Spectral-based Image Reproduction Workflow

From Capture to Print

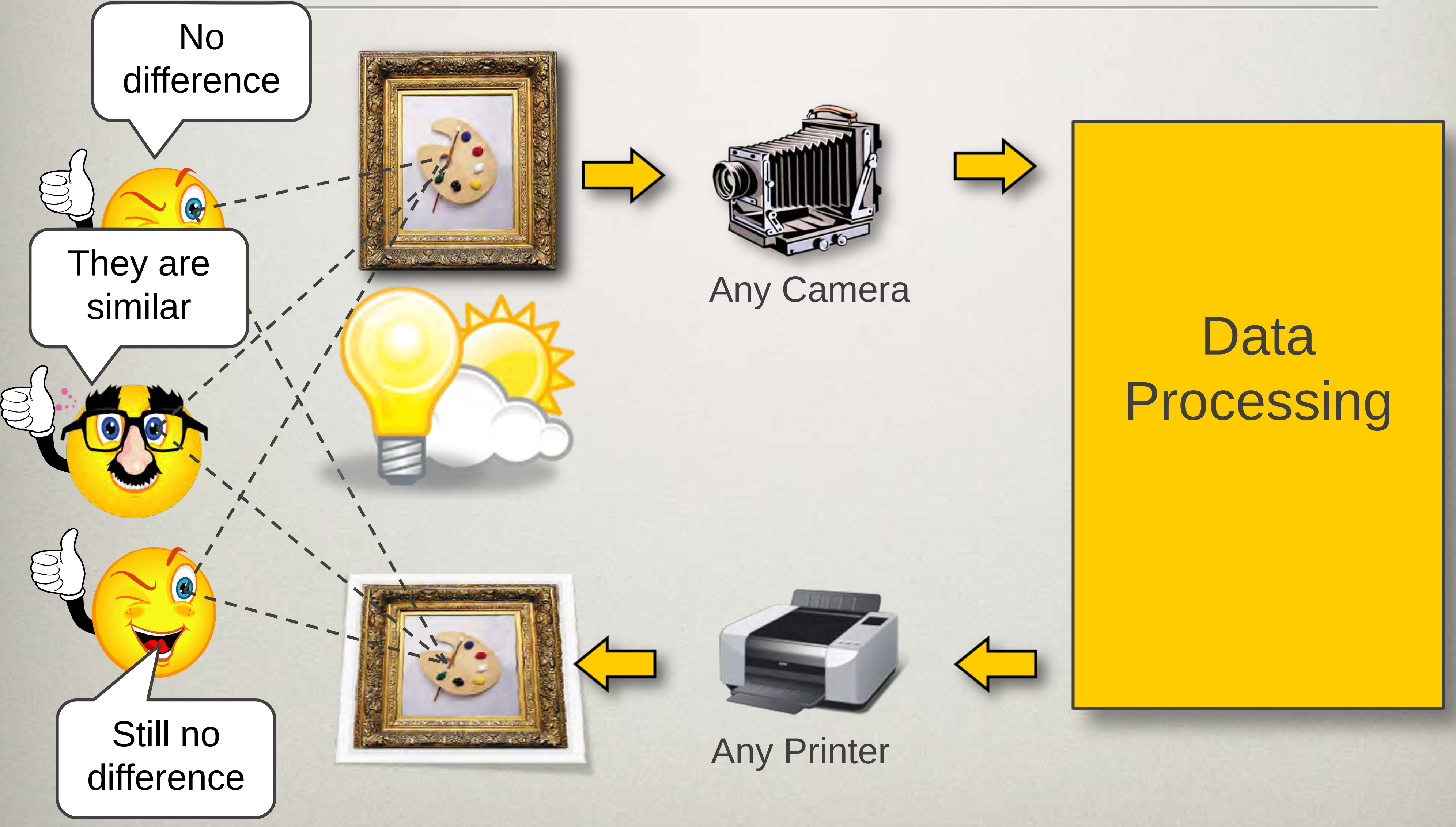
Philipp Urban

