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Color Management: ICC Profiles,
Color Management Modules and Devices

Dr. Michael Vrhel

TC 707 Basis of modern techniques for color specification, measurement, control and communication.
11/17/2010

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Early Color Management: Closed systems

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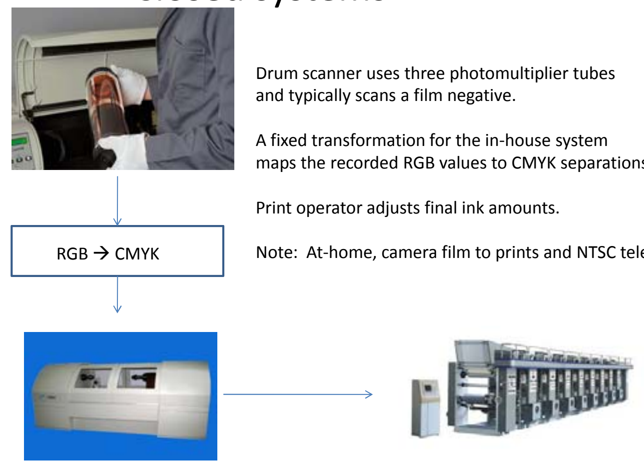

Drum scanner uses three photomultiplier tubes and typically scans a film negative.

A fixed transformation for the in-house system maps the recorded RGB values to CMYK separations.

Print operator adjusts final ink amounts.

Note: At-home, camera film to prints and NTSC television.

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Recording Devices, Image Creation

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Reproduction Devices

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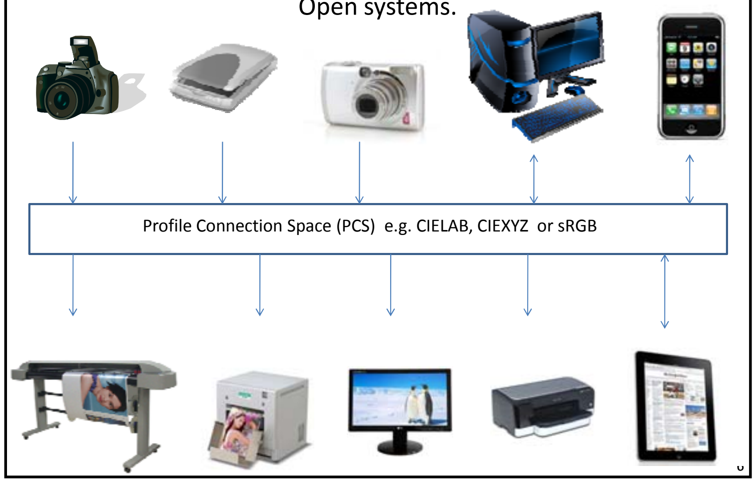
Modern Color Communication: Open systems.

Modern Color Communication: Open systems.



Modern Color Communication: Open Systems.

Postscript color management was the first adopted solution providing a connection Space 1990 in PostScript Level 2.

Apple ColorSync was a competing solution introduced in 1993.

International Color Consortium (ICC) developed a standard that has now been widely adopted at least by the print industry. Organization founded in 1993 by Adobe, Agfa, Kodak, Microsoft, Silicon Graphics, Sun Microsystems and Taligent.

HP introduced sRGB as a "cheap" easy solution. A common default today.

Microsoft Windows Color System (WCS). What happened?

Film industry and digital camera industry still working on solutions.

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Standards, Standards, Standards..

Printing Industry: ICC profile as an ISO standard
ISO 15076-1:2005 Image technology colour management
Architecture, profile format and data structure -- Part 1: Based on ICC.1:2004-10

Camera characterization standards
ISO 22028-1 specifies the image state architecture and encoding requirements.
ISO 22028-3 specifies the RIMM, ERIMM (and soon the FP-RIMM) RGB color encodings.
IEC/ISO 61966-2-2 specifies the scRGB, scYCC, scRGB-nl and scYCC-nl color encodings.
ISO 17321-1 Colour characterization of digital still cameras.
IEC 61966-9 Simplified measurement and transform determination for digital cameras.

Film Industry
No real standards!
There is the Image Interchange Framework which specifies a file format and the use of SMPTE RDD 15-2007 which is a "Color Transformation Language".
Lots of customized mappings that keeps color scientists well employed.

