Spectral Print Inversion Strategies

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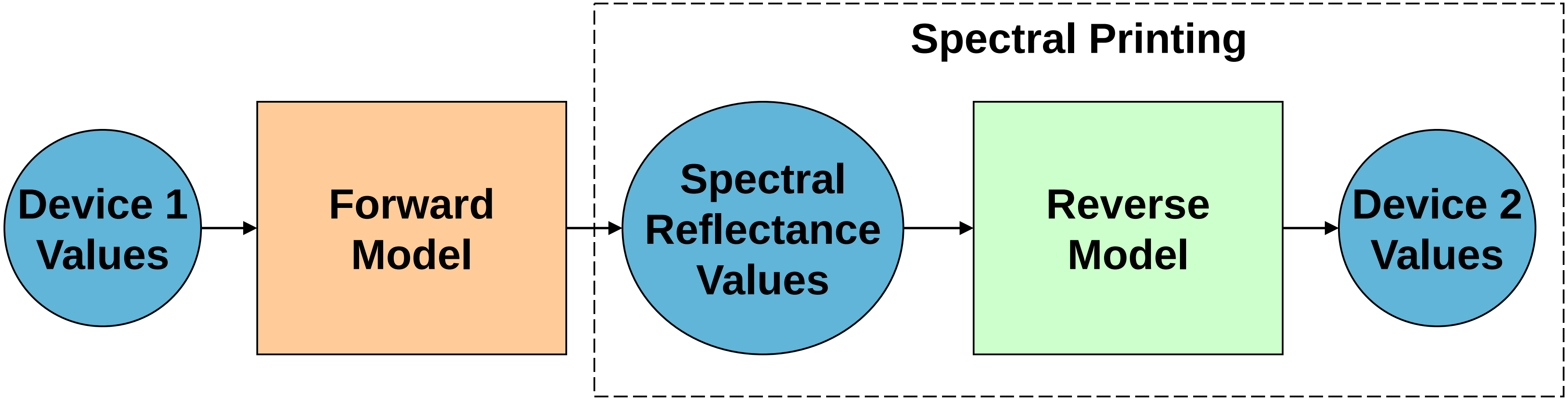
Digital Print Conference

Agenda

- Spectral print color management
- Forward model review
- Reverse model basics
- Spectral Gamut Mapping
- Strategies of inverting forward models
- Wrap Up

Spectral Print Color Management (101)



- Device 1 values come from source image
- Device 2 values are used to drive printing
- Forward model can be either camera model or printer model
- We will focus on Spectral printing

Forward Print Model Review

- **Camera model involves measuring spectral values of object, capturing object as image (to get device values) and establishing relationship between image values and expected measurement of captured object**
  - Beyond context of this presentation
- **Print model involves printing various device values, spectrally measuring printed results and establishing relationship between device values and expected measurement**
  - Examples in following slides

Basic Print Forward Model 1 – Yule-Neilson

$$R_{output,\lambda}^{1/n} = \sum_{i=1\to 2^k} P_i R_{i,\lambda}^{1/n} \qquad P_i = \prod_{j=1\to k} \begin{Bmatrix} a_j & \text{if } j \text{ is in primary } i, \\ (1-a_j) & \text{if } j \text{ is not in primary } i \end{Bmatrix}$$

- **Device values are linearized so that area coverages for ink j (a_j) are associated with $R^{1/n}$ reflectances**
- **Neugebaur primaries (total of 2^k) are made up of zero and 100% combinations of *k* inks**
  - Spectral measurement of Neugebaur primaries needed
- **Essentially performed in two stages**
  1. Calculation of Neugebaur probabilities from area coverages (right equation)
  2. Summing product of probabilities times reflectance$^{1/n}$ of Neugebaur probabilities (left equation)
- **Yule-Neilson can be thought of *k*-dimensional linear interpolation of reflectances raised to the 1/n power**
- **Cellular Yule-Neilson involves using same technique on smaller cubes of device values (take advantage of better local linearity)**
  - Requires mapping of device values to proper cube and address in cube

