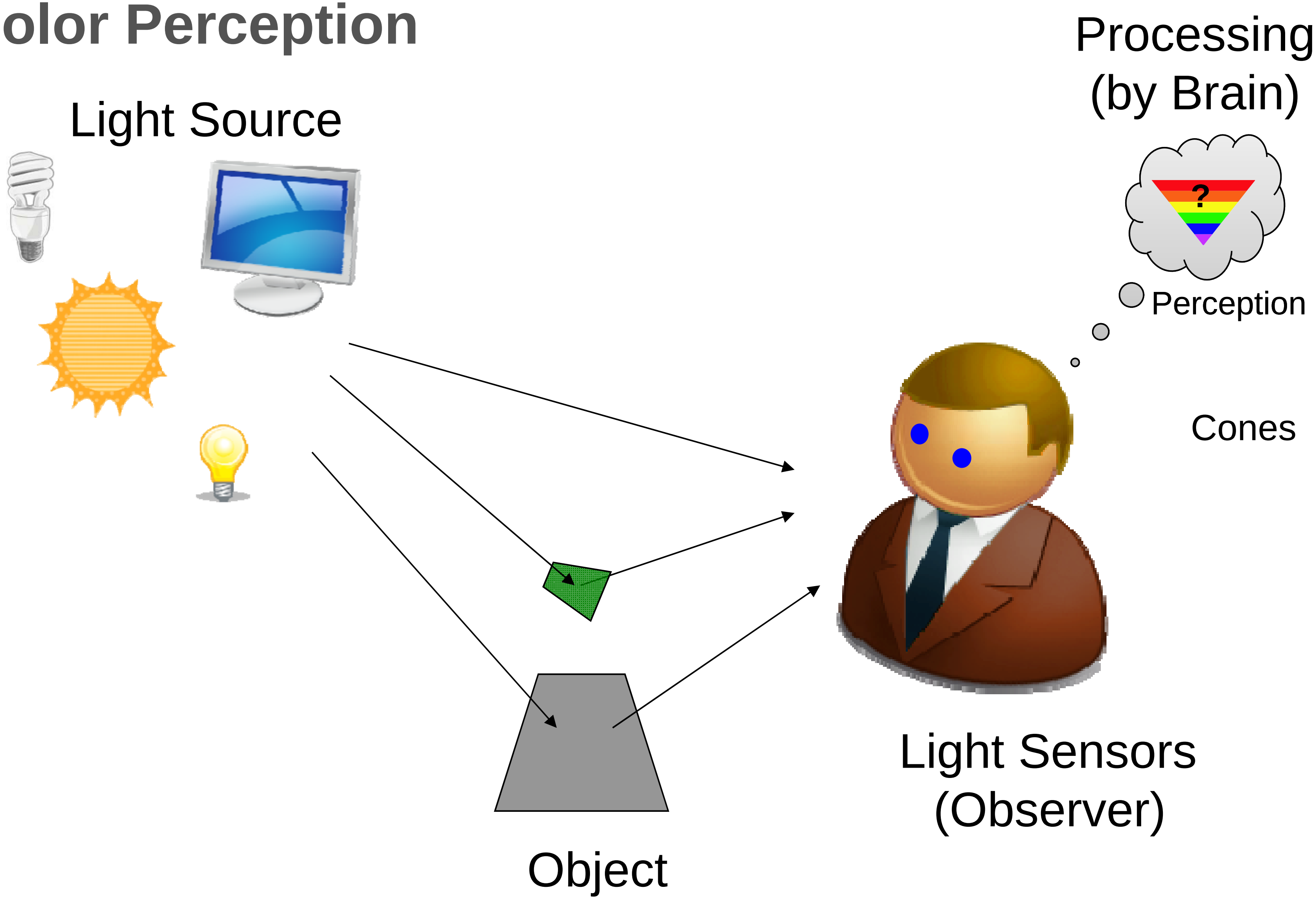
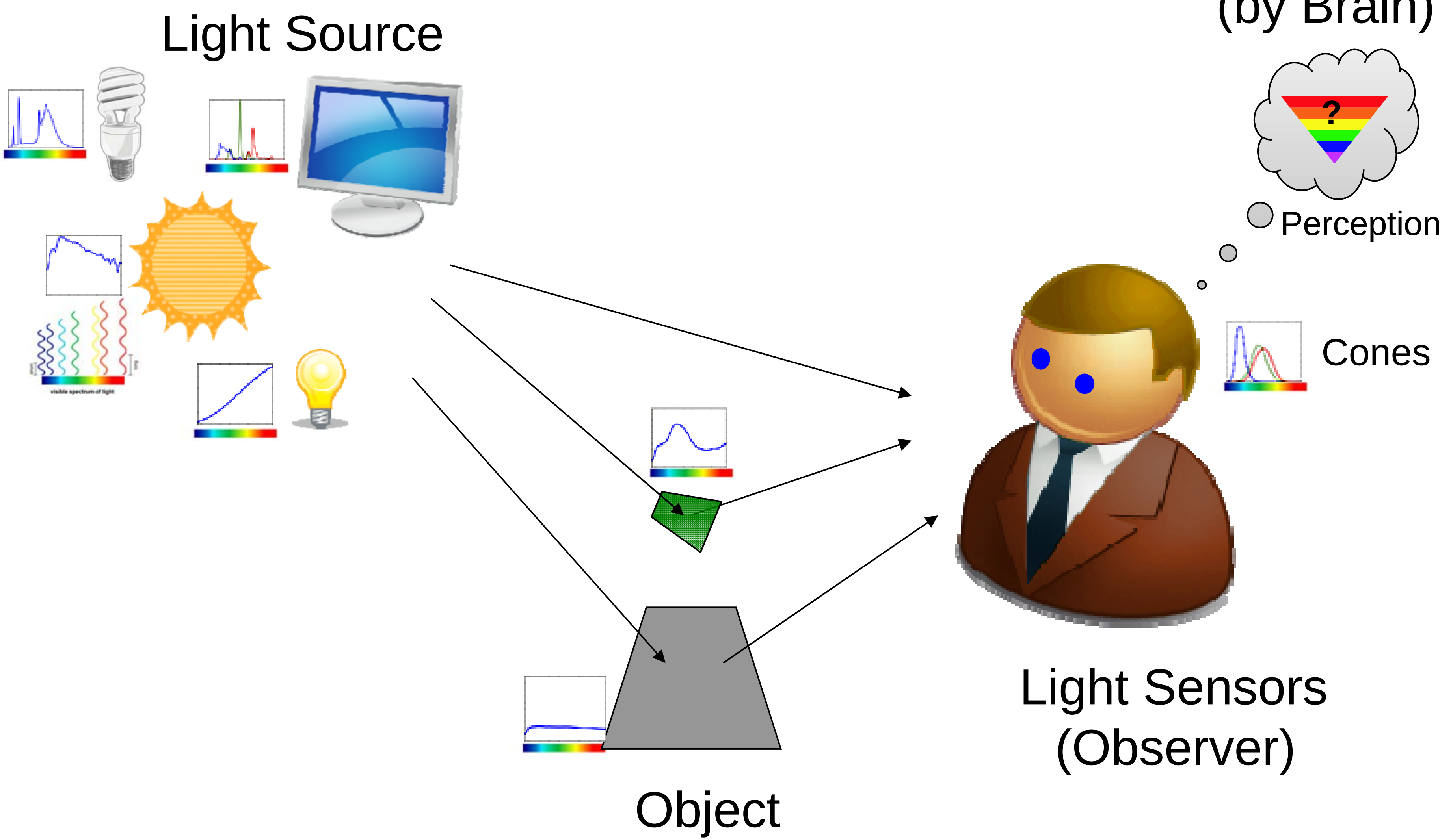
Color Perception