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ICC Specification

Printing Industry: ICC profile as an ISO standard
ISO 15076-1:2005 Image technology colour management
Architecture, profile format and data structure -- Part 1: Based on ICC.1:2004-10

Specification is available at www.color.org

Most profiles created today are of the Version 2 (V2) variety.

Today the ICC is heavily promoting Version 4 (V4) profiles. Adoption has been slow. CMMs have Begun to support it though. V4 profiles are allowed in PDF documents. V4 primarily introduces new structures that can be used as well as the concept of a Perceptual Rendering Media Gamut (PRMG). This is in essence a target gamut to which everyone could map too. Possible to ensure colorant purity across devices.

New addendums have been introduced to allow flexible pipelines of operations as well as floating point precision. I have never run across one of these.

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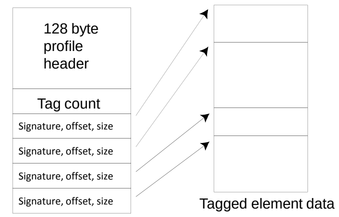
ICC Specification



ICC profile is a uni- or bi-directional mapping between a device color space (e.g CMYK, RGB) and a perceptual color space (e.g.) CIEXYZ or CIELAB.

- Tag-based
- Public required tags
- Public optional tags
- Private tags
- MLUT based mappings
- Matrix based mappings
- Profile Connection Space (PCS) can be CIEXYZ or CIELAB

Most MLUT ICC profiles use CIELAB as PCS. Matrix profiles use CIEXYZ.

PCS White point is D50.

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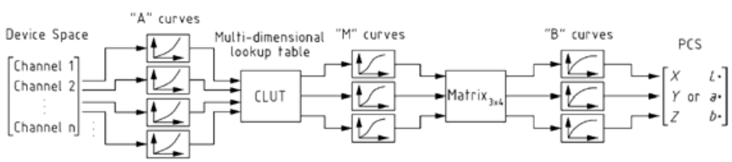
MLUT mapping: Device Color to PCS



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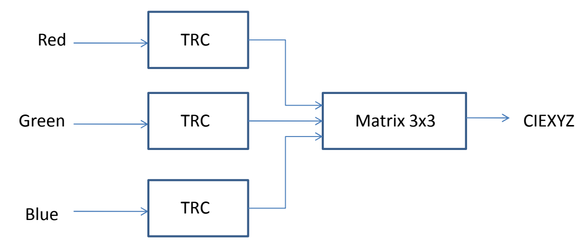
Matrix Based



Model developed for displays. Note that this model is often inverted by CMM. Danger if TRC is not readily invertible.

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Profiles are output referred rendering

The MLUT or the matrix mapping always supply D50 CIEXYZ or D50 CIELAB.

Which is to say that an input of RGB = [1,1,1] would give a CIEXYZ value of [0.9642 1.0000 0.8249]

There is a white point tag contained in the profile which indicates the true white point of the medium. Since you have to map this to D50 (which affects all the colors), the ICC recommends a 3x3 matrix to adjust your XYZ measurements to D50.

$$\mathbf{t}_{D50} = \mathbf{M}\mathbf{t}_{src}$$

$$\mathbf{M} = \begin{bmatrix} X_{D50}/X_{src} & 0 & 0 \\ 0 & Y_{D50}/Y_{src} & 0 \\ 0 & 0 & Z_{D50}/Z_{src} \end{bmatrix}$$

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chromaticAdaptationTag

$$\mathbf{t}_{i,L_{pcs}} = \mathbf{A}^T\mathbf{L}_{pcs}\mathbf{f}_i \qquad \mathbf{t}_{i,L_{src}} = \mathbf{A}^T\mathbf{L}_{src}\mathbf{f}_i$$

$$\min_{\mathbf{M}_{adapt}} E\left\{\left\| F\left(\mathbf{t}_{i,L_{pcs}}\right) - F\left(\mathbf{M}_{adapt}\mathbf{t}_{i,L_{src}}\right)\right\|^2\right\}$$