Basic Print Forward Model 2 – Math with regression

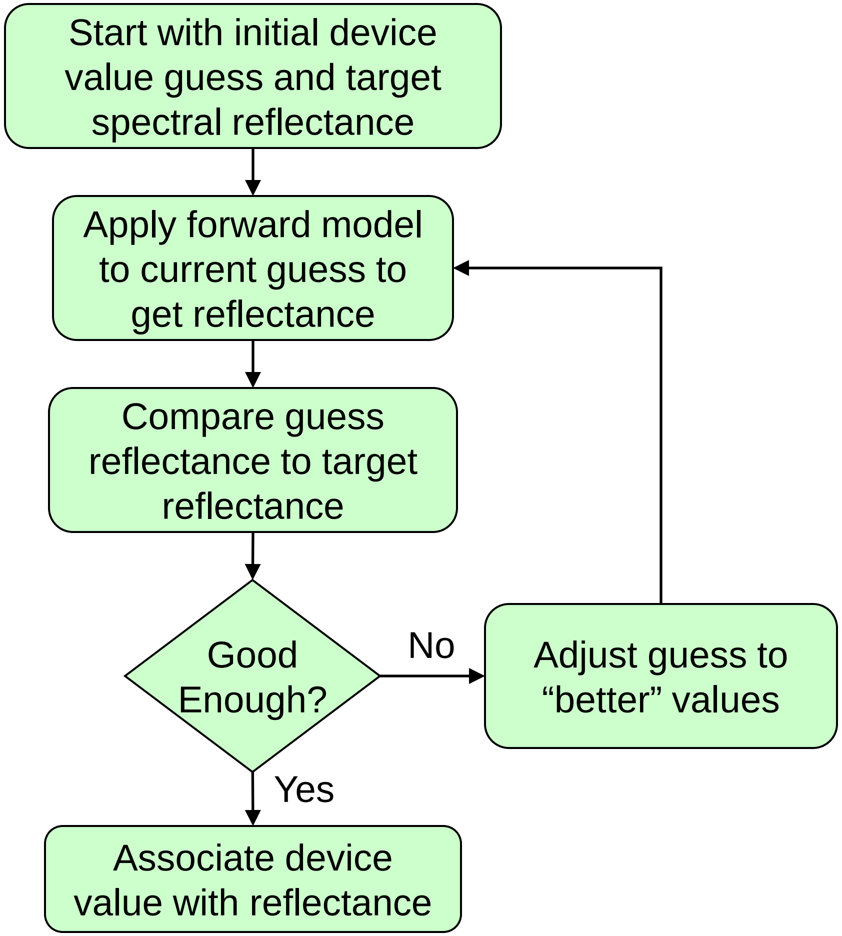
$$R_{output,\lambda} = \sum_{i=1\rightarrow n} a_i f_i(d_1, d_2, \ldots, d_k)$$

- **Output reflectance is first expressed as a sum of scaled functions of device values (Example: terms of polynomial combinations of device values)**
  - The magic is deciding what functions $f_i()$ to use
- **Prints of various device combinations made and spectral measurements taken**
- **Use least squares regression to solve for coefficients (a_i)**
- **Optimization ?**
  - Solve for $R^{1/n}$ instead of R

Reverse Model Basics

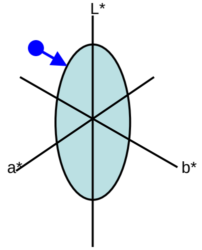
- **Going from spectral reflectance to device values**
  - Generally over-determined and dimensionally large
- **Use forward model with a search strategy to find "best" device values combination to achieve spectral reflectance**
  - Not all spectral reflectances are possible (some "gamut" mapping most likely needs to be performed)
- **Use direct inversion of forward model**
- **Separate inversion process into stages**

General Inversion Process

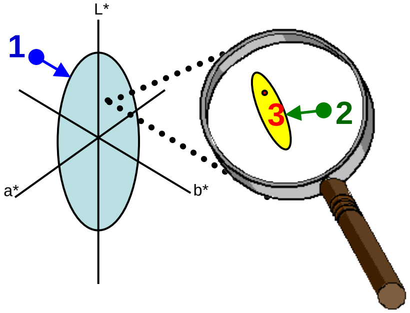


- **Inversion using forward model is a process of searching for device values that achieve the target spectral reflectance**
- **Different approaches implement each block differently**
  - In some cases a guess is actually a set of guesses
- **Several important and related questions:**
  - How does gamut mapping fit in?
  - How do you compare spectral reflectances?
  - What is "good enough"?
  - How do you adjust to get better?

