Spectral Imaging Workflows

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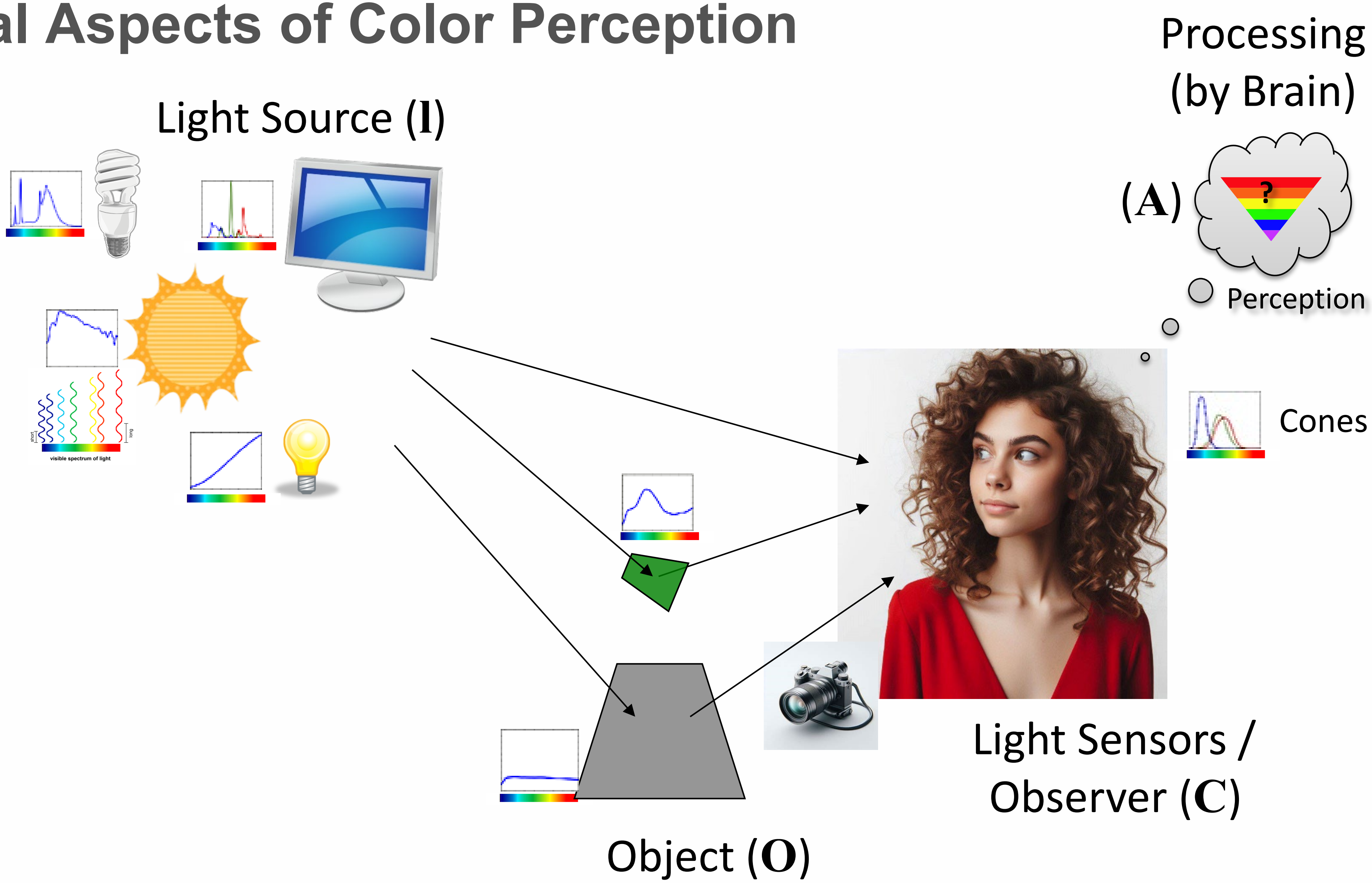
Agenda

- **Background and Definitions**
- **Spectral Workflows**
  - Color Space Workflows
  - Print Workflows
  - Display Workflows
  - Capture Workflows
  - Identification Workflows
- **Final Thoughts**