TECHNISCHE UNIVERSITÄT DARMSTADT

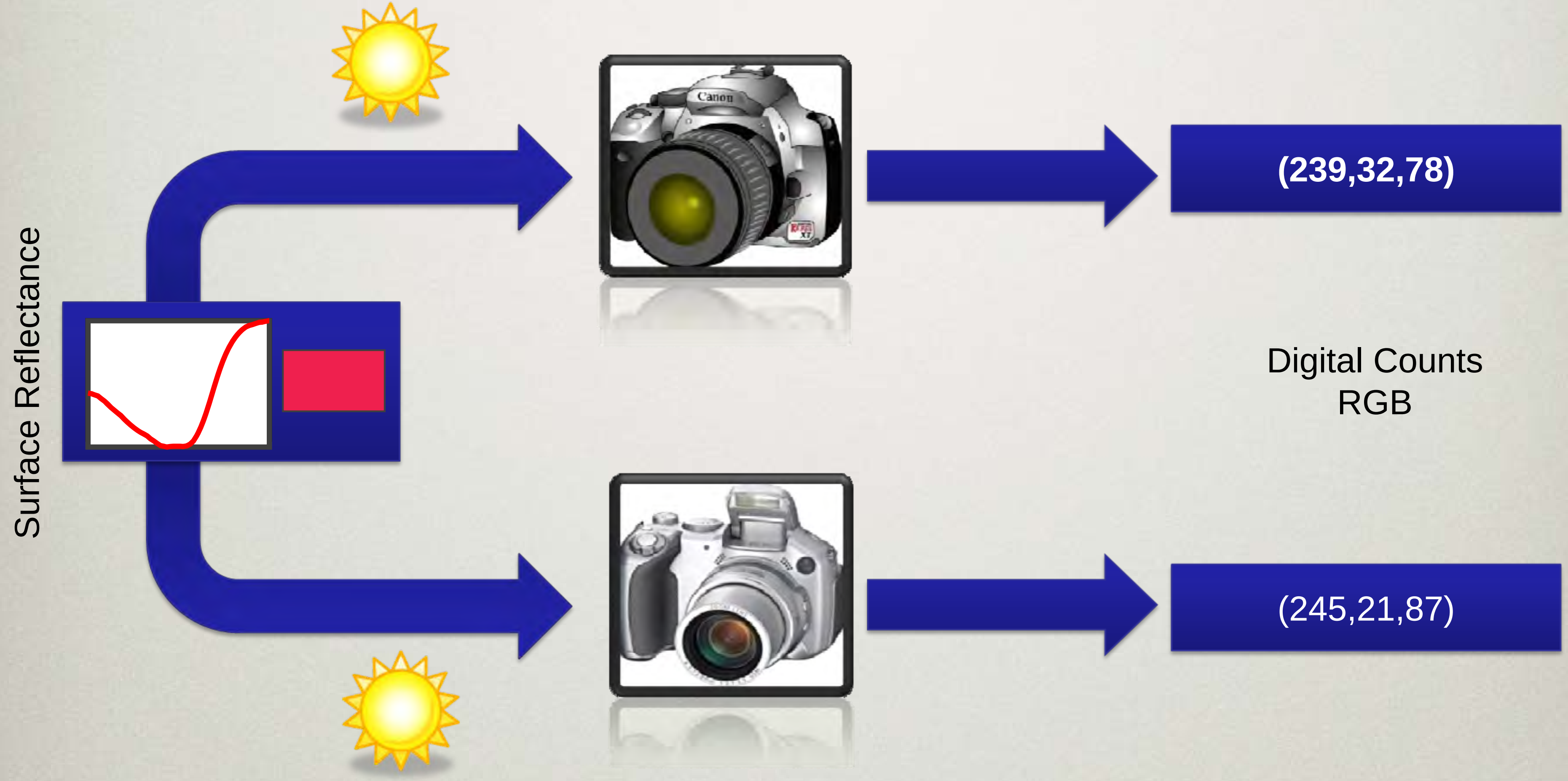
idd printing science technology

Why Color Management?