Often recommended to use diagonal mapping in "cone space". Bradford Transformation

$$\begin{bmatrix} \rho \\ \gamma \\ \beta \end{bmatrix} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{N}_{BFD}\mathbf{t}_{i,L_2}$$

$$\mathbf{M}_{adapt} = \mathbf{N}_{BFD}^{-1} \begin{bmatrix} \rho_{L_{pcs}}/\rho_{L_{src}} & 0 & 0 \\ 0 & \gamma_{L_{pcs}}/\gamma_{L_{src}} & 0 \\ 0 & 0 & \beta_{L_{pcs}}/\beta_{L_{src}} \end{bmatrix} \mathbf{N}_{BFD}$$

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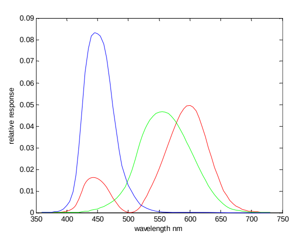
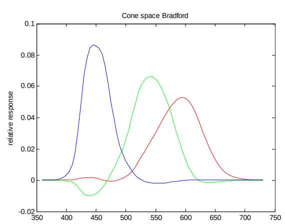


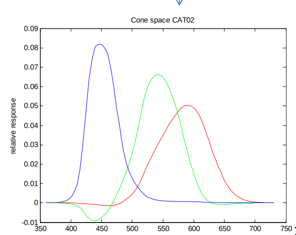
Bradford

$$\begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix}$$

CAT02

$$\begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.003 & 0.0136 & 0.9834 \end{bmatrix}$$





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Profile Classes: Input

Typically used for scanners, cameras.

Required Tags: LUT Based → AToB0Tag
PCS can be CIEXYZ or CIELAB

Matrix Based → redMatrixColumnTag
PCS is CIEXYZ greenMatrixColumnTag
Model for display source blueMatrixColumnTag
redTRCTag (Note TRC = Tone Reproduction Curve)
greenTRCTag
blueTRCTag

$\mathbf{c} = \mathbf{N}^T\mathbf{L}\mathbf{f}$ Recorded data

$\mathbf{t} = \mathbf{A}^T\mathbf{L}_{D50}\mathbf{f}$ Adjusted to D50 (output referred)

$$\min_F E\left\{\left\| G(\mathbf{t}) - G\left(F(\mathbf{c})\right)\right\|^2\right\}$$

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Output Profiles

Used for printers, complex displays

Required Tags:
AToB0Tag , AToB1Tag, AToB2Tag
BToA0Tag, BToA1Tag, BToA2Tag
gamutTag
colorantTableTag (for the xCLR colour spaces)

AToB0Tag: Forward mapping from device values to PCS. Perceptual rendering.
BToA0Tag: Inverse mapping from PCS to device values. Perceptual rendering.

AToB1Tag: Forward mapping from device values to PCS. Colorimetric rendering.
BToA1Tag: Inverse mapping from PCS to device values. Colorimetric rendering.

AToB2Tag: Forward mapping from device values to PCS. Saturation rendering.
BToA2Tag: Inverse mapping from PCS to device values. Saturation rendering.

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Rendering Intents

Relative Colorimetric – White point of the medium is mapped to the white point of the reference illuminant. Maintain hue and lightness in gamut mapping.

Absolute Colorimetric – No media white point mapping. Uses chromatic adaptation tag.

Perceptual – Implementation specific. Gamut compressed or expanded, intended to give visually pleasing result for images.

Saturation – Implementation specific. Preserve saturation at expense of hue and lightness. Intended for graphics.

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Forward Table Creation

Forward tables A2B0, A2B1, A2B2 map from device values (A) to PCS values (B).

Creation of this table is straight forward since the table grid points are in device space (i.e. RGB or CMYK).

This amounts to printing out a grid of sample values and measuring with a colorimeter or a spectrophotometer.

