International
Color Consortium

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Multi-ink proofing & Spectral methods using ICC profiles

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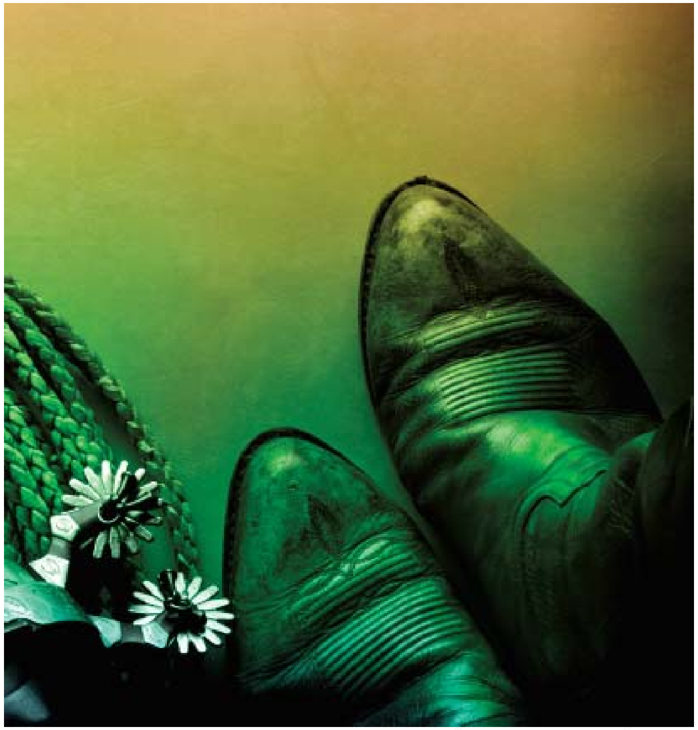
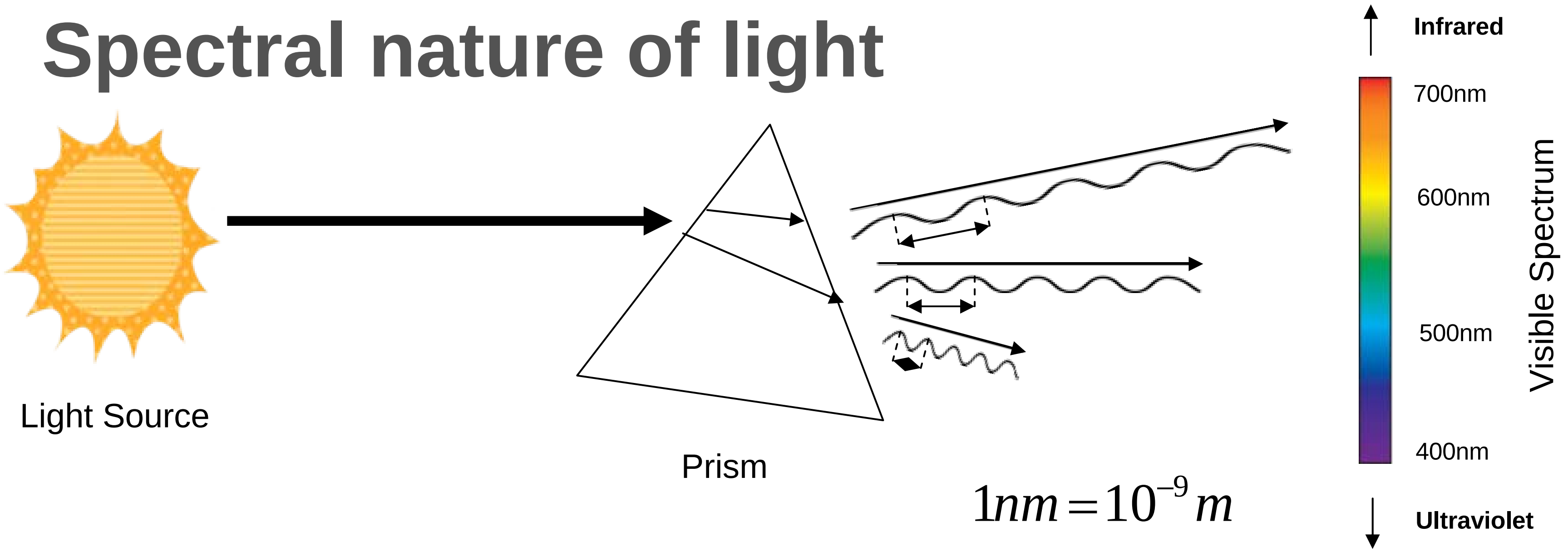


Overview

- Review spectral nature of color
- Basics of ICC profile generation
- Approaches to spectral printer modeling
- Introduce Extended Ink Printers
- Profiling Extended Ink Printers
- Direct Encoding of a Spectral Model in an ICC profile
- Going Beyond Colorimetry