Spectral Aspects of Color Perception



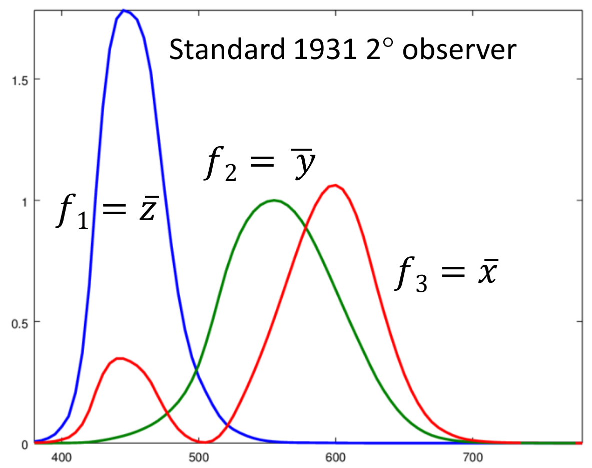
Quantifying Color

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

$$c_i = k \iint f_i(\omega)\, o(\omega, \square) l(\lambda) d\omega d\lambda$$

$$X = c_1, Y = c_2, Z = c_3$$

$$k = \frac{100}{\int \bar{y}(\lambda) l(\lambda)}$$



Color Matching Functions

$$\mathbf{f_i} = \begin{bmatrix} f_i(\omega_1) \\ \vdots \\ f_i(\omega_n) \end{bmatrix}$$

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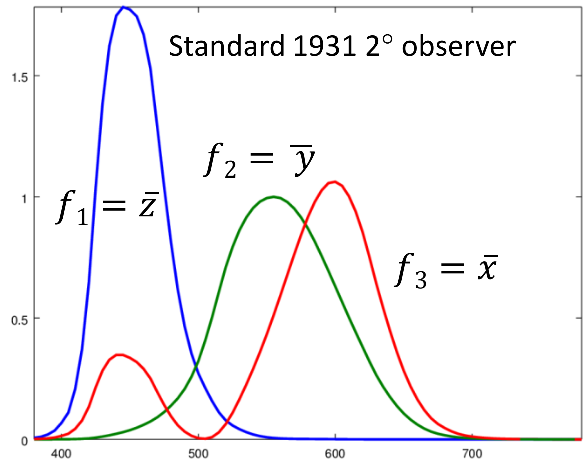


Color Matching Functions

$$\mathbf{f_i} = \begin{bmatrix} f_i(\omega_1) \\ \vdots \\ f_i(\omega_n) \end{bmatrix}$$

Discrete Color Equation

$$\boxed{\mathbf{c} = \mathbf{COl}}$$

Colorimetry / Cone response / Camera Vector

$$\mathbf{c} = \begin{bmatrix} c_1 \\ \vdots \\ c_m \end{bmatrix}$$

Color Matching/ Sensor Functions Matrix

$$\mathbf{C} = k \begin{bmatrix} \mathbf{f}_1^T \\ \vdots \\ \mathbf{f}_n^T \end{bmatrix}$$

$$\mathbf{c} = \mathbf{Ce}$$

Object "reflectance" (Donaldson) Matrix

$$\mathbf{O} = \begin{bmatrix} o(\omega_1, \lambda_1) & \cdots & o(\omega_1, \lambda_n) \\ \vdots & \ddots & \vdots \\ o(\omega_m, \lambda_1) & \cdots & o(\omega_m, \lambda_n) \end{bmatrix}$$

$$\mathbf{e} = \mathbf{Ol}$$

Light / Emission Vector

$$\mathbf{e}, \mathbf{l}, \mathbf{p} = \begin{bmatrix} l(\lambda_1) \\ \vdots \\ l(\lambda_n) \end{bmatrix}$$

Color Perception

Perceptual aspects involve a transform of color matching or sensor values to a color appearance / color equivalency representation

$$\mathbf{a} = \mathbf{ACOl} \qquad \text{Where } \mathbf{A}_{\mathbf{C},\mathbf{l}} = f(\mathbf{C}, \mathbf{l}_{white})$$

<u>*Examples*</u>

CIELAB "Appearance"

$$\begin{bmatrix} L \\ a \\ b \end{bmatrix} = \mathbf{A}_{\mathbf{C},\mathbf{l}}\mathbf{c} = CIELAB(\mathbf{c}, \mathbf{C}, \mathbf{l}_{white})$$