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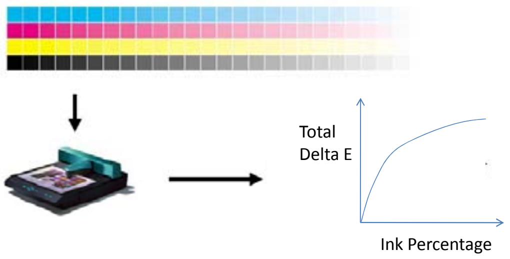
Creating ICC Profiles: Printer Case

Step 1: Linearization



Since linear interpolation is usually used in the MLUT, it is desirable to linearize

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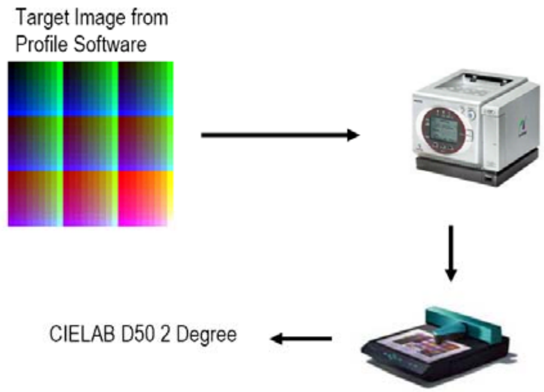
Step 2. Print linearized chart
Measure with spectrophotometer



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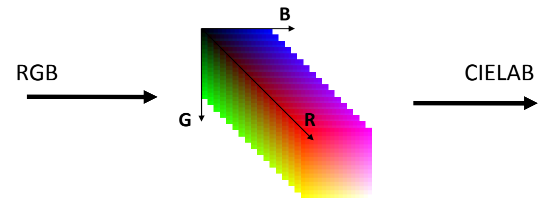
Forward Table

MLUT transformation (e.g. 9x9x9 entries)



$$F(\mathbf{c}) = G\left(\mathbf{A}^T \mathbf{L} \mathbf{f}\right)$$

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Inverse Table

$$\mathbf{c} = F^{-1}\left(G\left(\mathbf{A}^T \mathbf{L} \mathbf{f}\right)\right)$$

The inverse table is indexed in the PCS and maps from PCS values to device values (e.g. RGB).

Issues:

There may be values which are outside the range of c (outside gamut).

Quantization errors in the PCS may be an issue. Inverse table may need to be larger.

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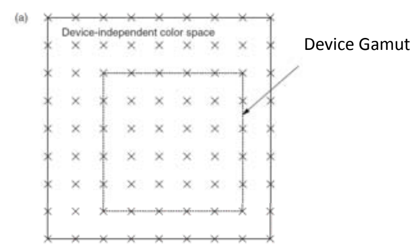

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An algorithm for constructing the inverse table

1. Step through all device values and use forward table to compute CIELAB value.

$$F(\mathbf{c}) = G\left(\mathbf{A}^T \mathbf{L} \mathbf{f}\right)$$

2. Check if CIELAB is within a delta value of a grid point in the inverse table.
   a. If it is within delta then assign the grid point storing the delta value
   b. If an existing point is already assigned, compare deltas, keeping the closest.
   c. Mark in a gamut table, those points that have been assigned.

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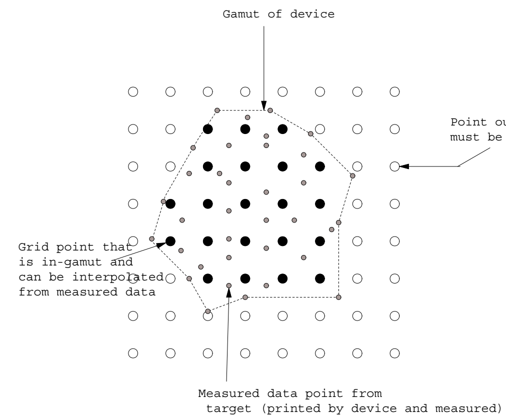

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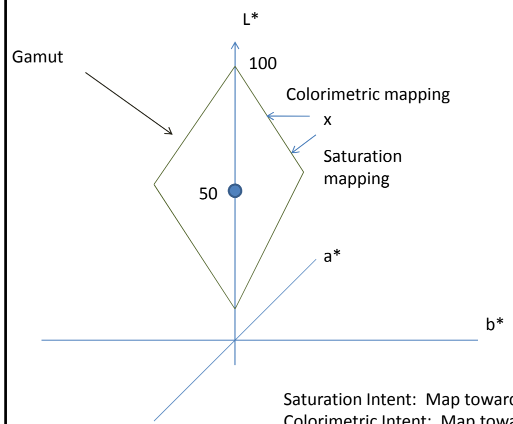
Rendering Intent and gamut mapping



Perceptual Intent is where specialized methods can be introduced.