Spectral Gamut Mapping



- Colorimetric gamut mapping involves mapping a point outside colorimetric gamut of a device to a point that can be achieved by a device
- A spectral gamut is the set of all possible spectral reflectances that can be achieved by a device
  - Can conceptually be thought of as a set of metamer sets



- Spectral Gamut mapping is potentially three-fold
  1. Desired color is outside colorimetric gamut for any light source
  2. Desired color is inside colorimetric gamut for at least one light source but cannot be spectrally matched (outside spectral gamut)
  3. Desired color can be spectrally matched (inside spectral gamut)
- May be performed as part of cost function or possibly as an adjustment to the desired target reflectance before search

Comparing Spectral Reflectances

- **Spectral reflectance conveys appearance potential rather than simply appearance**
  - Actual appearance requires light source and observer
  - Different appearances with different light sources and/or observers
- **RMS comparison**

  $$RMS = \sqrt{\sum_{\lambda}\left(r_2(\lambda) - r_1(\lambda)\right)^2},$$

  - Zero if spectra are same, but doesn't compare perceptual differences (Example: near IR and UV spectral differences are less noticeable to observers)
- **Multiple Colorimetric comparisons**

  $$\Delta S = \sum_i c_i \Delta E_i$$

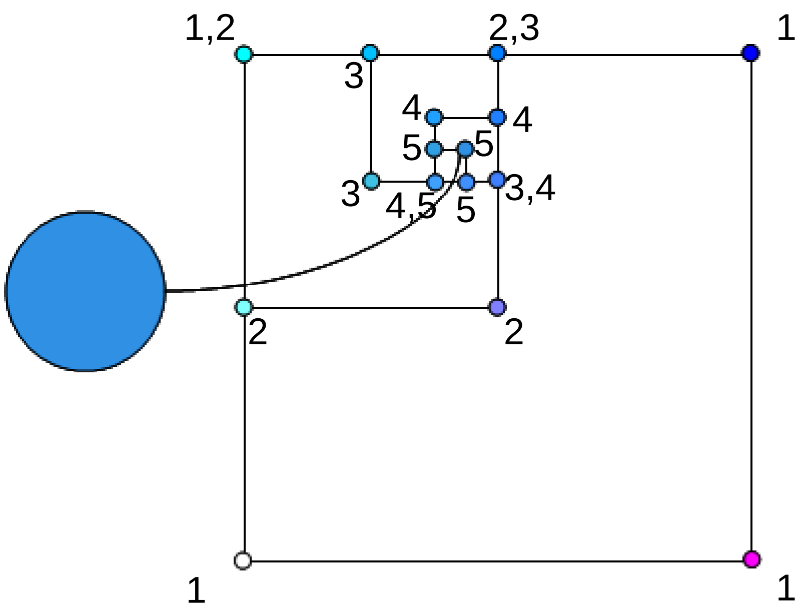
  - Use fact that when spectral reflectances are the same, the colorimetric differences for all observers and light sources will be zero
  - Use weighted sum of colorimetric color differences that are important (What light sources/observers are important? …)
  - Hint: For performance possibly use ΔXYZ_i instead of ΔE_i
- **Use weighted combination of RMS and Multiple Colorimetric comparisons**

A Brief List of Search Strategies

(Non-exhaustive)