Spectral Aspects of Color Perception



Quantifying Perception (Color Matching)

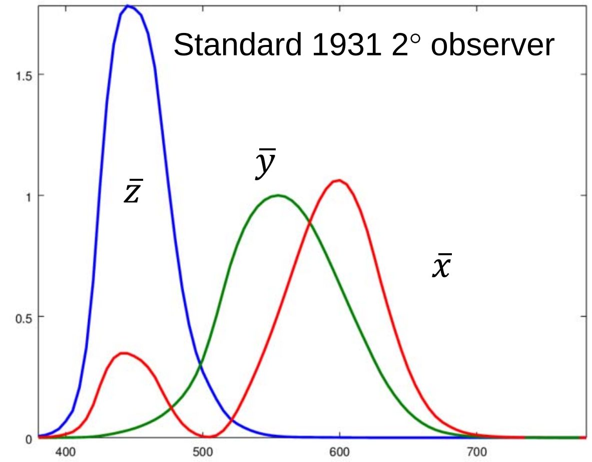
Color matching functions are used to define XYZ (Tristimulus) values

Two colors "match" if XYZ values are the same

$$X = 100\frac{\int s(\lambda)\cdot r(\lambda)\cdot \bar{x}(\lambda)d\lambda}{\int s(\lambda)\cdot \bar{y}(\lambda)d\lambda}$$

$$Y = 100\frac{\int s(\lambda)\cdot r(\lambda)\cdot \bar{y}(\lambda)d\lambda}{\int s(\lambda)\cdot \bar{y}(\lambda)d\lambda}$$

$$Z = 100\frac{\int s(\lambda)\cdot r(\lambda)\cdot \bar{z}(\lambda)d\lambda}{\int s(\lambda)\cdot \bar{y}(\lambda)d\lambda}$$



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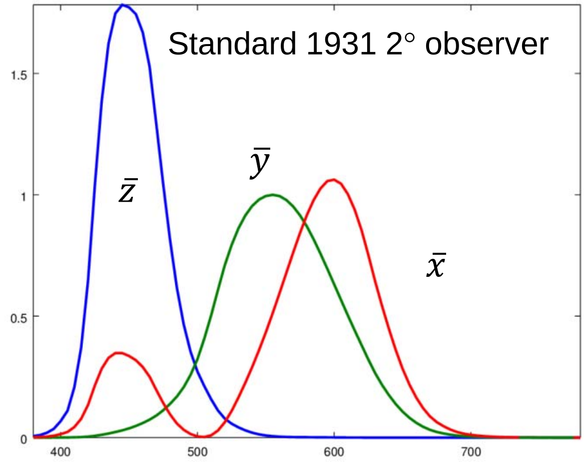
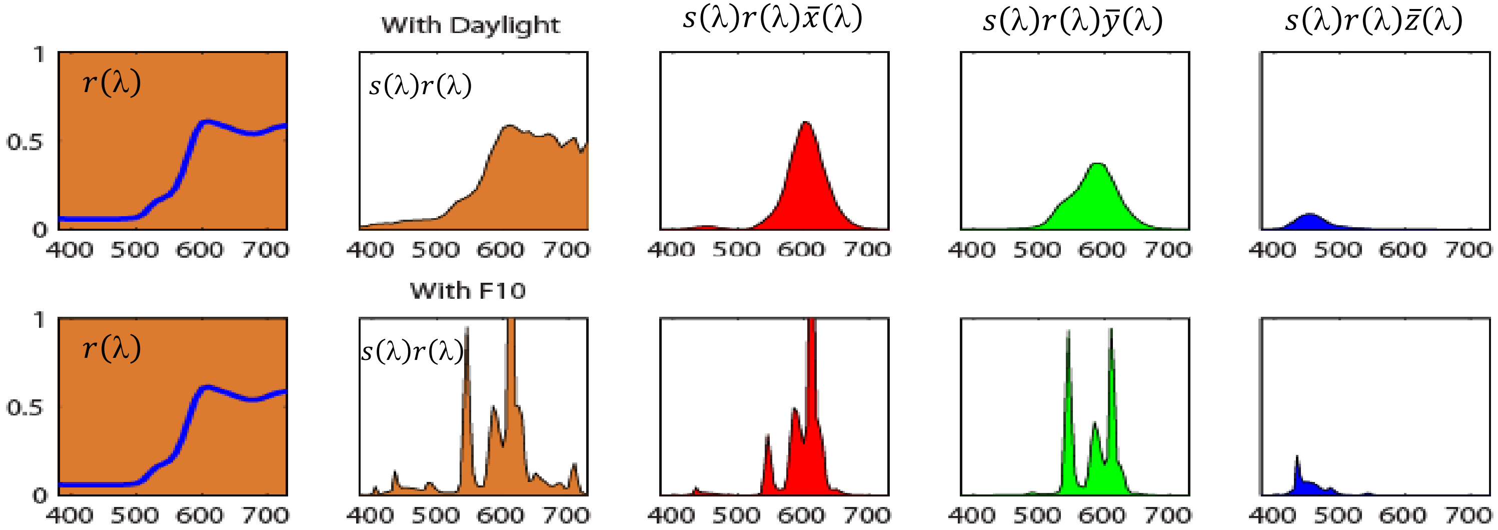