CIECAM "Appearance"

$$\begin{bmatrix} J \\ a \\ b \end{bmatrix} = \mathbf{A}_{\mathbf{C},\mathbf{l}}\mathbf{c} = CIECAM(\mathbf{c}, \mathbf{C}, \mathbf{l}_{white}, \dots)$$

White Balance for Chromatic Adaptation

$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \mathbf{A}_{\mathbf{C},\mathbf{l}}\mathbf{c},$$

$$\mathbf{A}_{\mathbf{C},\mathbf{l}} = diag^{-1}(\boldsymbol{m}_{white})\mathbf{M}_{sharp},$$

$$\boldsymbol{m}_{white} = \mathbf{M}_{sharp}\mathbf{c}_{\mathbf{C},\mathbf{l}_{white}}$$

Waypoint Color Equivalency

$$\begin{bmatrix} W \\ p \\ t \end{bmatrix} = \mathbf{A}_{\mathbf{C},\mathbf{l}}\mathbf{c}, \quad \mathbf{A}_{\mathbf{C},\mathbf{l}} = f_{Wpt}(\mathbf{C}, \mathbf{l}_{white})$$

Waypoint Normalization

Chromatic Adaptation / Adjustment

- **Combining transforms "to" and "from" a color appearance / color equivalence representation allows the conversion from one observing condition to another**

$$\mathbf{c}_2 = \left(\mathbf{A}_2^{-1}\mathbf{A}_1\right)\mathbf{c}_1$$

Example:

- Observing condition 1 is for 10° observer under Illum A
- Observing condition 2 is for 2° observer under D65

Note: Most appearance / color equivalency representations don't allow for different observers (IE they MUST be the same)

Reflectance Factor

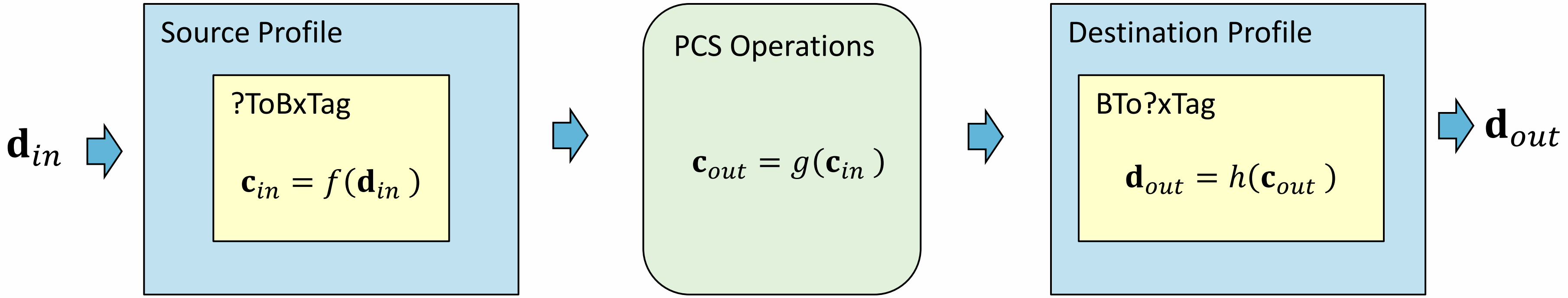
- **Reflectance factor is the relative amount of light reflected relative to the amount of radiant light shown on an object**

$$\mathbf{O}_{\boldsymbol{r}} = diag(\mathbf{r})$$

$$\mathbf{r} = \begin{bmatrix} r(\lambda_1) \\ \vdots \\ r(\lambda_n) \end{bmatrix} = diag^{-\mathbf{1}}\left(\mathbf{l}_{reflected\_white}\right)\mathbf{O}\ \mathbf{l}_{radiant\_white}$$

Color Workflows with ICC profiles

- **ICC color workflows generally involve applying a transform from a color space / device encoding ($\mathbf{d}_{in}$) to a Profile Connection Space (PCS) from one profile followed by applying an inverse transform from PCS to another color space / device encoding ($\mathbf{d}_{out}$)**



Notes:

1. *CMM control operations select which transforms to use*
2. *Needed PCS operations $g()$ are determined by the CMM*

Spectral Color Workflow

Definition: A color workflow where parts of the color equation (COI) in profile color transforms are either missing or supplied and applied separately by the CMM

Spectral Color Space Profiles

Profile Connection Conditions (PCC)