Search Strategy 1 – Recursive Descent

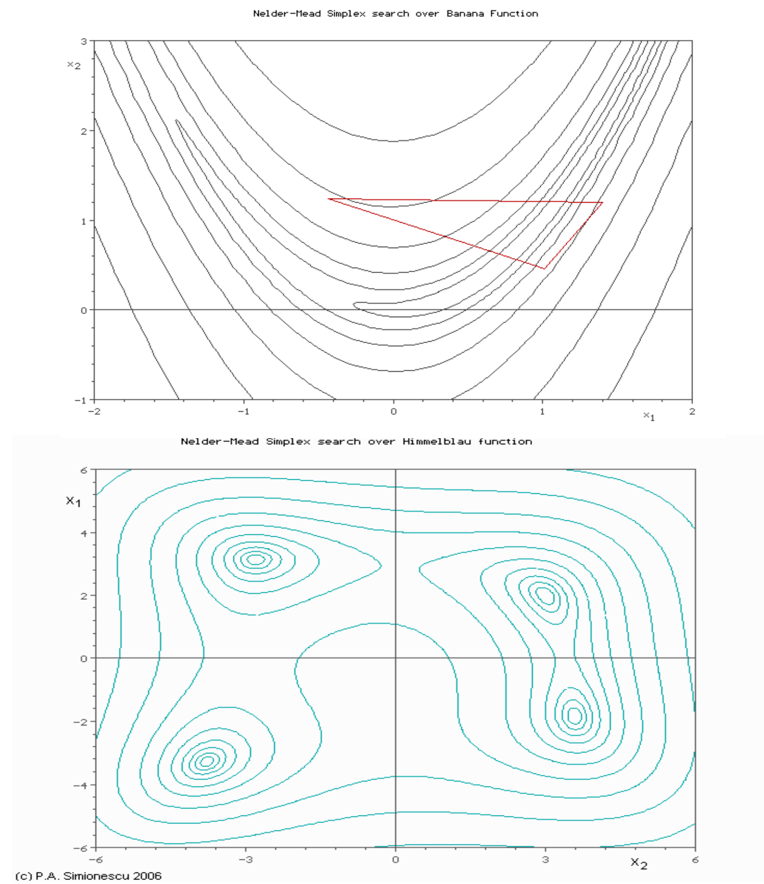
- **Initial guess is the Neugebaur primaries**
- **Find which guess closest to desired answer**
- **Next guess includes "cube" containing closest point and those some partial way from closest point**
- **Repeat until reflectance "matches" or sub-cube edge size is "small enough"**
- **Notes:**
  - Quick and easy to implement
  - Fast decent
  - Susceptible to local minima



Sample 2-dimensional recursive decent

Search Strategy 2 – Downhill Simplex Method

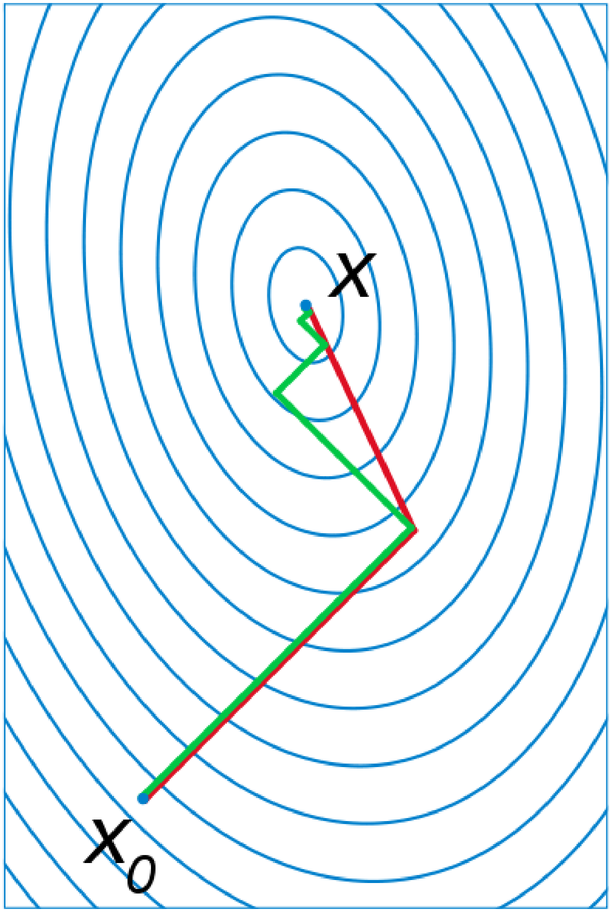
- **“Somehow” pick k+1 non-colinear points forming k-dimensional simplex**
  - Note: k is num of device channels
- **Calculate and order closeness of points**
- **Reflect, expand, contract, or reduce to improve “worst” point**
- **Repeat until “close enough” or simplex is “small enough”**
- **Notes:**
  - Fairly easy to implement
  - Search is not always quick
  - Susceptible to local minima
  - Starting points critical to get best results



Sample Simplex Search

Search Strategy 3 – Gradient Decent

- **Pick some starting point**
- **Calculate (estimate) slope of "closeness" function at point**
  - Gradient may be determined from forward function (if you have one)
  - May require using forward transform on several points fairly near guess point to estimate gradient
- **Use "slope" of gradient to determine next guess**
- **Repeat until "close enough" or distance to next guess is "small enough"**
- **Notes:**
  - Several varieties of gradient decent
  - Fairly quick to find solution
  - Susceptible to local minima
  - Starting point is critical to best results