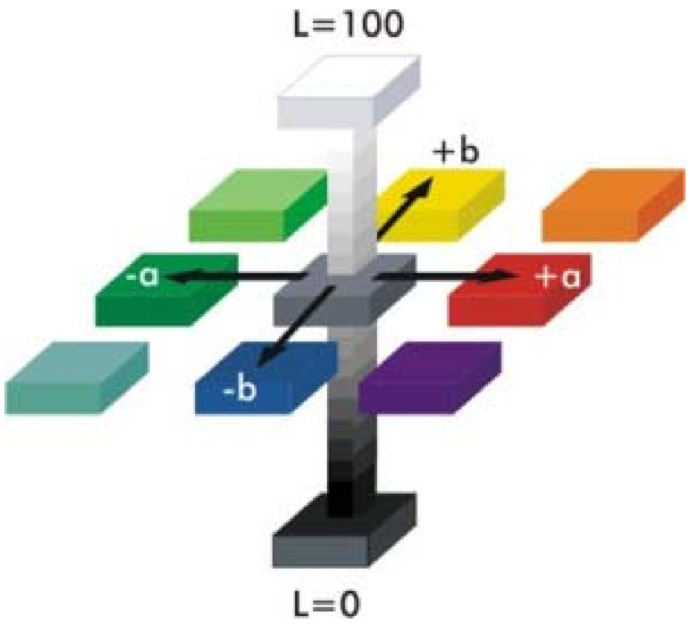
X=40.44
Y=31.06
Z= 4.97

X=39.66
Y=30.88
Z= 4.88

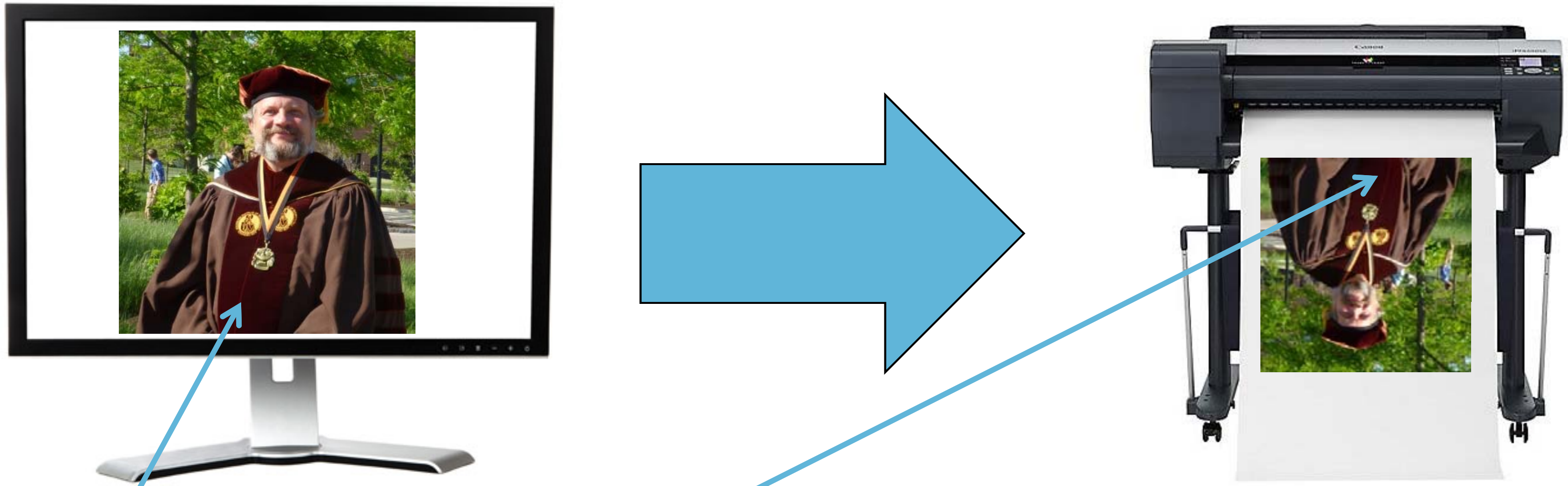
The CIELAB Color Space

$$L^* = 116\ f(Y / Y_n) - 16$$
$$a^* = 500\ [f(X / X_n) - f(Y / Y_n)]$$
$$b^* = 200\ [f(Y / Y_n) - f(Z / Z_n)]$$
$$where\ :$$
$$f(t) = \begin{cases} t^{1/3} & \text{when} \quad t > \left(6/29\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$

- **Distances between XYZ colors are not perceptually uniform**
- **The CIELAB color space is a more uniform 3-dimensional color space:**
  - CIELAB is defined in terms of XYZ
  - The L* dimension represents lightness
  - The a* axis transitions from green (-a*) to red (+a*) extremes
  - The b* axis transitions from blue (-b*) to yellow (+b*) extremes
  - Combinations of a* and b* define intermediate colors
  - Neutral (grayscale) colors are described when a* and b* are both zero
  - *CIELAB values are relative to the illuminant*
    - *L*=100, a*=0, b*=0 is white regardless of illuminant*



Restating the color management questions



Questions:

- **How much ink is needed to match pixels on screen?**

or

- **What XYZ/L*a*b* value does this (RGB) pixel have?**
- **How much (CMYK) ink is needed to get the same XYZ/L*a*b* value?**

ICC Profile Specification

- **ISO 15076-1:**
  - —v4 ICC profile
  - —Defines standard container for specifying color management interchange
  - —Widely used around the world
  - —Predominant in graphic arts workflows.
  - —Widespread adoption in commercial and academic software.
  - —First published as ISO standard in 2005.
  - —Very successful at spreading color management to many parts of the world.