Color Space Profile — *Reflectance PCS Profile*

DToBx tag	BToDx tag	svcn tag	CustomToStd tag	StdToCustom tag
$\mathbf{r} = r(\mathbf{d})$	$\mathbf{d} = r^{-1}(\mathbf{r})$	$\boxed{\mathbf{C}}$ $\boxed{\mathbf{l}}$	$\mathbf{A}_{2deg,D50}^{-1}\mathbf{A}_{\mathbf{C},\mathbf{l}}$	$\mathbf{A}_{\mathbf{C},\mathbf{l}}^{-1}\mathbf{A}_{2deg,D50}$

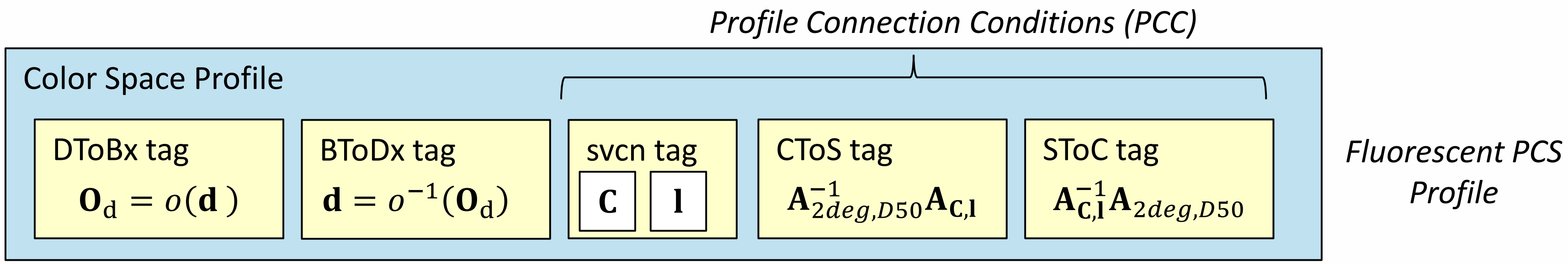
Color Space Profile — *Transmittance PCS Profile*

DToBx tag	BToDx tag	svcn tag	CustomToStd tag	StdToCustom tag
$\mathbf{t} = t(\mathbf{d})$	$\mathbf{d} = t^{-1}(\mathbf{t})$	$\boxed{\mathbf{C}}$ $\boxed{\mathbf{l}}$	$\mathbf{A}_{2deg,D50}^{-1}\mathbf{A}_{\mathbf{C},\mathbf{l}}$	$\mathbf{A}_{\mathbf{C},\mathbf{l}}^{-1}\mathbf{A}_{2deg,D50}$

Color Space Profile — *Emissive PCS Profile*

DToBx tag	BToDx tag	svcn tag	CustomToStd tag	StdToCustom tag
$\mathbf{e} = e(\mathbf{d})$	$\mathbf{d} = e^{-1}(\mathbf{e})$	$\boxed{\mathbf{C}}$ $\boxed{\mathbf{l}}$	$\mathbf{A}_{2deg,D50}^{-1}\mathbf{A}_{\mathbf{C},\mathbf{l}}$	$\mathbf{A}_{\mathbf{C},\mathbf{l}}^{-1}\mathbf{A}_{2deg,D50}$

Fluorescent Color Space Profiles



Example Spectral PCS Color Space Workflows

$\mathbf{d}_{in}$ → **Source Profile** (DToBxTag: $\mathbf{r}_{in} = f(\mathbf{d}_{in})$) → **PCS Operations** ($\mathbf{r}_{out} = g(\mathbf{r}_{in})$) → **Destination Profile** (BToDxTag: $\mathbf{d}_{out} = h(\mathbf{r}_{out})$) → $\mathbf{d}_{out}$