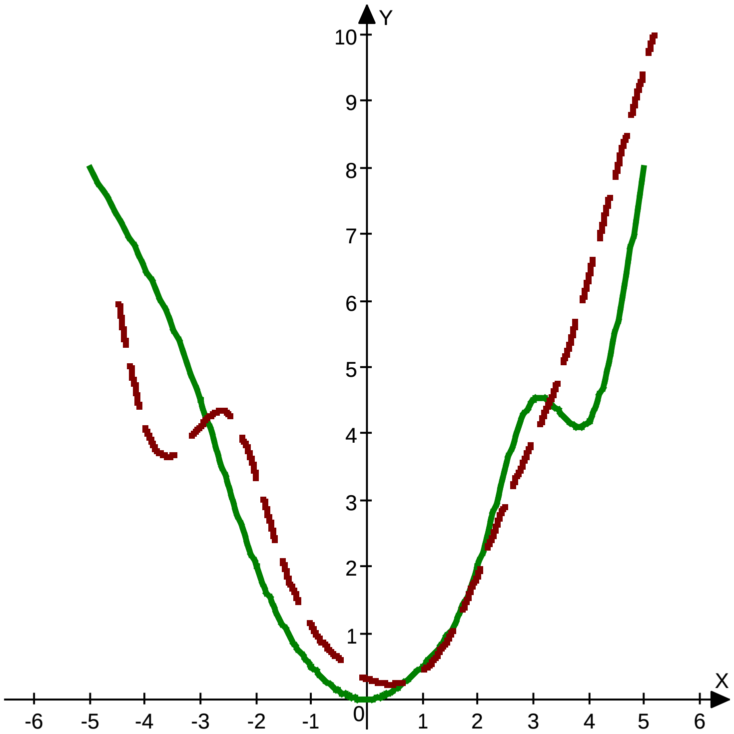


Dealing with Local Minima

- **Q) How do you determine if a search only found a local minima?**

- **A) Search again (possibly several times) with some sort of “an adjustment”:**
  - Use last result with some adjustment
    - Use a different search strategy
    - Use a different cost functions (see figure)
  - Use a different random starting point

- **Multiple different searches may help to gain confidence that minima is not local**



Different closeness functions may result in different minima results

Strategy 4 – Direct Inversion of Yule-Neilson

- **Reverse the stages of forward model**
  - Use constrained linear regression to solve for Neugebaur probability vector $\mathbf{p}_{\mathbf{Neug}}$
  - Multiply probability vector by channel participation matrix to find area coverages
  - Convert area coverages to device values
- **Excellent at finding device values for target reflectance inside spectral gamut of printer**
- **Regression provides poor gamut mapping strategy if outside spectral gamut of printer**
- **Provides excellent first guess going into a secondary search strategy**

1. Solve for $\mathbf{p}_{\mathbf{Neug}}$ in :

$$\mathbf{r}_{\mathbf{target}} = \mathbf{R}_{\mathbf{Neug}}\mathbf{p}_{\mathbf{Neug}}$$

Where :

$$\mathbf{R}_{\mathbf{Neug}} = [\mathbf{r}_1 \quad \mathbf{r}_2 \quad \cdot \quad \mathbf{r}_{2^k}],$$

$\mathbf{r}_\mathbf{i}$ is reflectance$^{1/n}$ vector for the i^{th} Neugebaur primary

$$\mathrm{p} = [p_1 \quad p_2 \quad \cdot \quad p_{2^k}]^T$$

with the constraint that

$$0 \le p_i \le 1$$

2. Solve for area coverages :

$$\mathbf{a} = \mathbf{D}\,\mathbf{p}_{\mathbf{Neug}}$$

Where :