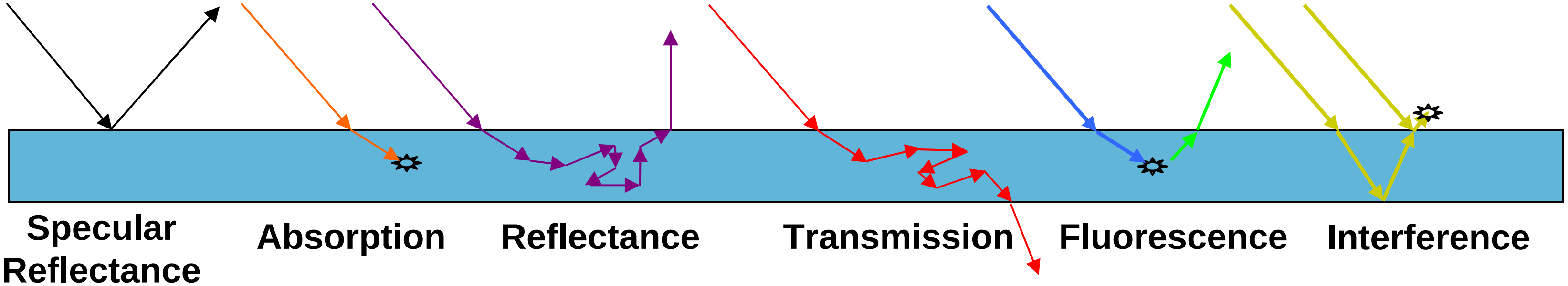
Spectral nature of light



$$1nm = 10^{-9} m$$

- **Light is emitted by a source that releases energy in the form of electro-magnetic radiation**
  - Light travels as waves of alternating electric and magnetic fields
  - The wavelength (often denoted by ‘λ’ - lambda) is the distance between waves as measured in nanometers (nm)
  - Wavelengths of Visible Light range from 400nm to 700nm
  - The energy level determines the wavelength of the light with higher energy levels resulting in light with smaller wavelengths
- **A prism can separate the wavelengths of light in a light beam**
  - Light refracts (bends) based upon wavelength of light
- **Light sources can (and often do) emit light at multiple wavelengths at the same time**
  - A spectral power distribution (SPD) shows the wavelength makeup of light

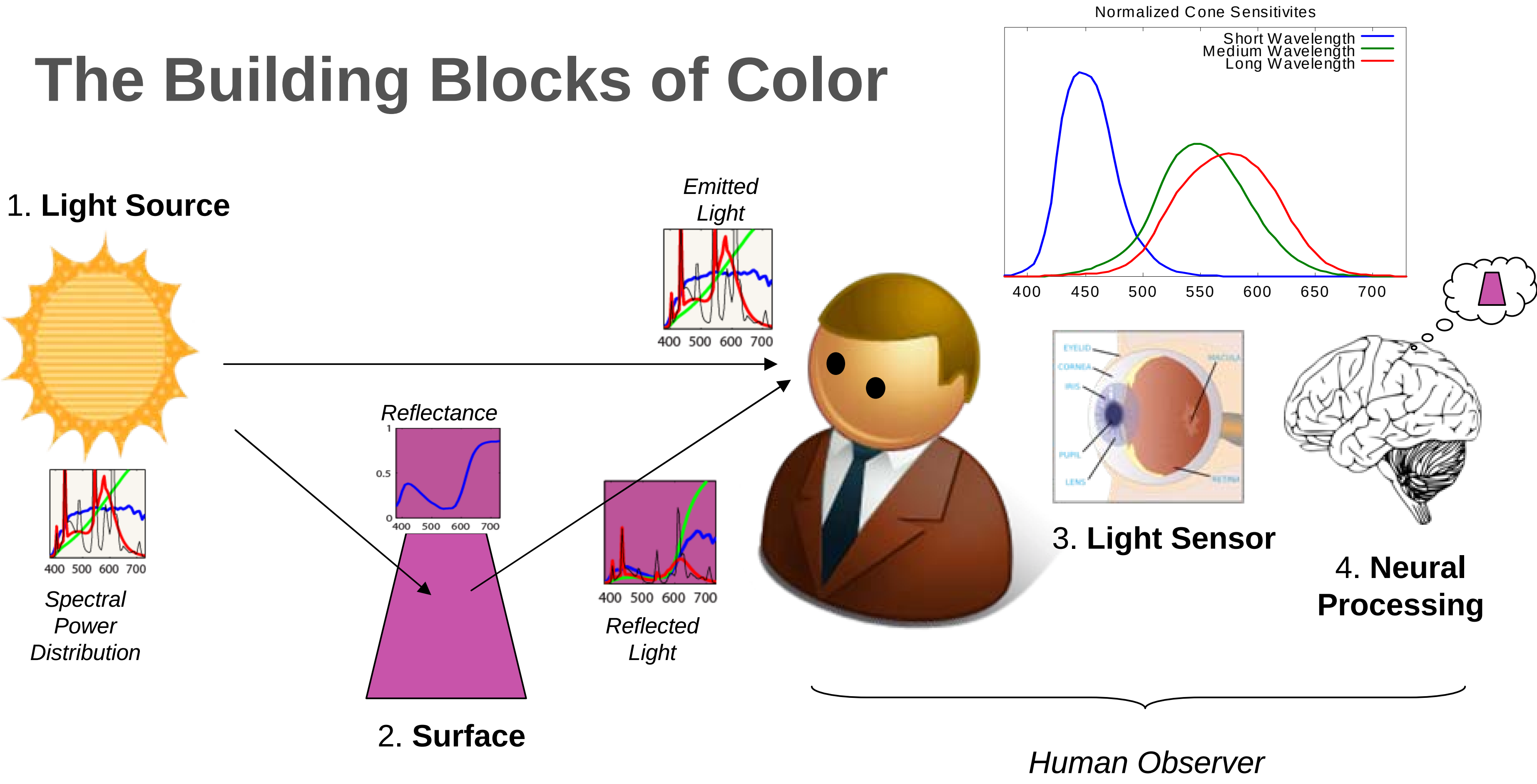
Possible interactions of light with a surface