Saturation Intent: Map toward L* = 50 neutral axis.
Colorimetric Intent: Map toward neutral axis. Constant hue and lightness.

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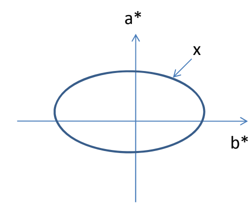
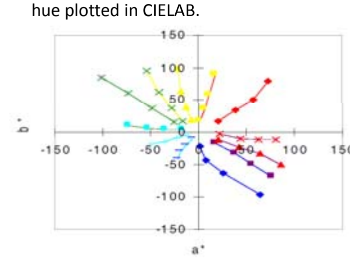
Radii are not constant hue in CIELAB!

CIECAM02 often used for this today.

WCS uses a CIECAM02 PCS



Hung and Berns lines of constant perceived hue plotted in CIELAB.



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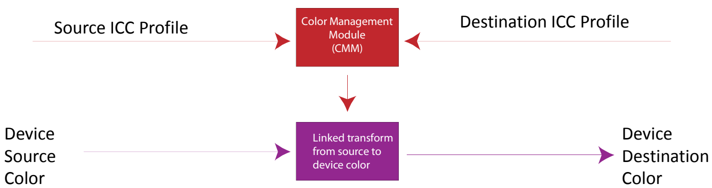
Color Management Module (CMM): Bringing it all together



CMM typically creates a new object, e.g. 1-D LUTs, MLUT, 1-D LUTs.

An application (e.g Photoshop, Acrobat etc.) can have its own CMM which applies ICC profile transformations.

Windows and Apple both have an Application Programming Interface (API) that applications can use to the system CMM.

A print driver may also use the system API to apply the printer profile.

Problems of multiple color management operations do exist!

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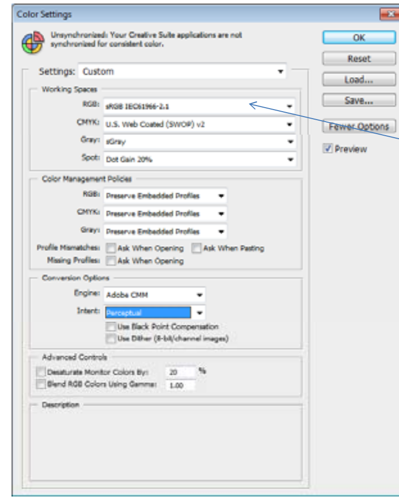

Photoshop working space is sRGB.

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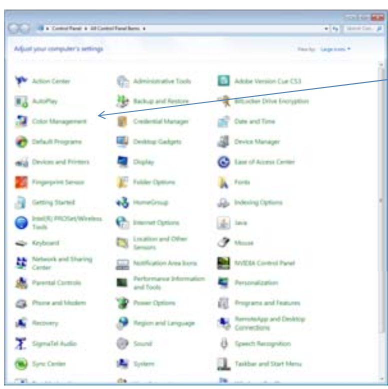
Color Management from in the print driver



This tool allows you to (un) associate a profile with a particular device.

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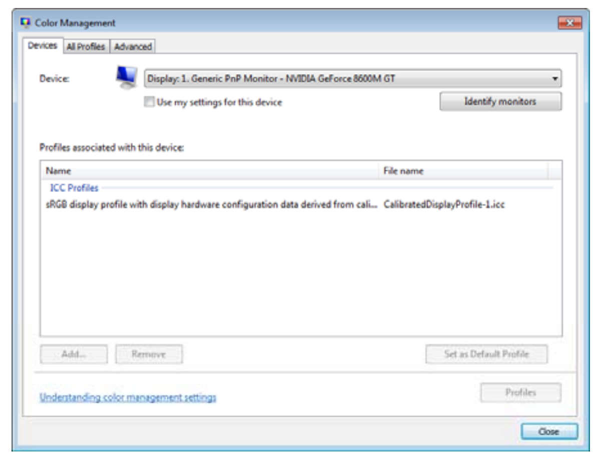