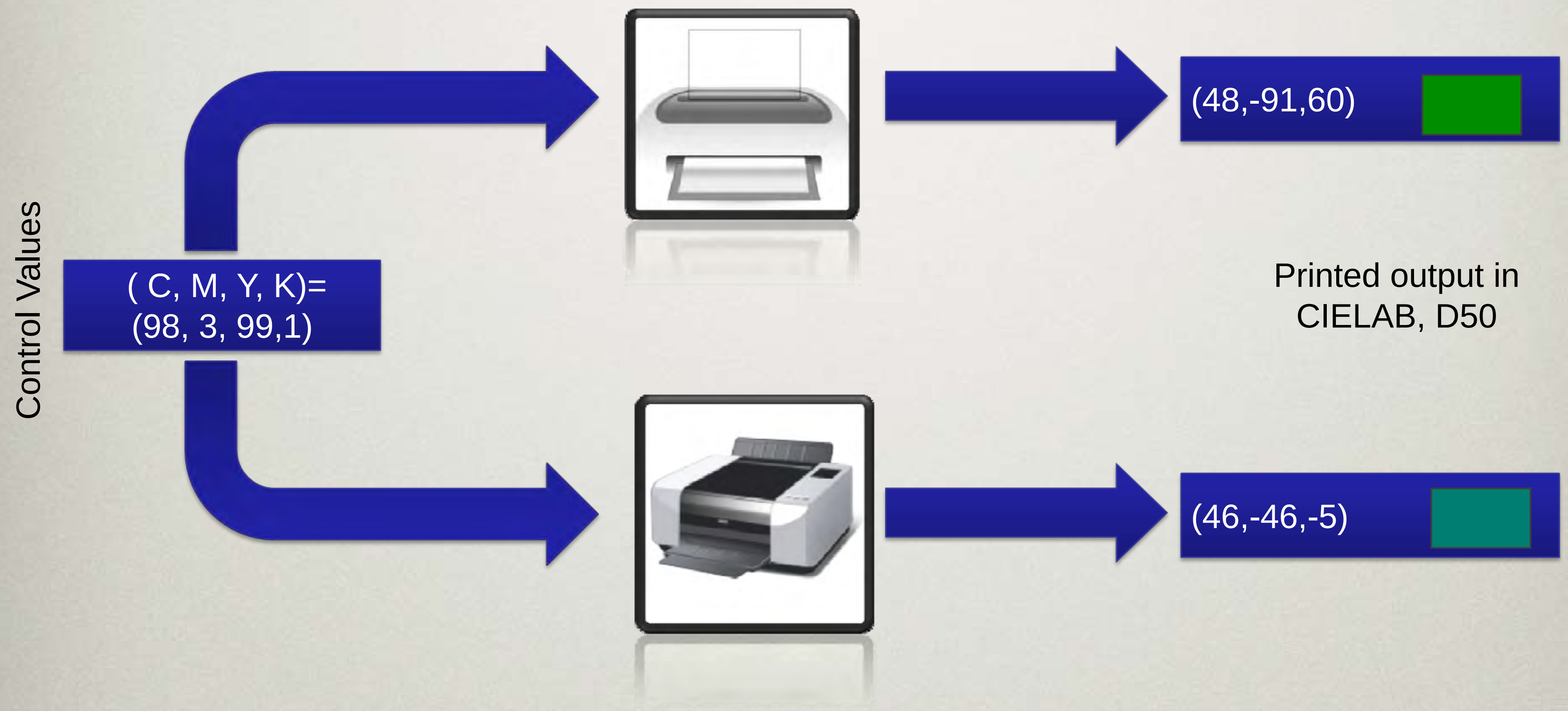
The Ultimate Goal



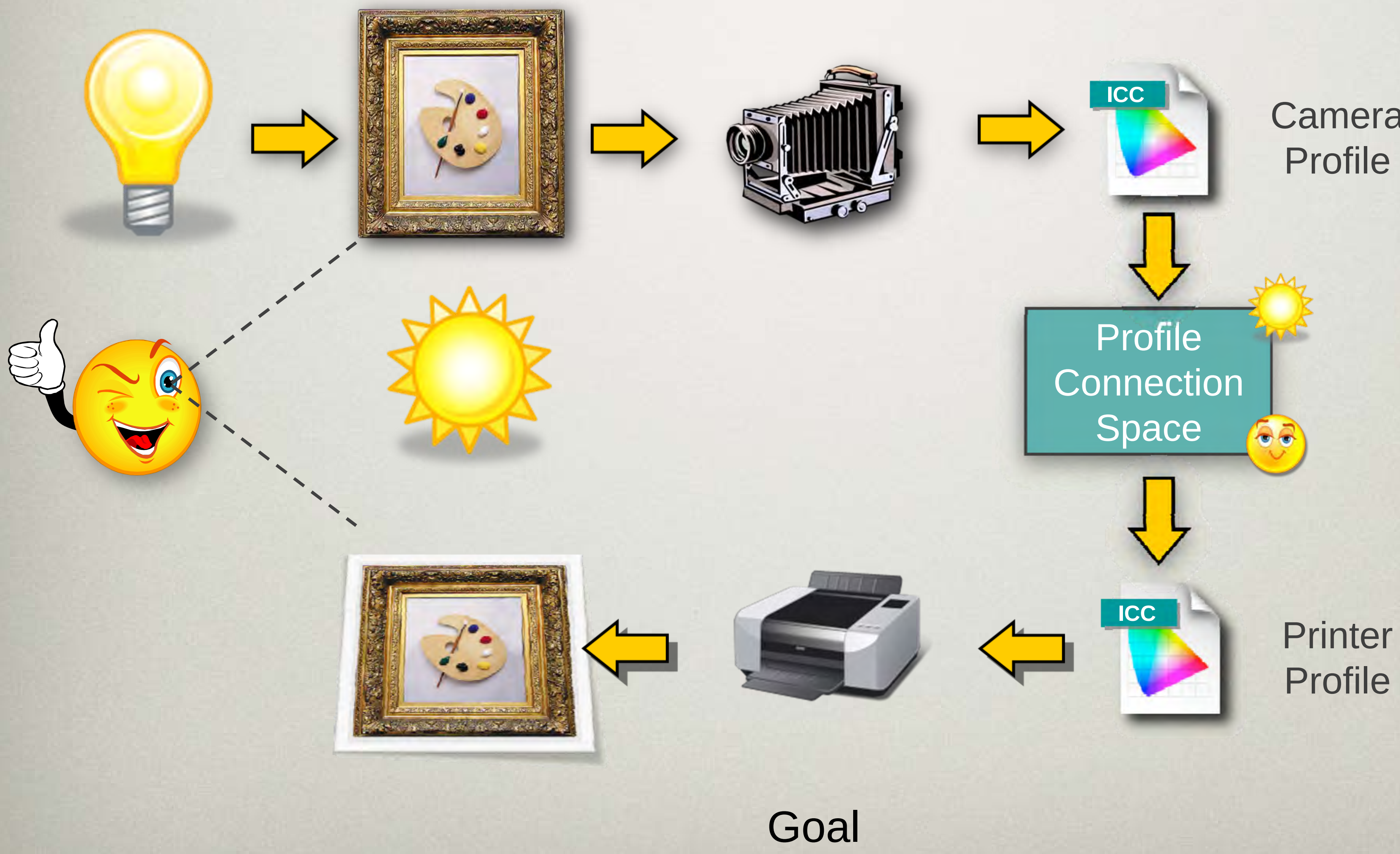
Each Device is Different