- **Specular Reflectance – light bounces off surface at the opposite angle unchanged**
- **Absorption – light enters surface, bounces around and is absorbed – thus raising the energy level of the surface (e.g. thermal heat)**
- **Reflectance – light enters surface, bounces around, and eventually leaves surface unchanged at possibly an arbitrary angle**
- **Transmission – light enters surface, bounces around, and eventually leaves opposite surface unchanged at possibly an arbitrary angle**
- *Fluorescence – light enters surface, bounces around, is absorbed and then re-emitted at a lower energy level (with a longer wavelength), bounces around, and eventually leaves (either) surface.*
- *Interference – light enters surface bounces from opposite service where it interferes (constructively or destructively) with light just hitting surface*

- ***Note: How a photon interacts with a surface is wavelength dependent***

The Building Blocks of Color



1. **Light Source**

Spectral Power Distribution

Reflectance

2. **Surface**

Emitted Light

Reflected Light

3. **Light Sensor**

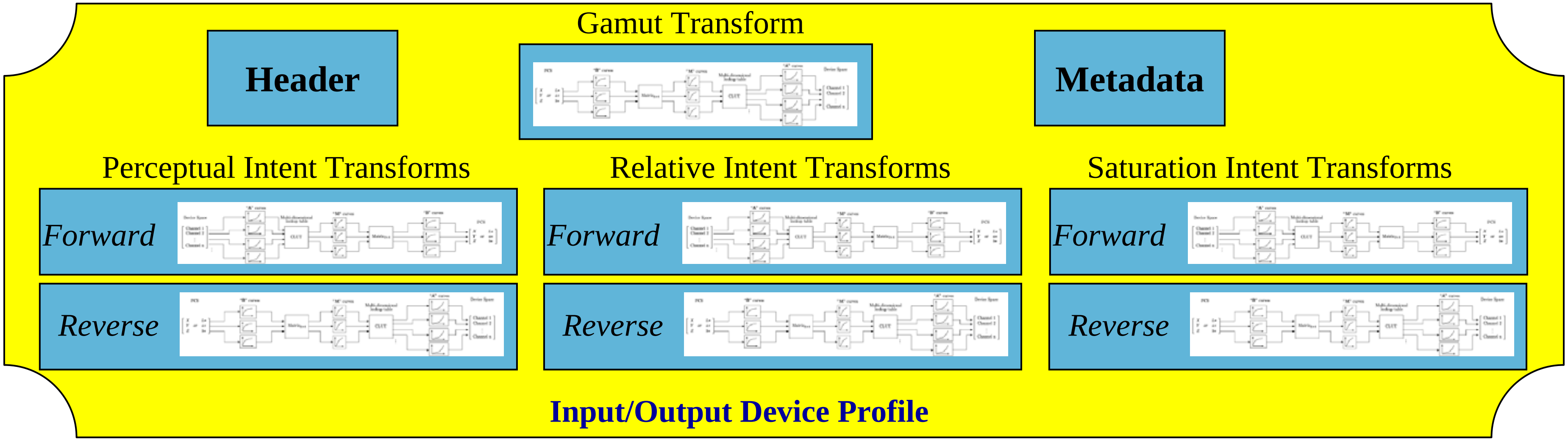
4. **Neural Processing**

Human Observer

Note: Color is a Human Perception

ICC Profile (Generation) Basics

Basic ICC Profile Contents



Gamut Transform

Header

Metadata

Perceptual Intent Transforms

Forward

Reverse

Relative Intent Transforms

Forward

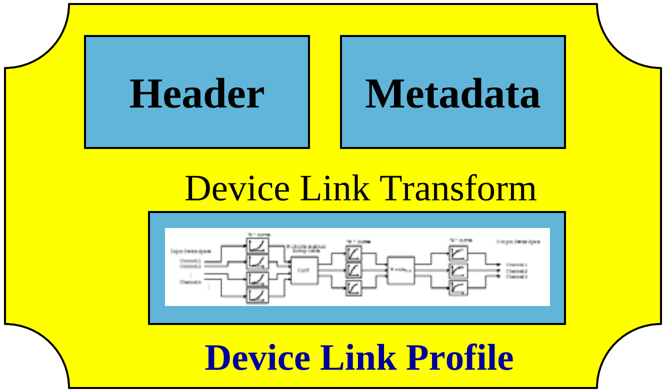
Reverse

Saturation Intent Transforms

Forward

Reverse

Input/Output Device Profile

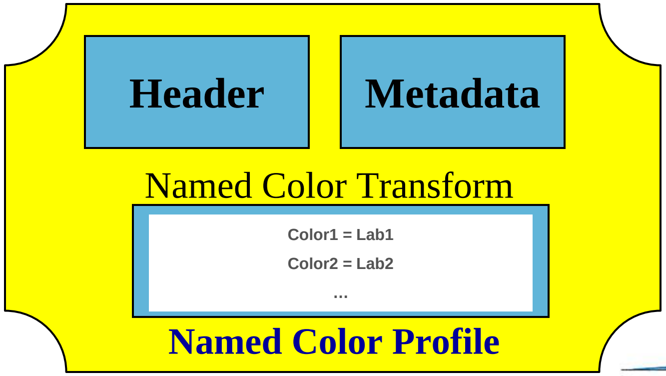


Header

Metadata

Device Link Transform

Device Link Profile



Header

Metadata

Named Color Transform

Color1 = Lab1

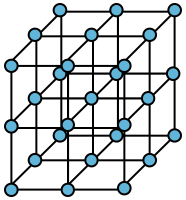
Color2 = Lab2

…

Named Color Profile

Basics of ICC printer profile generation (101)

- **1. Correctly populate header and metadata tags**
- **2. Populate Forward Tags (eg AtoB tags)**
  - Use model or measurements of actual device output to establish transform that maps device values to PCS values
  - For each Device combination address in N-Dimensional table:
    - Use transform to find corresponding PCS value
    - Potentially adjust PCS value to achieve preference aims
    - Store PCS value in table at the Device combination address



- **3. Populate Reverse Tags (eg BtoA tags)**
  - For each PCS address in 3-Dimensional table:
    - Potentially remap corresponding PCS value to different PCS value
      - Map to point inside gamut if PCS value is outside gamut