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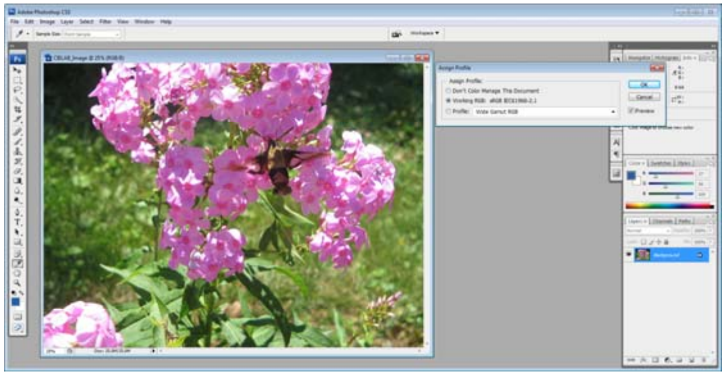

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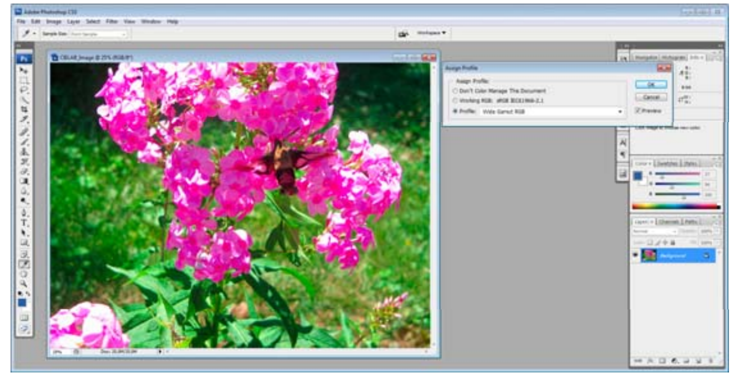

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Wide gamut
green xy
chromaticity

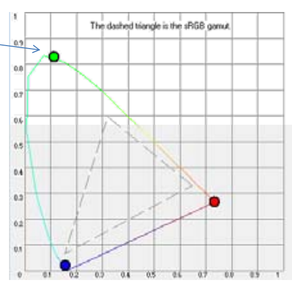

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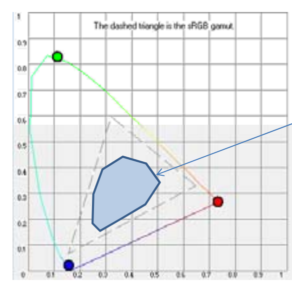
Image xy values
when defined to
be in sRGB



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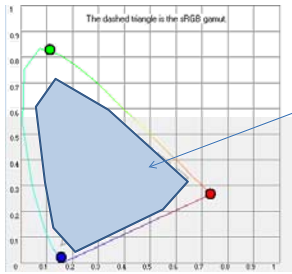

Image xy values when defined to be in wide gamut

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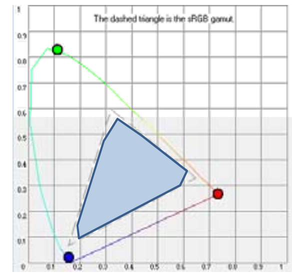

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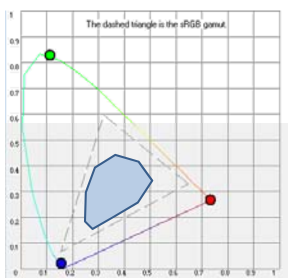

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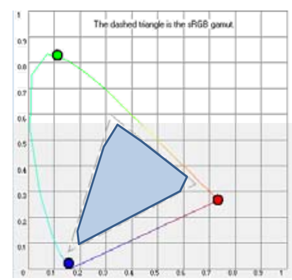

$F:$ ICC Mapping of Wide Gamut RGB to XYZ

$G:$ ICC Mapping of sRGB to XYZ ← Gamut Mapping!

$$\mathbf{c}_{sRGB} = G^{-1}\left(F\left(\mathbf{c}_{wide}\right)\right)$$

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Embedded color management

Some color management operations take place internally in a device.

These operations are often carried out with ARM or PPC processors with special hardware accelerators.

The entire system is often placed on a single chip. "System on a chip" (SoC) In essence an ASIC with one or more microcontrollers.