Each Device is Different



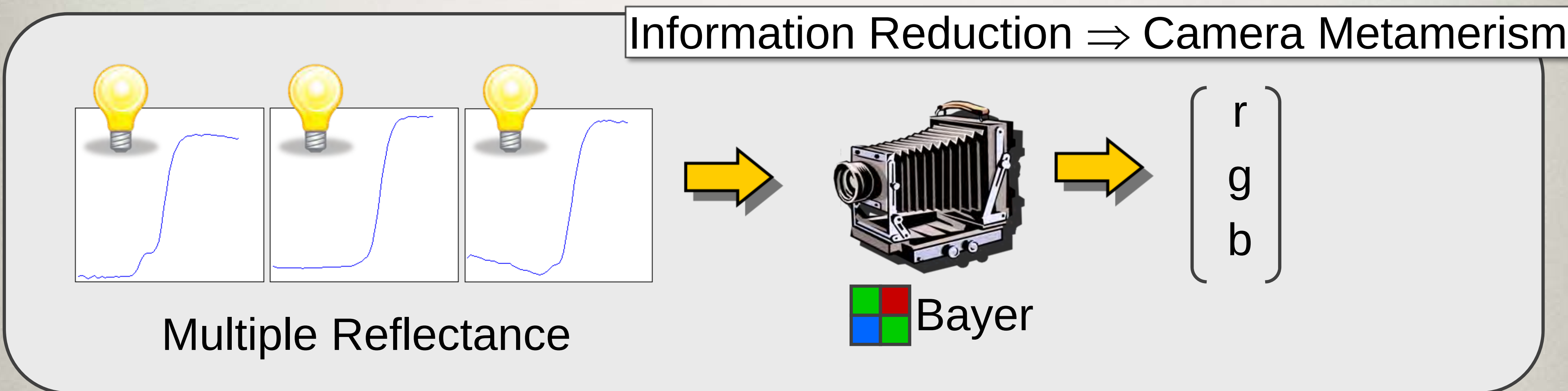
Typical Metameric Workflow (ICC)

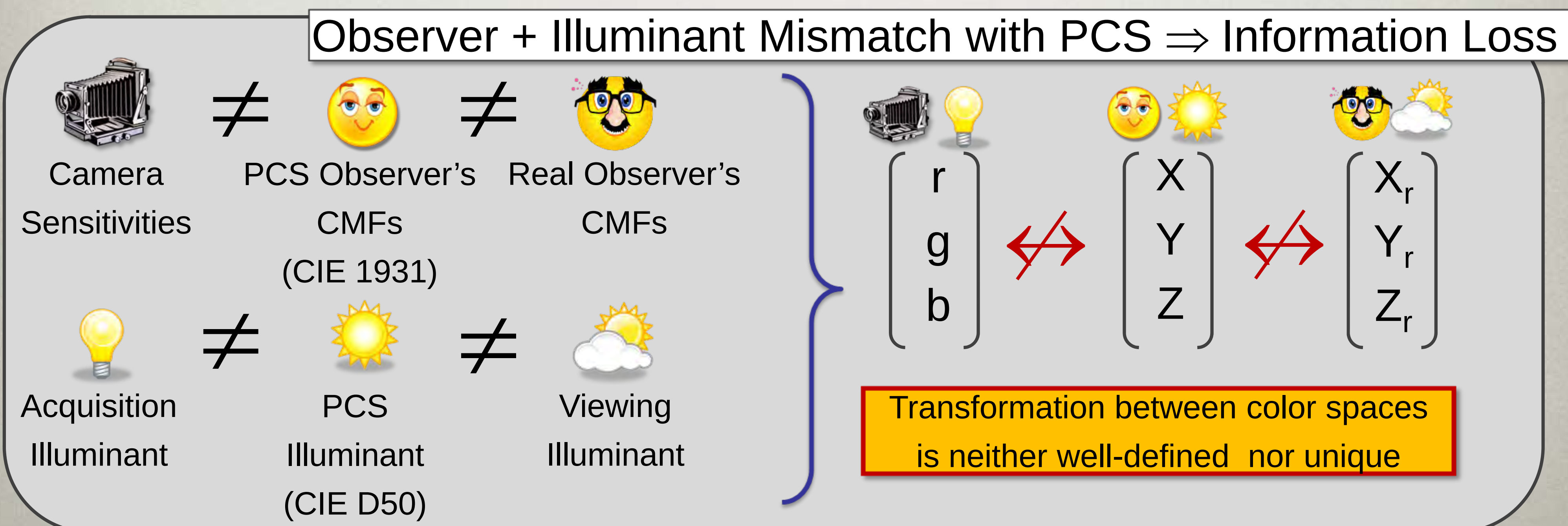


Success Story of Metameric Reproduction

Limitations of the Metameric ICC-Based Reproduction

Limitations of a Typical Metameric Workflow (ICC)