      - Re-rendering for preference aims
    - Find a device value combination using transform from step 2 that achieves PCS value
    - Store found device value combination in the table at the PCS value address
- **4. Populate Gamut table**
  - For each PCS address in N-dimensional table:
    - Mark value zero if PCS value in gamut / non-zero if outside

Basic Printer Spectral Modeling

Basic Printer Spectral Modeling (1)

- **One Dimensional Modeling (Murray-Davis)**

$$R_{output,\lambda} = (1\text{-}c)\cdot R_{paper,\lambda} + c\cdot R_{color,\lambda}$$

Where:

  - $R_{x,\lambda}$ represents reflectance for x at wavelength λ
  - c represents area coverage of the color

- **Represents a parametric form of linear interpolation between reflectance of paper and reflectance of color**
- **Doesn’t account for non-linear aspects**

Basic Printer Spectral Modeling (2)

- **Multi-Dimensional**
  - Consider all possible 0% and 100% combinations with multiple inks (Neugebaur)
    - Note: With N inks there 2^N Neugebaur primaries
  - Equations express N-dimensional interpolation of reflectance of Neugebaur primaries (Demichel)

Two Dimensional case:

$$R_{\mathrm{output},\lambda} = (1-c_1)(1-c_2)\cdot R_{paper,\lambda} + c_1(1-c_2)\cdot R_{c1,\lambda} + (1-c_1)c_2\cdot R_{c2,\lambda} + c_1\cdot c_2\cdot R_{c1+c2,\lambda}$$

Three Dimensional case:

$$R_{output,\lambda} = (1-c_1)(1-c_2)(1-c_3)\cdot R_{paper,\lambda} + c_1(1-c_2)(1-c_3)\cdot R_{c1,\lambda} + (1-c_1)c_2(1-c_3)\cdot R_{c2,\lambda} + c_1\cdot c_2(1-c_3)\cdot R_{c1+c2,\lambda} + (1-c_1)(1-c_2)c_3\cdot R_{c3,\lambda} + c_1(1-c_2)c_3\cdot R_{c1+c3,\lambda} + (1-c_1)\, c_2\cdot c_3\cdot R_{c2+c3,\lambda} + c_1\cdot c_2\cdot c_3\cdot R_{c1+c2+c3,\lambda}$$

Where:

- $R_{x,\lambda}$ represents reflectance measurement for x at wavelength λ
- c_i represents area coverage of the i^{th} color

- **Also doesn't account for non-linear aspects**

Basic Printer Spectral Modeling (3)

- **Accounting for Non-linear aspects (Yule-Nielsen)**
  - Discovered that non linear relationships could be better described using a power function

$$R^{1/n}_{output,\lambda} = (1-c)\cdot R^{1/n}_{paper,\lambda} + c\cdot R^{1/n}_{color,\lambda}$$

Where:

- $R^{1/n}_{x,\lambda}$ represents reflectance measurement raised to power of 1/n for x at wavelength λ
- c represents area coverage of the color
- n represents value use for fitting relationship

- **Value for n is empirically determined through fitting algorithm**
- **Converts non-linear system into linear system**