Size is an issue as this is the cost factor. Goal is to try to do more with less.

Typically significant memory constraints and number of operations per pixel becomes great importance.

Processing often pipe-lined and care must be taken to ensure nodes are not "starved".

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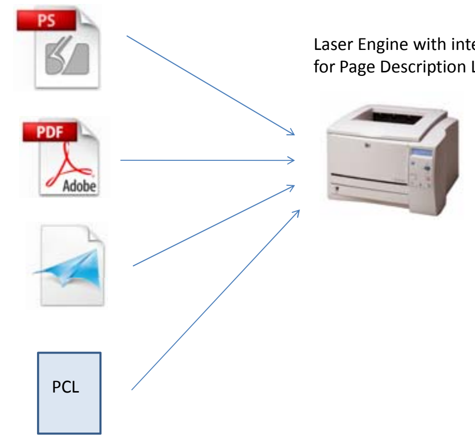
Embedded color management



Laser Engine with interpreter
for Page Description Languages (PDL)

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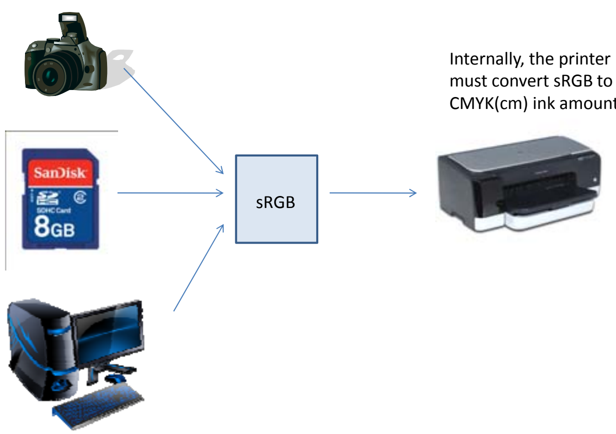
Embedded color management



Internally, the printer must convert sRGB to CMYK(cm) ink amounts.

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Embedded color management

Multi-function peripheral (MFP) requires conversion from scanner RGB to CMYK ink amounts.

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Embedded color management

Camera Raw

sRGB

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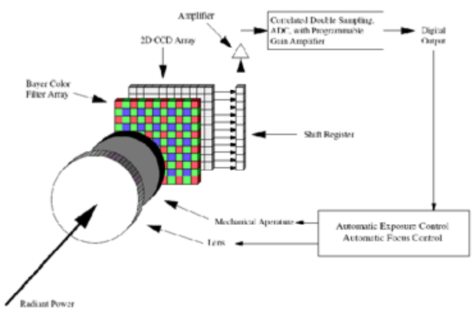
Scene referred rendering

Ndependent upon any output referred medium white point like the ICC profile.

Although recording could be colorimetric, the goal is usually to obtain an "appearance match" as opposed to a colorimetric match. This should be factored into the cost function of optimization problems via measures that account for illumination/adaptation e.g. CIECAM02.

The appearance cost function is used to compute the transformation from recorded values to colorimetric values. Additional transformations may occur to account for final viewing conditions.

Camera Color Management



Camera characterization problem unique due to lack of control over the illumination.

General Camera Problem

Image is captured under one illuminant. Goal is to map recorded values to CIEXYZ values for a variety of illuminants.

$$\mathbf{c}_r = \mathbf{N}^T \mathbf{L}_r \mathbf{f}$$

$$\mathrm{T}_{r1}(\mathbf{c}_r) \rightarrow \mathbf{t}_1 = \mathbf{A}^T \mathbf{L}_1 \mathbf{f}$$

$$\mathrm{T}_{r2}(\mathbf{c}_r) \rightarrow \mathbf{t}_2 = \mathbf{A}^T \mathbf{L}_2 \mathbf{f}$$

$$\vdots \qquad \vdots$$

$$\mathrm{T}_{rJ}(\mathbf{c}_r) \rightarrow \mathbf{t}_J = \mathbf{A}^T \mathbf{L}_J \mathbf{f}$$

Cost Function

$$\min_{\mathrm{T}_{ri}} E\left\{\mathrm{F}\left(\mathbf{t}_i, \mathrm{T}_{ri}\left(\mathbf{c}_r\right)\right)\right\}$$

Error metric F could be CIE Delta E, CIECAM, Euclidean norm in XYZ, etc.