Color Management with ICC profiles

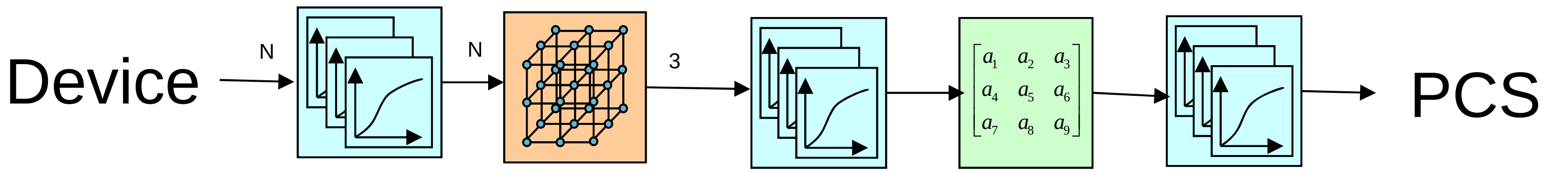
- **Color Management questions are answered by having a Color Management Module (CMM) apply transform tags from profile files as follows:**

1. **Input profile converts from RGB to XYZ**
   - What XYZ/L*a*b* value does this (RGB) pixel have?
2. **The CMM converts from XYZ to L*a*b***
   - Profile Connection Space (PCS) conversion
3. **Output profile converts from L*a*b* to CMYK**
   - How much (CMYK) ink is needed to get the same XYZ/L*a*b* value?

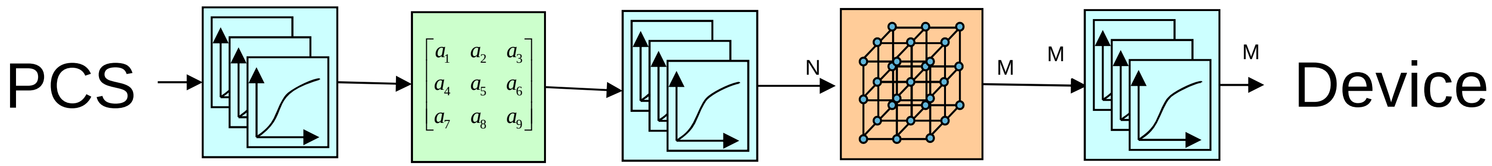
- **Rendering intents use different transform tags in ICC profiles**

v4 ICC transforms have a fixed order

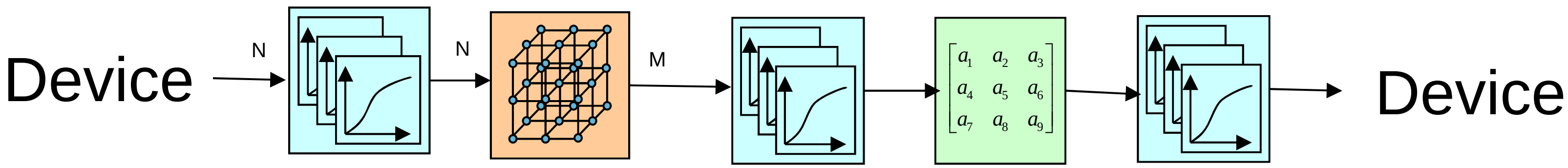
- **Input Profiles**



- **Output Profiles**



- **Device Link Profiles**



Note: In each case steps may be excluded

Limitations of ICC v4 profiles

- **Limited ability to answer "What does it look like?"**
  - Profile Connection Spaces are defined in terms of a single light source and observer
    - D50 illuminant for 1931 2° standard observer
  - Cannot describe how color changes due to lighting or viewing angles
    - Diffuse uniform illumination assumption
- **Limited ability to answer "What is it?"**
  - Structure of ICC v4 unsuitable for some lightweight workflows
- **Limited ability to define transforms**
  - Fixed order and limited set of transform elements
  - Simple transforms are effectively limited to low dimensionality
- **Unable to answer "How does it relate to or interact with light?"**

ICC v4 can be too restricted

- **Example: package print, process + spot colors, with gloss and metallic inks**
  - —V4 LUT structure not practical beyond 6-7 colors (profiles too large, too slow…)
  - —Spot color inks often defined spectrally, but no support for spectral data
  - —Cannot define directional appearance of ink in profile
  - —Cannot preview appearance of package on display or proof
  - —Cannot predict under different observer/viewing conditions

Introducing iccMAX

- **iccMAX is the result of nearly ten years work by the Architecture Working Group (AWG) of the ICC**
- **Aspects (guiding principles) of this work include:**
  - —Understanding various color management workflows not addressed or difficult to implement using ICC version 2 and 4 profiles
  - —Desire to provide open, cross platform, vendor neutral solutions
  - —Desire to open ICC color management to new industries
  - —Define specification document(s)
  - —Provide a reference implementation

iccMAX

ICC v4

- **Like a basic LEGO™ set, the ICC v2/v4 specifications provide basic building blocks for defining and implementing color management workflows**

ICC v4

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iccMAX

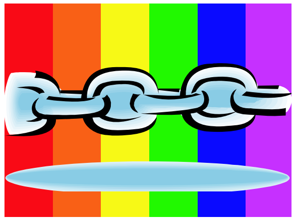
- iccMAX provides additional building blocks and capabilities to ask and answer more complex questions related to color management
- All while maintaining backwards compatibility with v2/v4

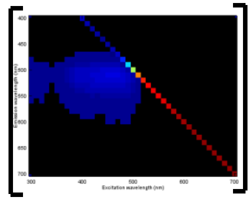
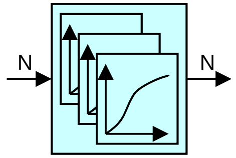
Defining color workflows with iccMAX