Basic Printer Spectral Modeling (4)

- **Yule-Nielsen-Neugebaur Model (YNN)**
  - Combine Yule-Nielsen to Neugebaur primaries

Two Dimensional case:

$$R^{1/n}_{output,\lambda} = [(1-c_1)(1-c_2)\cdot R^{1/n}_{paper,\lambda} + c_1(1-c_2)\cdot R^{1/n}_{c1,\lambda} + (1-c_1)c_2\cdot R^{1/n}_{c2,\lambda} + c_1\cdot c_2\cdot R_{c1+c2,\lambda}]^n$$

Three Dimensional case:

$$R^{1/n}_{output,\lambda} = [(1-c_1)(1-c_2)(1-c_3)\cdot R^{1/n}_{paper,\lambda} + c_1(1-c_2)(1-c_3)\cdot R^{1/n}_{c1,\lambda} + (1-c_1)c_2(1-c_3)\cdot R^{1/n}_{c2,\lambda} + c_1\cdot c_2(1-c_3)\cdot R^{1/n}_{c1+c2,\lambda} + (1-c_1)(1-c_2)c_3\cdot R^{1/n}_{c3,\lambda} + c_1(1-c_2)c_3\cdot R^{1/n}_{c1+c3,\lambda} + (1-c_1)\, c_2\cdot c_3\cdot R^{1/n}_{c2+c3,\lambda} + c_1\cdot c_2\cdot c_3\cdot R^{1/n}_{c1+c2+c3,\lambda}$$

Where:

- $R^{1/n}_{x,\lambda}$ represents reflectance measurement raised to power of 1/n for x at wavelength λ
- c_i represents area coverage of the i^{th} color

Partially accounts for non-linear aspects

- **Note: This model can be extended to interpolate between intermediate combinations of inks (IE include 50% combinations) - Cellular YNN (CYNN)**

Populating Forward Table with (C)YNN

I. **Setup to apply model**
   1. Simultaneously estimate n-factor while determining area coverage linearization for each color using spectral reflectance measurements of single color ramps
   2. Apply 1/n power to reflectance measurements of Neugebaur primaries
   3. Setup to interpolate between primaries

II. **Populate table by iterating through each grid point**
   1. Calculate associated ink amounts for grid point
   2. Apply linearization to determine area coverages for each ink
   3. Use area coverage values to interpolate between (involved) Neugebaur primaries to calculate estimated adjusted reflectance
   4. Raise interpolation results to nth power to get estimated reflectance
   5. Apply D50 light source and CIE 2-degree standard observer to get XYZ values – (covert to CIELAB if needed)
   6. Encode PCS value for grid point

Functional Printer Modeling

- **Another empirical approach to printer modeling might involve establishing a functional relationship directly from Device Values**

  Example:

$$\begin{aligned} R_{\lambda}(c, m, y, k) = a_0 &+ f_{c,\lambda}(c) + f_{m,\lambda}(m) + f_{y,\lambda}(y) + f_{k,\lambda}(k) + \\ &f_{cm,\lambda}(c, m) + f_{cy,\lambda}(c, y) + f_{ck,\lambda}(c, k) + \\ &f_{my,\lambda}(m, y) + f_{mk,\lambda}(m, k) + f_{yk,\lambda}(y, k) + \\ &f_{cmy,\lambda}(c, m, y) + f_{cmk,\lambda}(c, m, k) + f_{cyk,\lambda}(c, y, k) + \\ &f_{myk,\lambda}(m, y, k) + f_{cmyk,\lambda}(c, m, y, k) \end{aligned}$$

  Where:

  - R_{λ} is the output reflectance at wavelength λ
  - a_0 is a constant value
  - $f_{x0 \,..\, xn,\lambda}(x0, \ldots, xn)$ is a sub-function defining of a non-linear combination of variables x0 ... xn. (Note: A polynomial example would entail a constant times the product of the variables).

- **The nature of which sub-functions to use and the contents of each sub-function is domain specific and would probably need to be experimentally determined**
- **There is currently no direct way to directly encode such a functional printer model in an ICC Profile!**
- **The best approach is to populate an N-dimensional table by sampling the functional model for each grid point**

Reverse Table Generation

Reverse Table Generation Difficulties

- **Gamut mapping is non-deterministic**
  - A matter of finding the “right” wrong color
  - There is no 1 right way to do it (many methods exist)
    - For examples see proceedings of various CIC conferences
- **The PCS is 3-dimensional**
  - If device supports more than 3 colors then for some PCS colors there will be more than one Device Value combination that can achieve the same PCS color
  - Only one Device Combination can be stored for each PCS address
- **Ink separation needs to be determined**
  - No one right way exists to define ink separation