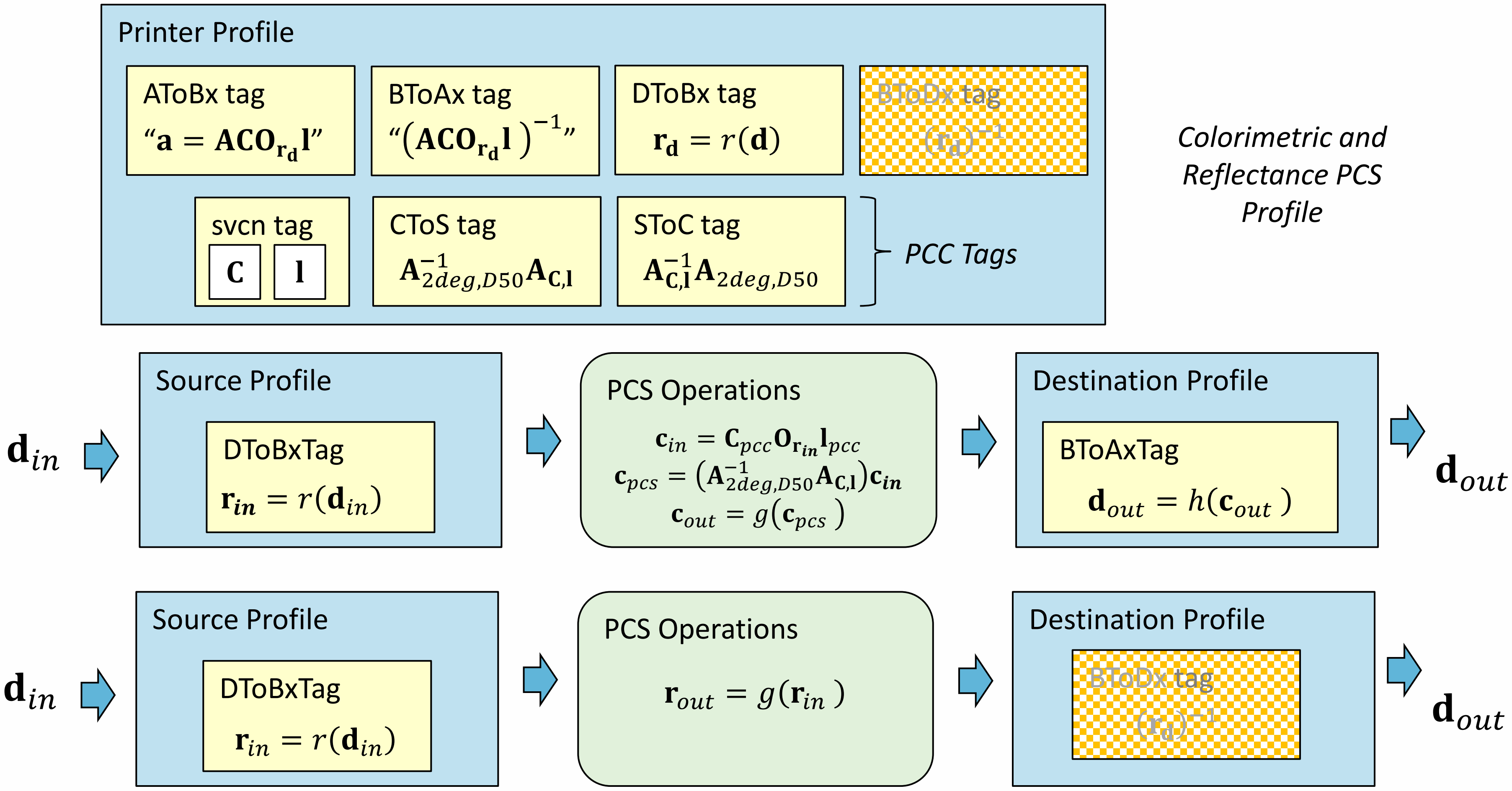
$\mathbf{d}_{in}$ → **Source Profile** (DToBxTag: $\mathbf{r}_{in} = f(\mathbf{d}_{in})$) → **PCS Operations** ($\mathbf{e}_{pcs} = \mathbf{O}_{\mathbf{r}_{in}}\mathbf{l}$; $\mathbf{e}_{out} = g(\mathbf{e}_{pcs})$) → **Destination Profile** (BToDxTag: $\mathbf{d}_{out} = h(\mathbf{e}_{out})$) → $\mathbf{d}_{out}$

$\mathbf{d}_{in}$ → **Source Profile** (DToBxTag: $\mathbf{r}_{in} = f(\mathbf{d}_{in})$) → **PCS Operations** ($\mathbf{c}_{in} = \mathbf{C}\mathbf{O}_{\mathbf{r}_{in}}\mathbf{l}$; $\mathbf{c}_{pcs} = (\mathbf{A}^{-1}_{2deg,D50}\mathbf{A}_{\mathbf{C},\mathbf{l}})\mathbf{c}_{in}$; $\mathbf{c}_{out} = g(\mathbf{c}_{pcs})$) → **Destination Profile** (BToAxTag: $\mathbf{d}_{out} = h(\mathbf{c}_{out})$) → $\mathbf{d}_{out}$