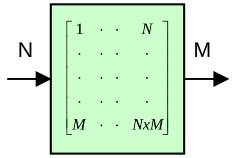
- **iccMAX provides a platform for defining specific color management workflows**
- **Each specific color workflow is defined using a subset of iccMAX as an Interoperability Conformance Specification (ICS) document**
- **An ICS is like defining a smaller kit built from the master set of building blocks**
  - Only those things needed from iccMAX are used
- **Products can choose which ICS workflows they support**
- **This allows for extensibility of iccMAX as new workflows can be defined (adding new blocks) without requiring existing ICSs (and products based on those ICSs) to change**

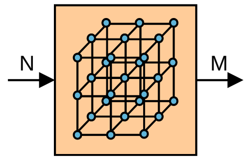
iccMAX Building Block Overview

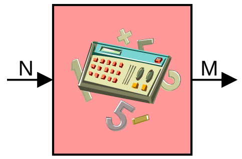
- **<u>Color Space Extensions</u>**
  - Spectral connection spaces
  - Profile Connection Condition (PCC) tags
  - PCS Transforms
  - Sparse matrix encoding
  - Material Connection Spaces
  - Increased number of Device Channels
- **<u>multiProcessingElements</u>**
  - 1-D Look Up Tables (LUTs)
  - Arbitrary sized matrices
  - N-dimensional LUTs
  - Calculator element
  - ICC Color Appearance Model element
  - Tint Array element
- **<u>Hierarchical tag types</u>**
  - Named Color Tag Array
  - Support for angular dependencies via Bidirectional Reflectance Distribution Functions (BRDF)
  - Profile Sequence Information
- **<u>Other Extensions</u>**
  - Color Space Encoding profiles
  - Gamut Boundary Description encoding
  - Color Measurement (CxF) tag encoding
  - UTF8 text & UTF16 encoding
  - Additional Numeric Array Types

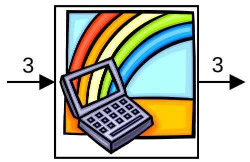


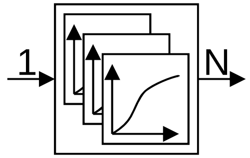



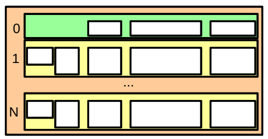


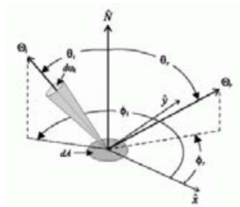
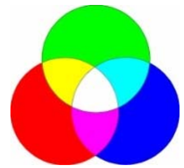
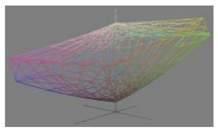










CxF

Two iccMAX Representations

- **Binary**
  - iccMAX specification extends on ICC v4 header and tag structures with additional tags and tag types
  - *Provides a compact format for embedding and communicating about color*
- **XML**
  - Reference implementation (RefIccMAX) provides tools to convert between binary and XML representations
  - *Human readable and modifiable*
  - *Complex tools not always required to create iccMAX profiles*

Questions answerable using iccMAX

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- What XYZ/L*a*b* value for a particular observer under a particular illuminant does this pixel value have?
- What device values are needed to get a XYZ/L*a*b* value for a particular observer under a particular illuminant?

- What is the XYZ/L*a*b* value for an RGB pixel that has a specified color encoding space?

- How do I convert XYZ/L*a*b* values for one observer and illuminant to XYZ/L*a*b* values for a different observer and/or illuminant?

- How is light absorbed / reflected / transmitted by a surface with specific device values?
- What device values are needed to get light absorbed / reflected / transmitted in a specific way?
- How do XYZ/L*a*b* values change as the observer and/or illuminant change?

More questions answerable using iccMAX

- How do you manipulate spectral reflectance?
- What is the perceived XYZ/L*a*b value of a printed color on a substrate with optical brighteners or printed using fluorescent ink?
- How do you handle lots of device channels?
- How does reflected light change as light angle and viewing angle change?
- What is the spectrum of light coming off a monitor?
- How does light from a monitor change due to viewing angle?
- How is light reflected by a tint of a named color?
- What is the probability that a pixel of a multi-spectral capture contains a specific material?

Q. What XYZ/L*a*b* value for a particular observer under a particular illuminant does this pixel value have?

Q. What device values are needed to get a XYZ/L*a*b* value for a particular observer under a particular illuminant?

- **iccMAX allows for color management to be defined in terms of arbitrary observers and illuminants**
  - Profiles define color matching functions of the observer, spectral power distribution of the illuminant, and transforms to convert to/from “standard” D50 illuminant with 2° observer

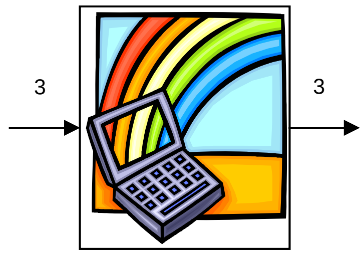
Q. What is the XYZ/L*a*b* value for an RGB pixel that has a specified color encoding space?

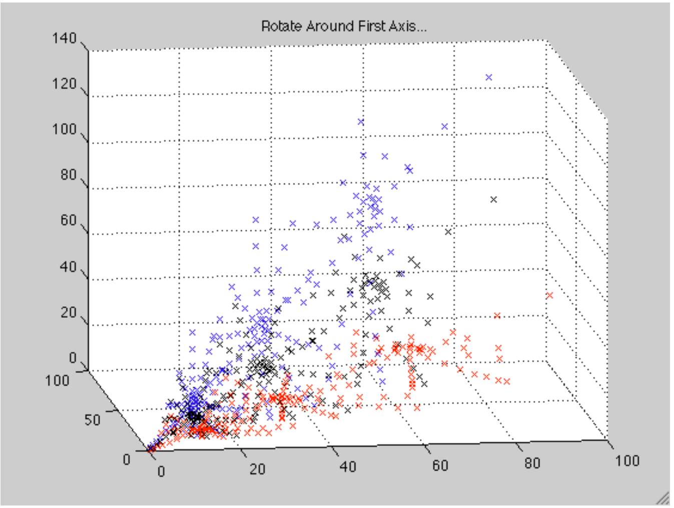
- Camera manufacturers have asked for simplified profiles that just specify the color encoding space of the pixels
- iccMAX color encoding space profiles only contain a rudimentary header and tag identifying the color encoding space
- The iccMAX CMM figures out what transform is appropriate to use and applies it

Q. How do I convert XYZ/L*a*b* values for one observer and illuminant to XYZ/L*a*b* values for a different observer and/or illuminant?