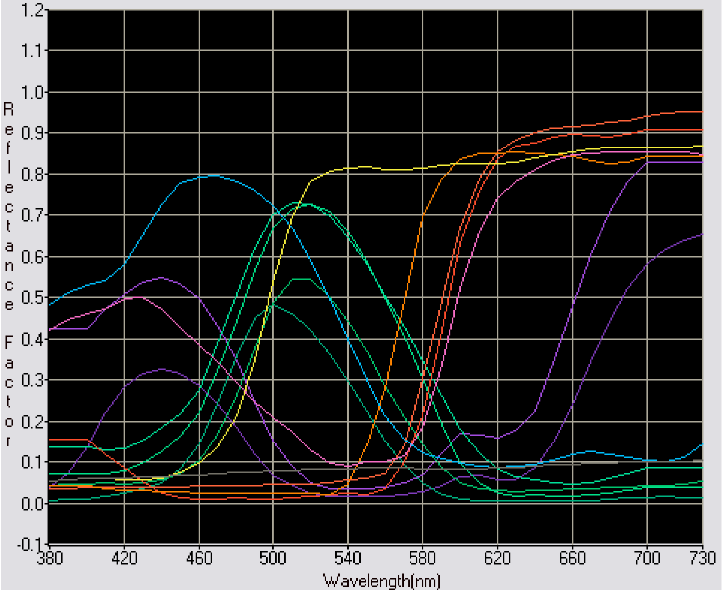
Ink Separation Criteria

- **Several factors can go into finding ink separation for populating Reverse Tables**
  - Achievable Output Gamut
    - They may not be the same as gamut achievable by device
  - Interpretability
    - Since interpolation is used for in between colors it is important that Device Values for adjacent PCS addresses are “close” to one another
  - Color Inconstancy
    - Some Device Combinations may change appearance more than others when the light source changes
  - Output Quality
    - Different Device Combinations can potentially negatively impact how the output will look
  - Total colorant usage
    - Total colorant load and cost may be a factor

Extended Ink Printers

Printing with Extended-Ink Printers

- **Several Ink Jet Printers support the ability to output with more than 4 colors.**
- **Extra colors can be broken up into three categories:**
  - Light Inks (eg, light cyan, light magenta, light black)
    - Helps improve the “optical resolution” of conventional process channels
    - Can be considered an extension of process channels that use 1-D lookup tables to provide the device value to ink output separation
    - Usually accounted for outside ICC workflow
  - Spot Color Inks (eg white ink, gloss, metallic colors)
    - Not generally accounted for by ICC workflows
    - Documents themselves define where and how inks are to be used
  - Hi-Fi Inks (eg Red, Orange, Green, Blue, and Violet inks)
    - Provide extended colorimetric as well as spectral gamuts
    - Commonly used with ICC workflows
    - Make partial spectrally based reproduction systems feasible (though currently not with ICC profiles)



Spectra for Various Inks

The exponential problem of more inks

- **Sampling grows exponentially larger with higher dimensionality**

Number of Inks

Sampling Granularity	3	4	5	6	7	8	9	**Spacing %**
2	8	16	32	64	128	256	512	100
3	27	81	243	729	2187	6561	**19683**	50
4	64	256	1024	4096	16384	**65536**	262144	33
5	125	625	3125	15625	**78125**	390625	1953125	25
6	216	1296	7776	46656	279936	1679616	10077696	20
7	343	2401	16807	**117649**	823543	5764801	40353607	17
8	512	4096	32768	262144	2097152	16777216	1.34E+08	14
9	729	6561	59049	531441	4782969	43046721	3.87E+08	13
10	1000	10000	100000	1000000	10000000	1E+08	1E+09	11
11	1331	14641	**161051**	1771561	19487171	2.14E+08	2.36E+09	10
13	2197	28561	371293	4826809	62748517	8.16E+08	1.06E+10	8
17	4913	83521	1419857	24137569	4.1E+08	6.98E+09	1.19E+11	6
19	6859	**130321**	2476099	47045881	8.94E+08	1.7E+10	3.23E+11	6
33	**35937**	1185921	39135393	1.29E+09	4.26E+10	1.41E+12	4.64E+13	3

- **If the approximate size of profile is maintained the Forward Tables become much less accurate**

Difficulties in Profiling Extended Ink Printers

- **Getting a good device characterization transform**
  - Measurement sampling becomes unwieldy
  - Models have to do more with less data
- **Forward table accuracy**
  - Either grows big or loose accuracy (due to sampling limits)
  - Proofing capability diminished with reduced accuracy
  - ***It would be nice to be able to directly encode a forward model rather than a sampling of one***
- **Reverse table accuracy**
  - Reverse tables are more likely to be used (for printing)
  - Base reverse tables on more accurate model rather than forward table
    - Results in better output accuracy but poorer round trip accuracy
- **Ink Separation becomes complicated**
  - Essentially Mapping N-dimensions to 3-dimensions
- **Ink limiting strategy becomes vital**
  - Media have limited ink carrying capacity

- **Things become much more complicated with more inks!**

Direct encoding of (C)YNN model in ICC profiles

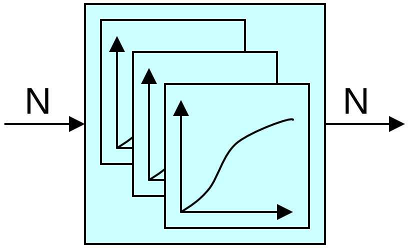
A (C)YNN spectral model can be directly encoded using a D2Bx tag