Notes:

- *PCS operations are determined by the CMM using PCC elements ($\mathbf{A}^{-1}\mathbf{A}$, $\mathbf{C}$, $\mathbf{l}$) as needed*
- *PCC elements can come from either the profile or provided separately as an alternate PCC*

Print Spectral Workflows



Note: The lower workflow is problematic for a few reasons

Problems with inverting $\mathbf{r_d} = r(\mathbf{d})$

- **The reflectance PCS vector likely has high dimensionality which is bad for creating lookup tables due to exponential growth**
- **Dimensionality can be reduced by adding an Interim Connection Space (ICS) by converting $\mathbf{r_d}$ to something like LabPQR or XYZPQR with (PQR representing metameric black dimensions) and using a lower dimensional lookup table**
- **This is a more manageable, but you still have a large lookup table with interpolation of device values by metameric black inputs**
  - Relationships may not be linear for device output values which requires more sampling to be more accurate which can result in unwieldy lookup table
  - Lookup table is much more complicated to create that a colorimetric lookup table
  - Complicated gamut mapping
- **An alternate approach would be for the CMM to use the destination profile's DToBx transform along with the $\mathbf{A}$, $\mathbf{C}$, and $\mathbf{l}$ from an alternate PCC to build a B2Ax type transform (using conventional profile creation approaches)**

$\mathbf{d}_{in}$ →

Source Profile

DToBxTag

$\mathbf{r}_{in} = f(\mathbf{d}_{in})$

→

PCS Operations

$\mathbf{c}_{pcs} = \mathbf{C}_{pcc}\mathbf{O}_{\mathbf{r}_{in}}\mathbf{l}_{pcc}$

$\mathbf{c}_{out} = g(\mathbf{c}_{pcs})$

→

CMM built tag

$(\mathbf{A}_{pcc}\mathbf{C}_{pcc}\mathbf{O}_{\mathbf{r_d}}\mathbf{l}_{pcc})^{-1}$

→ $\mathbf{d}_{out}$

Display Spectral Profiles

- **Display profiles could use an emissive PCS, but this would be computationally expensive**
- **Alternatively, spectral primary data and observer functions can be combined by CMM just before applying profiles to define runtime colorimetric transforms**
- **This allows use of custom observer provided by alternate PCC**
- **Legacy display profiles can be created from Display Spectral profiles to be used by legacy CMMs**

Display Profile

AToBx tag

$\mathbf{d}_{linear} = \gamma(\mathbf{d}_{in})$
$\mathbf{c} = \mathbf{M}\mathbf{d}_{linear}$

Before applying profile

$\mathbf{M} = \mathbf{C}_{pcc}\mathbf{P}$

BToAx tag

$\mathbf{d}_{linear} = \mathbf{M}^{-1}\mathbf{c}$
$\mathbf{d}_{out} = \gamma^{-1}(\mathbf{d}_{linear})$

Before applying profile

$\mathbf{M}^{-1} = \left(\mathbf{C}_{pcc}\mathbf{P}\right)^{-1}$

svcn tag

C | l

CustomToStd tag

$\mathbf{A}_{2deg,D50}^{-1}\mathbf{A}_{\mathrm{C,l}}$

StdToCustom tag

$\mathbf{A}_{\mathrm{C,l}}^{-1}\mathbf{A}_{2deg,D50}$

Primary Matrix from primary vectors

$$\mathbf{P} = \begin{bmatrix} \mathbf{p}_1^T \\ \vdots \\ \mathbf{p}_n^T \end{bmatrix}$$