- **Profile Connection Conditions (PCC) tags in an iccMAX profile provide transforms for an iccMAX capable CMM to make conversions when needed**
- **PCC tags can be populated using:**
  - Either a Chromatic Adjustment Transform (CAT) or more advanced Color Appearance Model CAM to adjust for differences in illuminant
  - OR - A Material Adjustment Transform (MAT) is appropriate for differences in observer and/or illuminant
- **MATs are defined based on a color equivalency representation**
  - Defined by "Wpt Normalization" from Max Derhak's PhD dissertation

Color Appearance Model

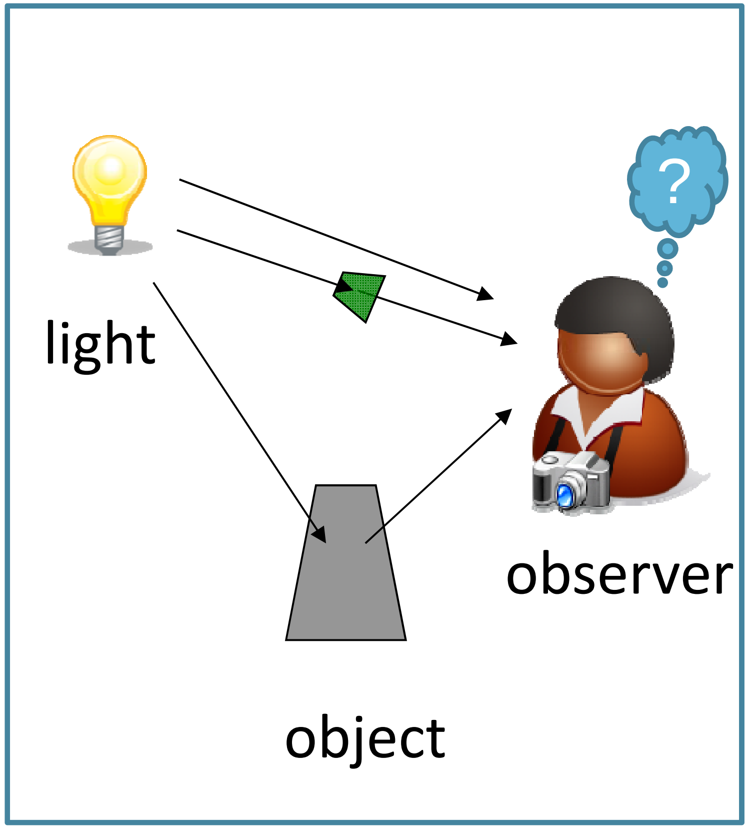




Wpt (Waypoint) Normalization

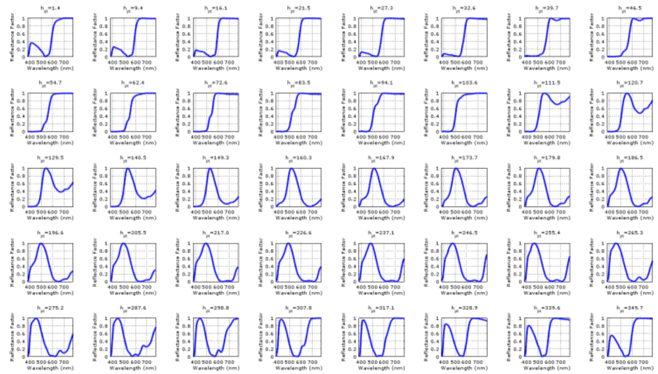
Q. How is light absorbed / reflected / transmitted by a surface with specific device values?
Q. What device values are needed to get light absorbed / reflected / transmitted in a specific way?
Q. How do XYZ/L*a*b* values change as the observer and/or illuminant change?

- **iccMAX profiles can be connected using spectrally based color spaces**
  - Reflectance, Transmittance, etc.
- **The iccMAX CMM applies observer and illuminant information as needed from Profile Connection Conditions (PCC) to determine XYZ/L*a*b* values**
- **This allows application of observing conditions to be deferred to time when profiles are applied**

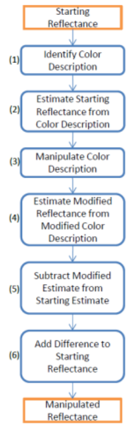


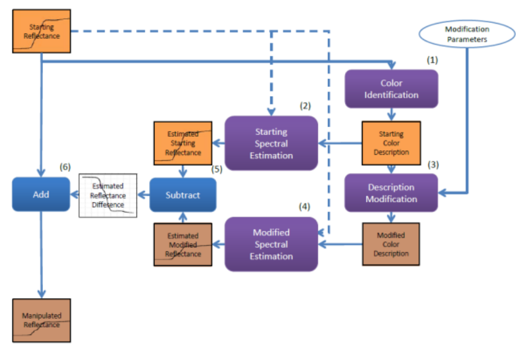
Q. How do you manipulate spectral reflectance?

- **Characteristic spectral reflectances can be associated on a hue by hue basis with polar “Wpt coordinates”**
  - See Max Derhak’s PhD dissertation
- **A simple (linear) method can then be applied to estimate and manipulate spectral reflectances**