Using Multi-Processing Element Tags

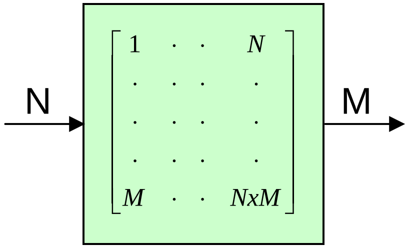
- **The soon to be released 4.3 version of ICC specification provides for new (optional) DtoBx/BtoDx tags based on MultiProcessingElement tag type (MPE tags)**
  - These tags were approved as an addendum to the ICC specification
  - Support for them has been implemented in various CMM's

- **MPE tags allow direct encoding of floating point transforms**
  - Unbounded input and output domain and range
  - Arbitrary order and number of processing elements
  - Each processing element transforms input values to output values
  - Can be organized in a sequence to convert between Device Values and PCS values

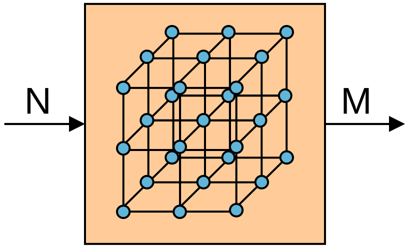
Multi Processing Elements



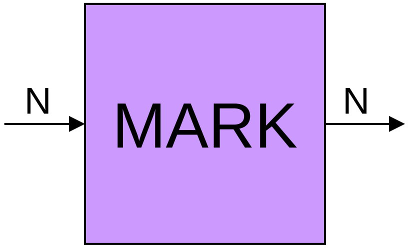
(A)



(B)



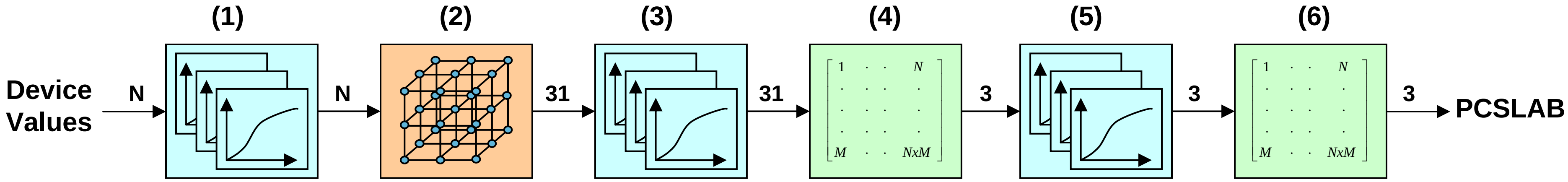
(C)



(D)

- **Repertoire of processing elements**
  - A. Sets of 1-dimensional functions that are made up of parametric and sampled curve segments
  - B. N x M linear matrix transform
  - C. N x M multi-dimensional lookup table
  - D. Marker elements that perform no operation on values

Encoding (C)YNN in a DtoB1 tag (relative colorimetric)

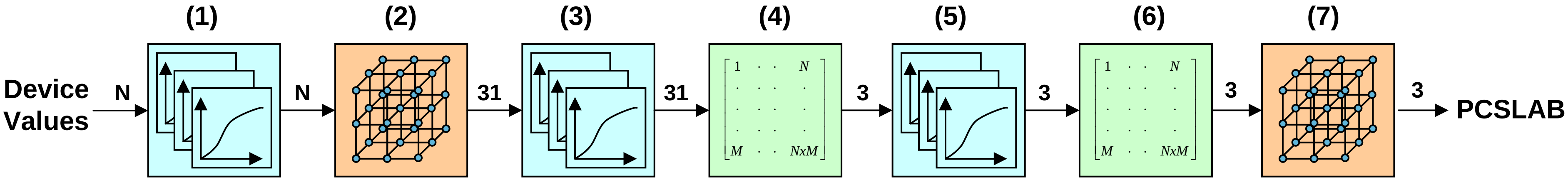


1. **Use sample curves to convert device values to area coverages**
2. **Use CLUT element to interpolate area coverages to $R^{1/n}$ reflectance**
3. **Use parametric curves to apply power function that converts $R^{1/n}$ reflectance to actual reflectance**
4. **Use matrix to convert reflectance to media relative CIEXYZ**
    - Represents concatenation of applying illuminant, standard observer and media relative transforms

$$\mathbf{M} = \begin{bmatrix} \frac{X_{D_{50}}}{X_{media}} & 0 & 0 \\ 0 & \frac{Y_{D_{50}}}{Y_{media}} & 0 \\ 0 & 0 & \frac{Z_{D_{50}}}{Z_{media}} \end{bmatrix} \times \begin{bmatrix} X_{obs,\lambda=400} & \cdot & \cdot & X_{obs,\lambda=700} \\ Y_{obs,\lambda=400} & \cdot & \cdot & Y_{obs,\lambda=700} \\ Z_{obs,\lambda=400} & \cdot & \cdot & Z_{obs,\lambda=700} \end{bmatrix} \times \begin{bmatrix} E_{\lambda=400} & 0 & \cdot & & \\ 0 & E_{\lambda=410} & \cdot & & \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ & & \cdot & E_{\lambda=690} & \\ & & \cdot & & E_{\lambda=700} \end{bmatrix}$$