T_{ri} could be linear or nonlinear. MLUT for example.

Expectation occurs over noise and distribution of reflectance spectra.

Distribution of spectral data exerts large influence.

Spectral Data Sets

Two types of data sets:

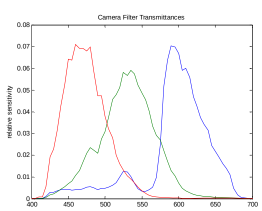
Controlled lab measurements:

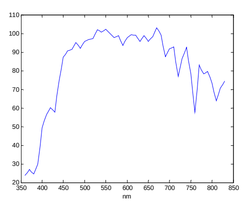
Made using spectroradiometer with controlled geometry, single illumination.
e.g. M. J. Vrhel, R. Gershon, and L. Iwan, "The Measurement and Analysis of Object Reflectance Spectra," *Color Research and Application*, vol. 19, no. 1, pp. 4-9, Feb. 1994.

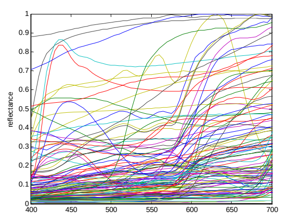
In-situ data:

Made in-field with spectroradiometer. Mutual reflectance, geometry and lighting.
e.g. D. Wueller, "In Situ Measured Spectral Radiation of Natural Objects," 17th Color Imaging Conference, pp. 159-163, Nov. 2009.

Transformation Example





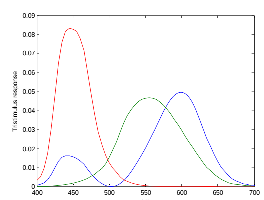


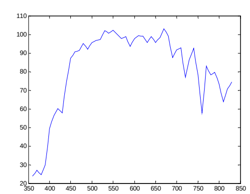
Real camera filters.
D50 Illumination.
In-Situ spectra (2000 +)

Simulated recorded data:

$$\mathbf{c}_r = \mathbf{N}^T \mathbf{L}_r \mathbf{f}$$

Transformation Example





Compute CIEXYZ values $\mathbf{t}_r = \mathbf{A}^T \mathbf{L}_r \mathbf{f} \approx \mathrm{T}\left(\mathbf{c}_r\right)$

Such that CIECAM02 difference is minimized. i.e. the correlates for lightness, colorfulness and hue (JMh)

$$\min_{T} E\left\{\mathrm{F}\left(\mathbf{t}_r, \mathrm{T}\left(\mathbf{c}_r\right)\right)\right\}$$

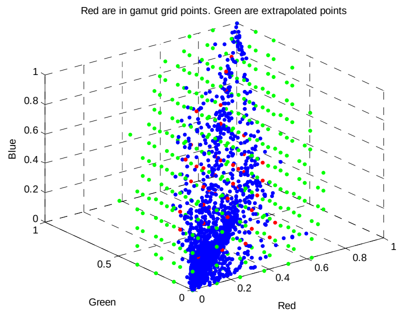
MLUT vs Matrix

Testing data (MacBeth Color Checker)

Matrix Avg 1.57 Max 5.28
MLUT Avg 1.27 Max 3.67 ΔE

Training data

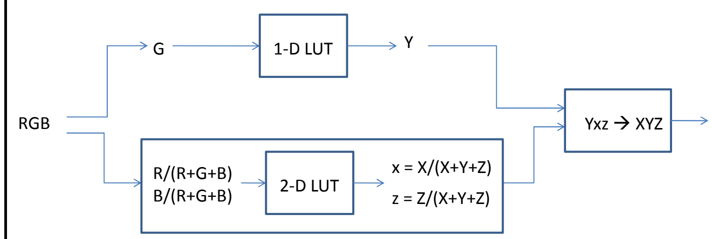
Matrix Avg 1.12 Max 11.43
MLUT Avg 1.52 Max 8.15 ΔE



MLUT constructed by solving matrix problem with N nearby points for each grid point.

"Out-of-gamut" points filled with global matrix results.

Alternative for reduced computation and footprint



One would not want to do the division. Alternatively map RGB to YCC.