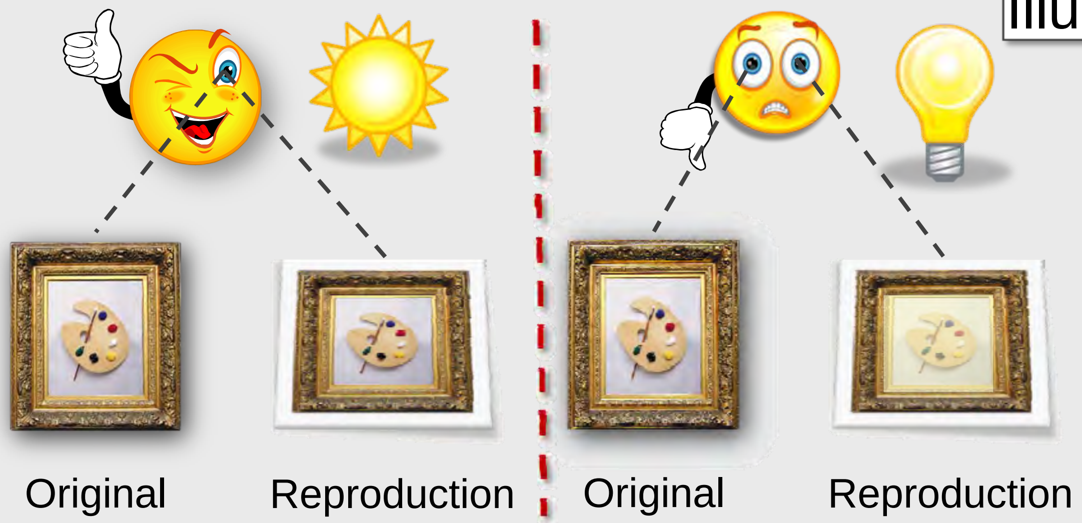




Limitations of a Typical Metameric Workflow (ICC)

Illuminant Metamerism

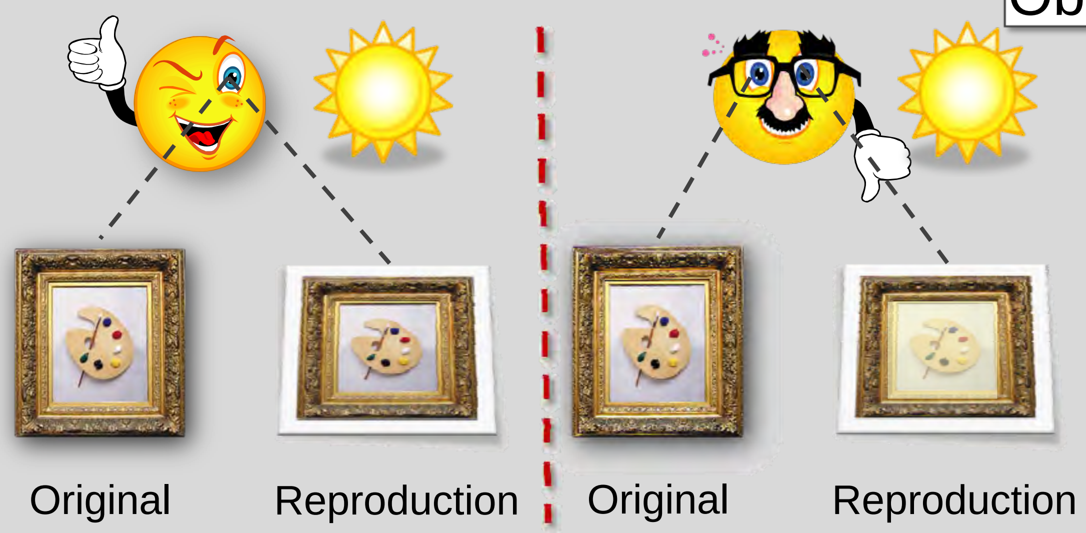
Ideally:
Match for single Observer and Illuminant