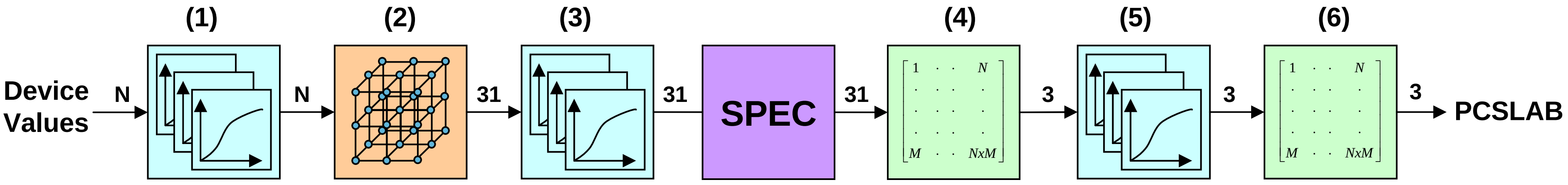
5. **Use curves to apply cubic portion of CIEXYZ to CIELAB conversion**
6. **Use matrix to finish CIELAB conversion**

Encoding perceptual and saturation intents



- The DtoB1 encoding used for the relative intent provides a means of getting device values to media relative PCS values (1-6)
- For the perceptual and saturation intents color re-rendering can be accomplished by appending the relative intent transforms with a 3-dimensional lookup table (7) that re-maps colors in PCSLAB space

Using the Spectral Reflectance Data?



- As CMM processes transforms in each processing element it doesn’t know the meaning of the intermediate values
- The marker elements provide a means for giving a suitably “smart” CMM to identify and use this intermediate data for color processing
- HOWEVER! - Such “smart” behavior is NOT currently defined and default behavior prescribes that marker elements perform no operation

What about the Reverse Tables?

- **We’ll leave nuances of colorimetric reverse table generation for another day**
- **Currently cannot encode transform from spectral reflectance in a reverse table**
  - —The Profile Connection Space is currently defined as being either CIELAB or CIEXYZ using the D50 illuminant and the 1931 CIE Standard Observer
  - —Need a Spectral Reflectance based PCS in order to implement a spectral reproduction system using ICC profiles
- **Repertoire of processing elements is limited**
  - —The only non linear multi-variable processing element is the multi-dimensional lookup table (which is limited to 16 input dimensions)
  - —Each element must perform operation on all connecting values
  - —Unable to separate out intermediate results to be used later

Going Forward… (ICC.2)

- **Members in Architecture Working Group are working on a next generation color management system (ICC.2)**
  - ***Not meant to replace ICC.1!***
  - Many users of ICC color management are happy with ICC.1.
- **Main goal of ICC.2 is to define a color management system that goes beyond D50 colorimetry**
  - Resulting in a V5 specification and profiles
  - Backwards compatible with V2 and V4 profiles
  - V5 profiles not expected to be compatible with V4 CMMs
- **ICC will seek to provide a reference implementation of a V5 CMM**

ICC.2 High Level Features

- **Support spectral communication of color information through an optional spectral PCS (reflectance, emission, fluorescence?)**
- **Support the use of color appearance processing in the PCS**
  - Facility to store appearance attributes in a V5 profile
- **Extended CMM functionality**
  - New Gamut Boundary Description
  - Spectral data
  - New encoding of Named Colors to support tints
- **Programmable transforms (direct encoding of device models)**
  - Functional operators, conditional evaluation, persistent variables, and vectorized operations for improved performance
- **Hierarchical data encoding**
- **Abbreviated profiles**
  - References to color encoding standard
  - References to existing profile

Useful References

- R. S. Berns, *Principles of Color Technology*, Wiley-Interscience, New York (2000)
- G. A. Klein, *Industrial Color Physics*, Springer, New York (2010)
- ICC.1-2001/ICC.1-2010 Specification, see specifications at http://www.color.org
- J. Morovic and M. R. Luo, “The fundamentals of gamut mapping: A survey,” *The Journal of Imaging Science and Technology, no.3 ISBN / ISSN: 1062-370*, vol. 45, pp. 283–290, (2001)
- H. J. Trussell, M. Vrhel, “Fundamentals of Digital Imaging”, Cambridge University Press, (2008)
- D. R. Wyble and R. S. Berns, “A critical review of spectral models applied to binary color printing,” Color Res. Appl. 25, 4-19 (2000).
- Y. Chen, R. S. Berns, L. A. Taplin, “A Multi-Ink color separation algorithm maximizing color constancy,” Proc. IS&T/SID Eleventh Color Imaging Conference, 277-281 (2003)
- Y. Chen, R. S. Berns, L. A. Taplin, “Six color printer characterization using an optimized cellular Yule-Nielsen spectral Neugebaur model”, J. Imaging Science, 48, 519-528 (2004).
- ICC.1 Revision “Floating Point Device Encoding Range”, see specifications at http://www.color.org

Questions / Comments

Thank You!