$$\mathbf{a} = [a_1 \quad a_2 \quad \cdot \quad a_k]^T,$$

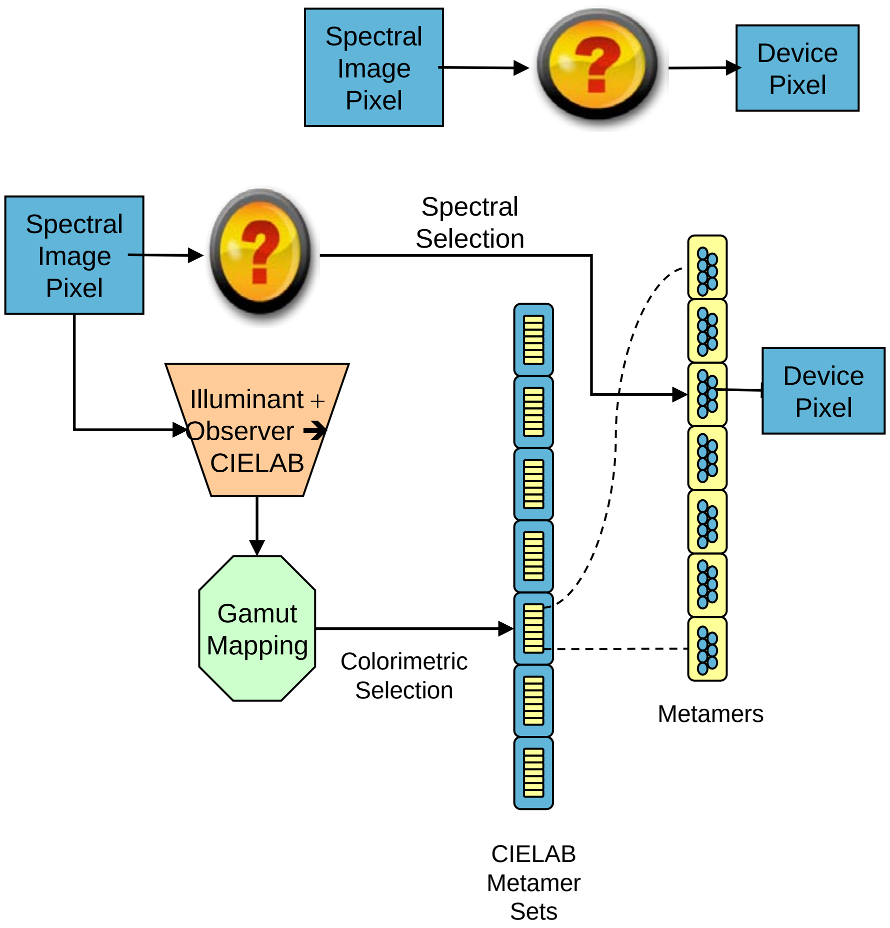
a_{m} is area coverage for ink m,

$$\mathbf{D} = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & \cdot & 1 \\ 0 & 0 & 1 & 1 & 0 & \cdot & 1 \\ 0 & 0 & 0 & 0 & 1 & \cdot & 1 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & \cdot & 1 \end{bmatrix},$$

$$d_{j,i} = \begin{Bmatrix} 1\text{-if ink } j \text{ (row) is 100\% in } i^{\text{th}} \text{ Neugebaur primary (column)} \\ 0\text{-if ink } j \text{ (row) is 0\% in } i^{\text{th}} \text{ Neugebaur primary (column)} \end{Bmatrix}$$

Using Multiple Stages

- **Place intermediate steps between going directly from spectral reflectance to device values**
- **Intermediate steps can use alternative forms of representing spectral information forming an interim connection space (ICS)**
  - Colorimetry under multiple light sources (SGMF)
  - Colorimetric information with additional metamer information (LABPQR)
  - Colorimetric information with alternative cone responses (LABRGB)
  - PCS decomposition of spectral reflectance
  - Multispectral “cone” responses
- **Interim steps provide for ability to gamut map and pre-cache output results for improved performance**



Strategy 5 – Iteration and Sorting

- **Iterate “all” possible device combinations**
- **Apply forward model and organize results**
  - Example: Store as recursive hash tables with hashes based on colorimetry under different light sources (SGMF)
- **Search from organized results after iteration complete**
- **Gamut mapping needs to be performed on valid but empty hash entries**
- **Notes:**
  - Not quick and requires extensive storage
  - Quantization issues
    - Consider iteration step size
    - Consider hashing bin sizes
  - Not subject to starting conditions