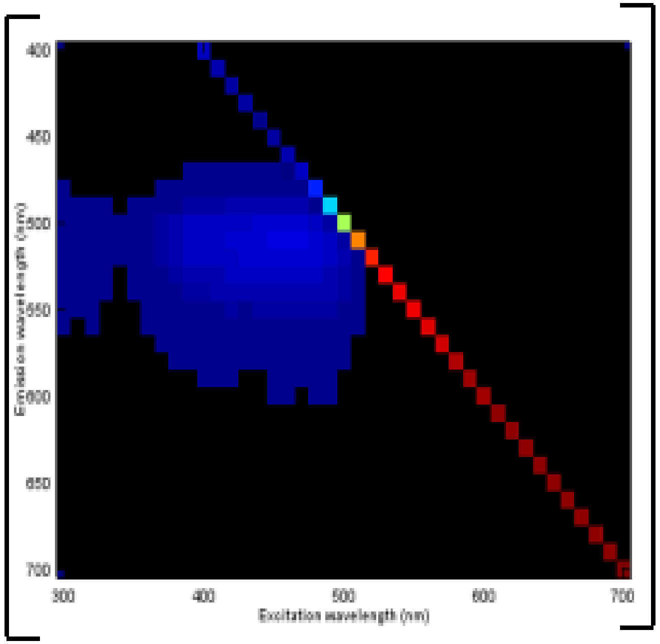
- **iccMAX profile creators can then incorporate these techniques to:**
  - Perform spectral gamut mapping
  - Perform spectral color rendering
  - Perform spectral adjustment in abstract profiles
  - Estimate spectral reflectance directly from sRGB





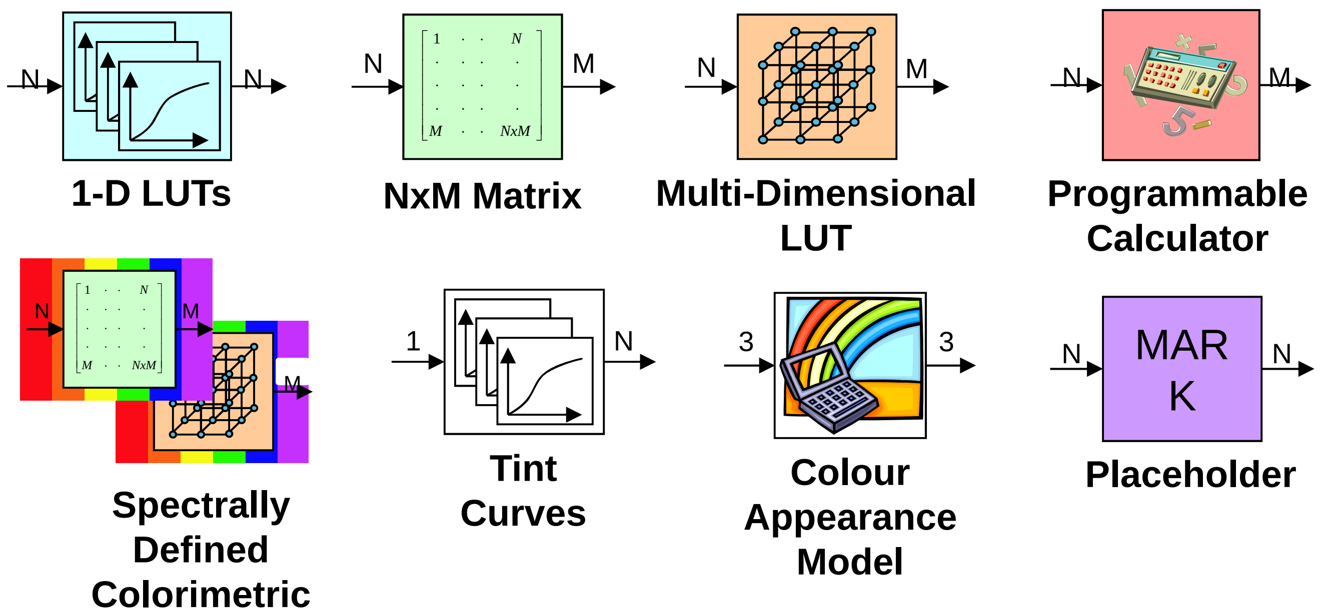
Q. How is reflected light affected by the use of a substrate with optical brighteners or printed using fluorescent inks?

- **Fluorescence occurs when the wavelengths of light are changed by a surface (rather than just being absorbed or reflected)**
- **Substrates with optical brighteners and fluorescent inks appear brighter as a result**
- **iccMAX provides support for modeling and characterizing these situations**



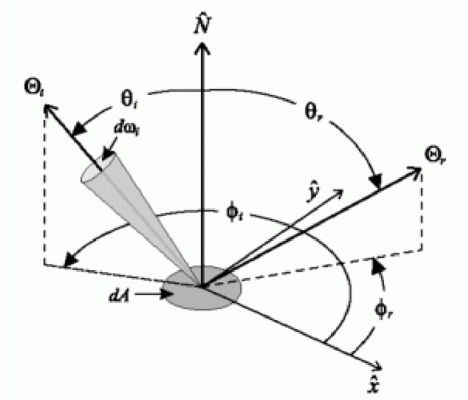
Q. How do you handle lots of device channels?

- **MultiProcesElements in an iccMAX profile allow for color transforms to be programmed**
  - Rather than be sampled in a multi-dimensional lookup table
- **iccMAX Profiles can be smaller and potentially more accurate**
  - Especially with lots of device channels



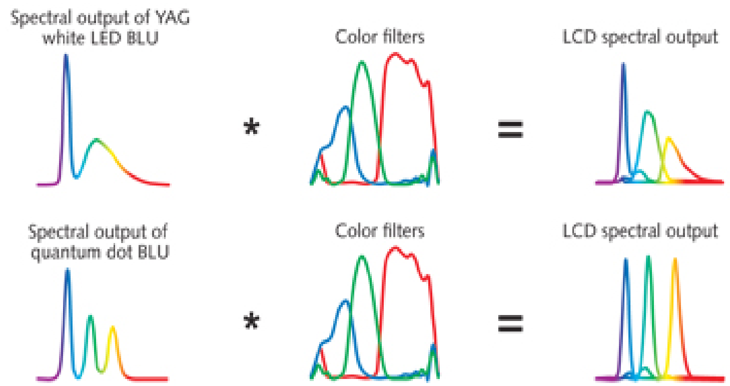
Q. How does reflected light change as lighting and viewing angles change?