Note: Spectral primaries may be associated with CICP tag

Spectral Capture Profiles

Capture Profile

ATоBx tag

$\mathbf{a} = \mathbf{ACO_{Md}l}$

or

$\mathbf{a} = \mathbf{Ac}$

$\mathbf{c} = \mathbf{Xd}$

DToBx tag

$\mathbf{r} = \mathbf{Md}$

BToDx tag

$\mathbf{d} = \mathbf{Sr}$

svcn tag

$\boxed{\mathbf{C}}$ $\boxed{\mathbf{l}}$

CustomToStd tag

$\mathbf{A}_{2deg,D50}^{-1}\mathbf{A}_{\mathbf{C,l}}$

StdToCustom tag

$\mathbf{A}_{\mathbf{C,l}}^{-1}\mathbf{A}_{2deg,D50}$

PCC Tags

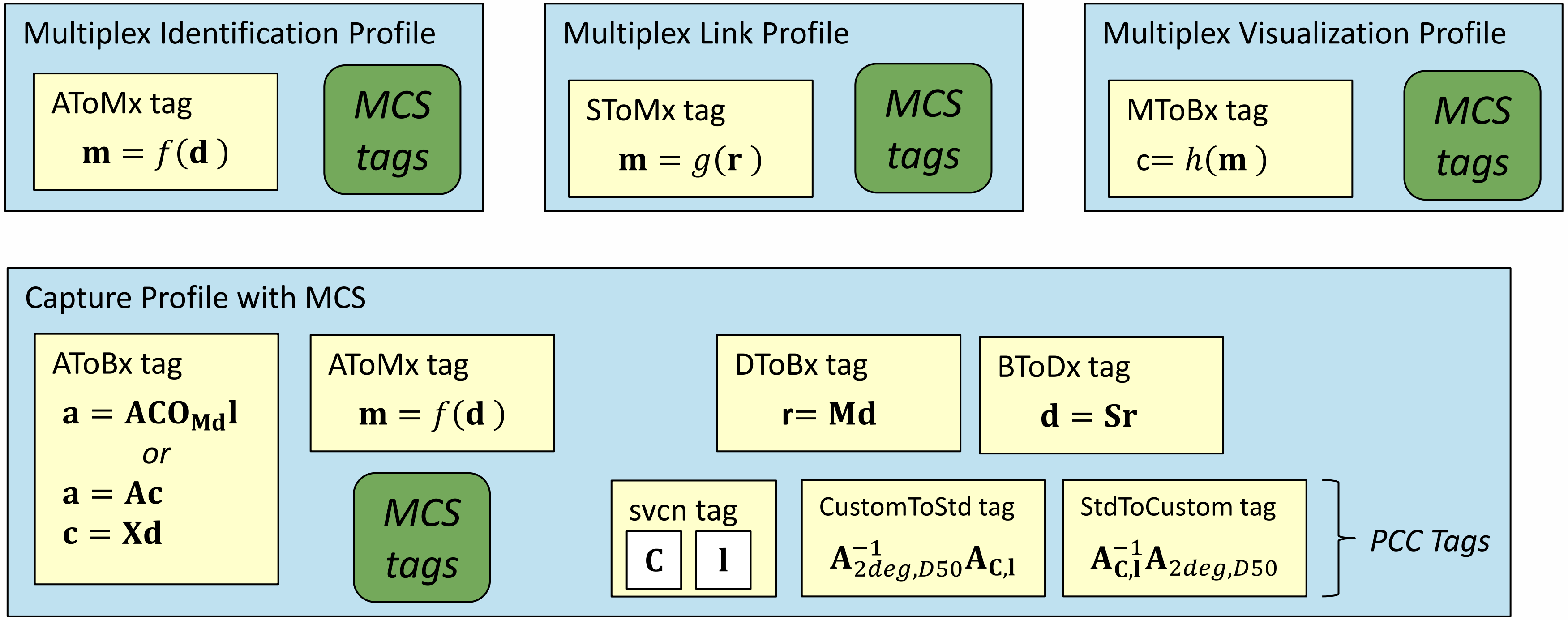
Finding matrices $\mathbf{X}$, $\mathbf{M}$, & $\mathbf{S}$:

1. Capture corresponding **d** vectors for objects with known r vectors and generating **c** vectors from $\mathbf{c} = \mathbf{CO_r l}$.
2. Assemble **d**, **r**, & **c** vectors into matrices $\mathbf{D}$, $\mathbf{R_d}$, and $\mathbf{C_d}$
3. Use pseudo inverse to find Matrices to populate tags:

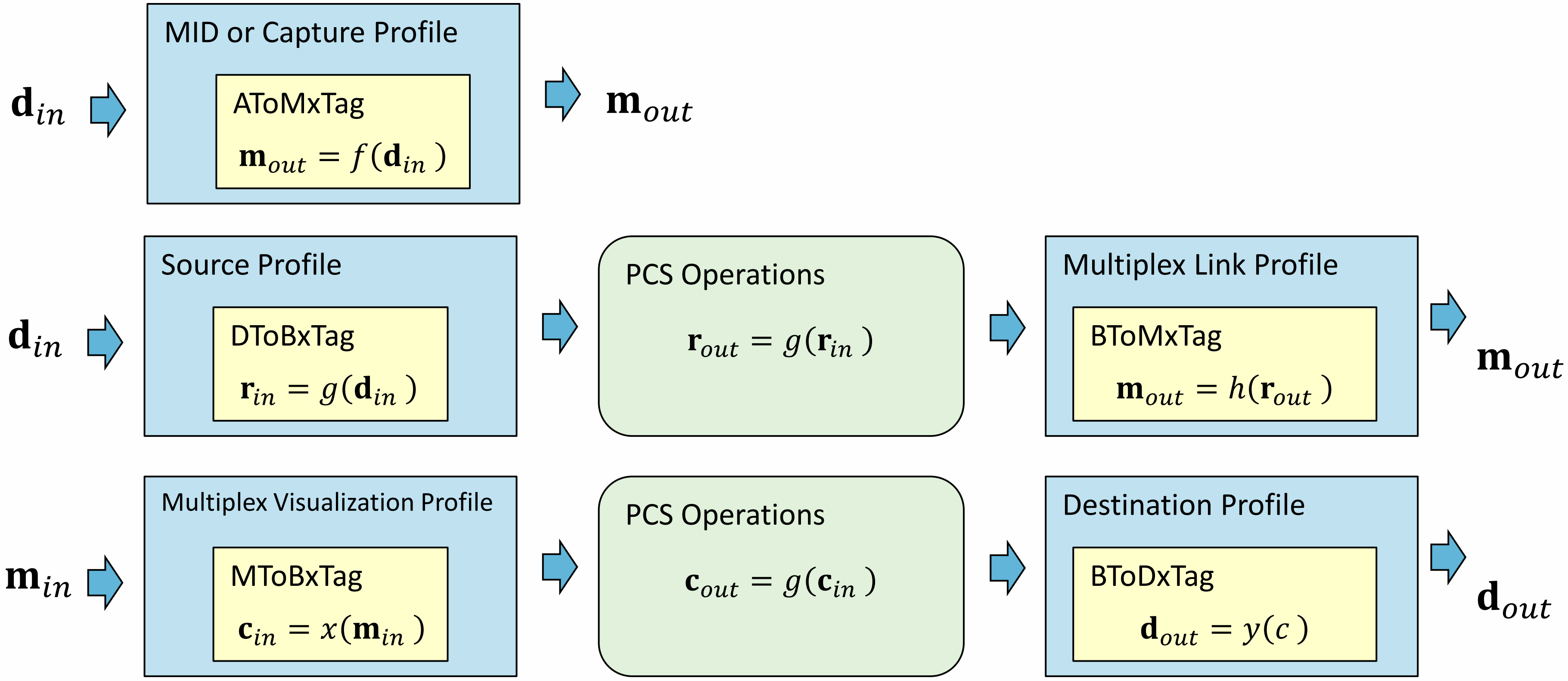
$$\mathbf{X} = \mathbf{CD^T}\left(\mathbf{DD^T}\right)^{-1} \qquad \mathbf{M} = \mathbf{RD^T}\left(\mathbf{DD^T}\right)^{-1} \qquad \mathbf{S} = \mathbf{DR^T}\left(\mathbf{RR^T}\right)^{-1}$$

Identification Profiles

- **Multiplex Connection Space profiles allow relationships with named channels ($\mathbf{m}$) to be identified by a profile**
  - Useful for pigment or feature identification



Identification Workflows



Notes:

- *Multiplex channels can be determined directly or from a spectral PCS*
- *Visualization can be colorimetric or spectral*

In Conclusion…

Last thoughts…

- **In spectral color workflows parts of the color equation $(\mathbf{COI})$ in profile color transforms are either missing or supplied and applied separately by the CMM**
- **Various Spectral Color Workflows are enabled using iccMAX profiles**
- **Spectral workflows discussed:**
  - Color space workflows involving a spectral PCS
  - Printing workflows communicating with spectral reflectance
  - Display workflows allowing for custom observer matching
  - Capture workflows to capture spectral characteristics of objects or scenes or greater spectral sampling to get better colorimetry
  - Identification workflows where pigment or features can be identified using spectral information

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?

iccMAX