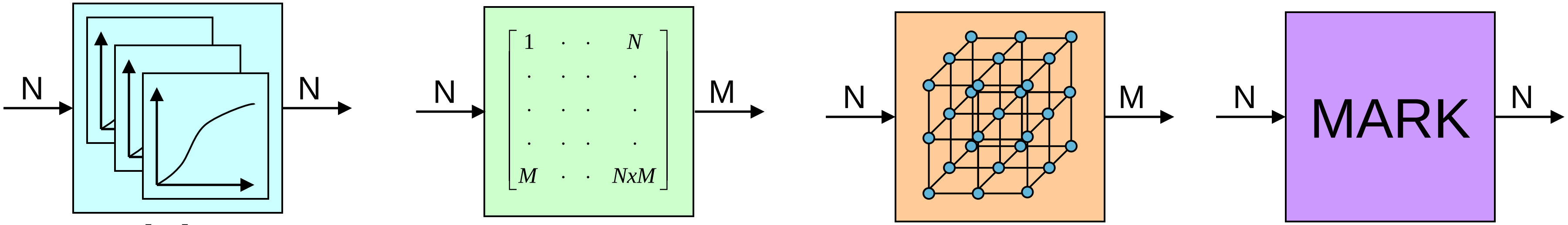
Strategy 6 – ICS with LUT interpolation

- **Use ICS to project spectral reflectance to lower-dimensional representation (4 – 6 dimensions)**
- **Populate interpolation Look Up Table (LUT) for ICS grid points (each grid point represents a spectral reflectance)**
- ***ICS sampling needs to be fine enough to provide local linearity of device values in neighboring grid points***
  - This may be more difficult for grid points that representing metamers (Example - interpolating across black generation)
- **For each grid point use some direct search strategy to find device values**
- **Gamut mapping should be performed for grid points outside of printer’s gamut**
- **Possible ICS’s include: LabPQR, LabRGB, (maybe PCA based?)**

Encoding spectral print with an ICC Profile

***Requires ICC spec change**

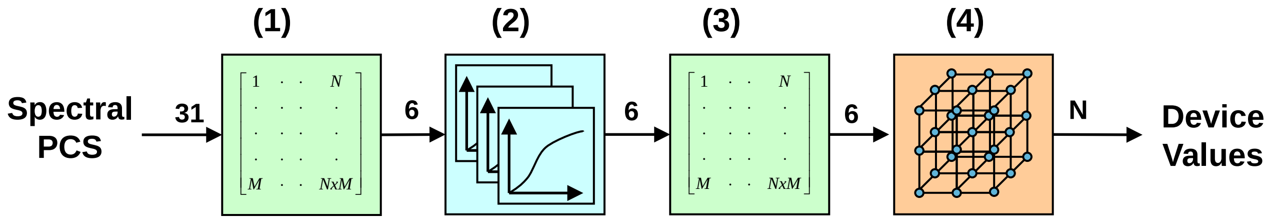
Review – ICC Multi Processing Elements Tag Type



(A) (B) (C) (D)

- **V4.3 profiles can have optional floating point tags with an arbitrary sequence of processing elements**
- **Repertoire of processing elements**
  - A. Sets of 1-dimensional functions that are made up of parametric and sampled curve segments
  - B. Non square N x M linear matrix transform
  - C. N x M multi-dimensional lookup table
  - D. Marker elements that perform no operation on values

Encoding LabPQR LUT in profile



- **Can be encoded using existing version 4.3 Multi Processing Elements Tag type**
  - Use matrix to convert spectral reflectance to XYZPQR
  - Use curves to apply cubic portion of XYZPQR to LabPQR conversion
  - Use matrix to finish XYZPQR to LabPQR conversion
  - Use CLUT element to interpolate from LabPQR to Device Values
- **Requires a profile specification that supports a Spectral PCS**

Wrap Up – Spectral Print Inversion

- **Having a really good forward model is critical!**
  - A perfect inversion of a bad forward model results in a bad reverse model
- **Using a combination of multiple search strategies and/or multiple cost functions can improve/verify search results**
- **Multi-stage approaches allow for gamut mapping flexibility and application performance**
- **Spectral print inversion could be possible in ICC like context with spectral PCS**

Various References

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- **M. W. Derhak and M. R. Rosen, "Spectral colorimetry using LabPQR - An interim connection space", J. Imaging Sci. Technol. 50, 53–63 (2006)**
- **ICC.1-2001/ICC.1-2010 Specification, see specifications at http://www.color.org**

Thank You

Questions?