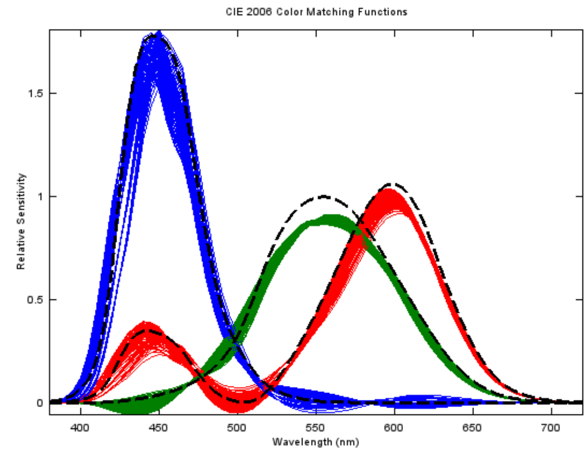
- **Glossy, metallic, and pearlescent surfaces reflect light based on both lighting and viewing angle**
- **Texture also factors into how light reflects from a surface**
- **iccMAX provides the ability to model and characterize how light reflects off a surface based on lighting and viewing angles**
  - Texture maps can also be included



Q. What is the spectrum of light coming off a display?

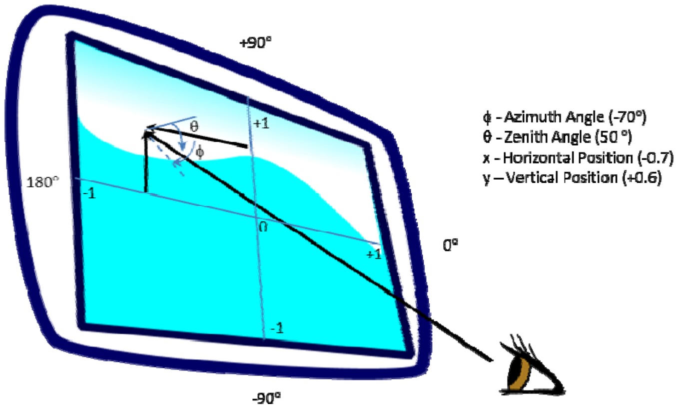
- **New quantum dot display technology results in emission spectra with larger gamuts using narrower emission bands**
- **Variability in observer sensitivity functions results in greater variability in color matching**
  - Observer specific color management may be needed for color critical work!
- **iccMAX provides support for spectrally modeling displays and applying observer specific sensitivity functions**





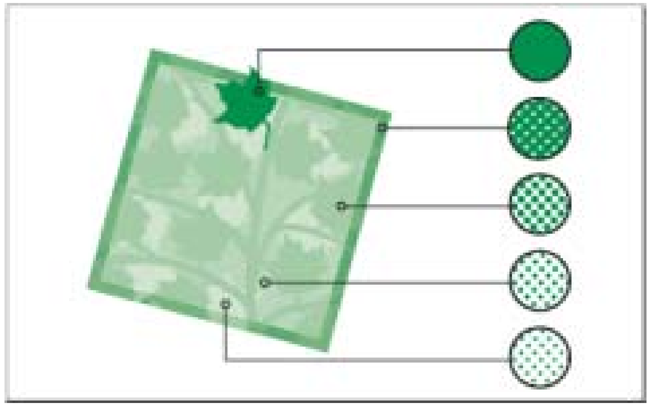
Q. How does light from a video display change due to position and viewing angle?

- **Various display technologies often change color appearance based on where you are looking from as well as where you are looking at on the display**
- **iccMAX provides support for both modeling and characterizing display output based on relative display location and viewing angle**



Q. How is light reflected by a tint of a named color?

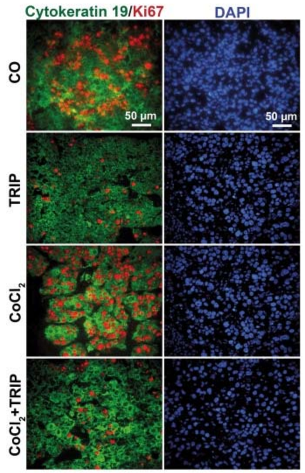
- **One or more of the following can be encoded for each named color in an iccMAX named color profile on a tint by tint basis:**
  - —Output Device values
  - —XYZ/L*a*b* values
  - —Reflectance / Transmittance / Fluorescence values
  - —Opacity/overprint characteristics
  - —How light changes by viewing and observing angle (BRDF)
- **Interpolation is used to find values for intermediate tints**



Q. What is the probability that a pixel of a multi-spectral image contains a specific material?

- **A multi-spectral image has multiple data channels for each pixel**
- **Identification transforms are applied to determine material probabilities of:**
  - —Biomarkers (medical imaging)
  - —Surface features (satellite imaging)
  - —Pigment concentrations (fine art imaging / conservation)
- **Visualization is then performed based upon these material identifications**

- **iccMAX provides support for both material identification and visualization**



Q. How does iccMAX help with Package Printing?

- **Spot colors are spectrally defined**
- **Any number of colorants are supported using programmable multi-processing elements which estimates spot color overprints**
- **Preview of directional effects of gloss and metallic inks**
- **Matches under different viewing conditions are supported by applying observer and illuminant changes**

Conclusions

iccMAX for the Real World

- **The complexities of color in the Real World are encompassed by iccMAX**
- **iccMAX provides the means to answer various questions related to color:**
  - What is it?
  - How is it formulated, controlled, or made?
  - What does it look like?
  - How does it relate to or interact with light?
- **iccMAX provides a platform with both flexibility as well as extensibility for modeling and defining color workflows**

iccMAX – Where are we now?

- **iccMAX has been published as a specification by the International Color Consortium (ICC)**
  - www.iccmax.org
- **Workflow specific ICS documents are under development**
- **ICC is providing and promoting educational opportunities for developers**
  - ICC DevCon
- **Work is currently underway to make iccMAX an ISO standard**
- **An open source reference implementation is available**
- **Individual companies are in process of evaluating and implementing iccMAX features into their products**
  - This will likely take time!

iccMAX

Reference Material

- **ICC web page**
  - http://www.color.org
- **iccMAX web page:**
  - http://www.iccmax.org
- **ICC specification documents:**
  - http://www.color.org/icc_specs2.xalter
- **iccMAX reference implementation:**
  - https://github.com/InternationalColorConsortium/RefIccMAX
- **Max Derhak’s PhD dissertation**
  - Spectrally Based Material Color Equivalency: Modeling and Manipulation
  - http://scholarworks.rit.edu/theses/8789/

Thank You

Questions?