In General:
Mismatch for **same** Observer and **different** Illuminant

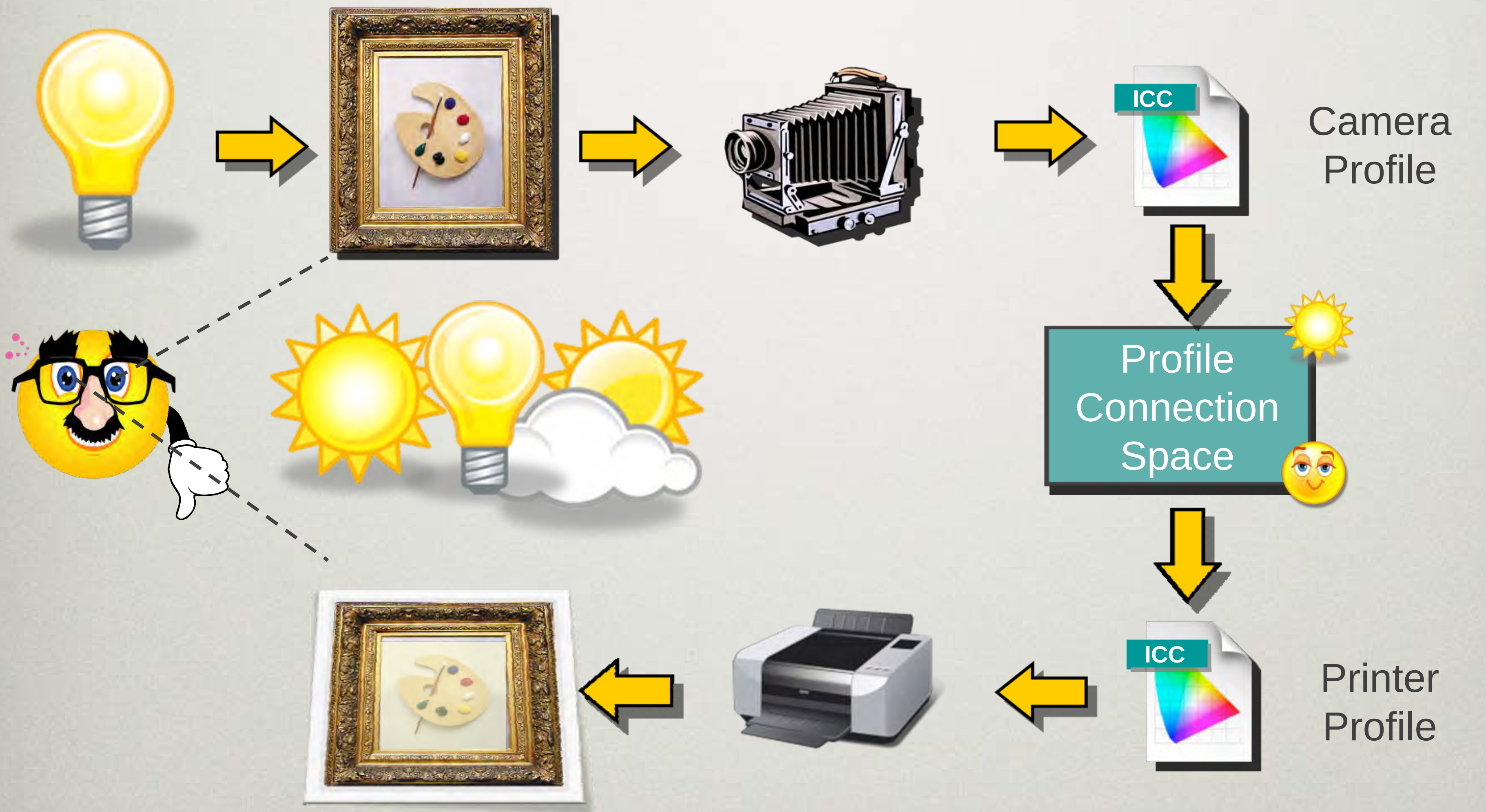
Observer Metamerism

Ideally:
Match for single Observer and Illuminant



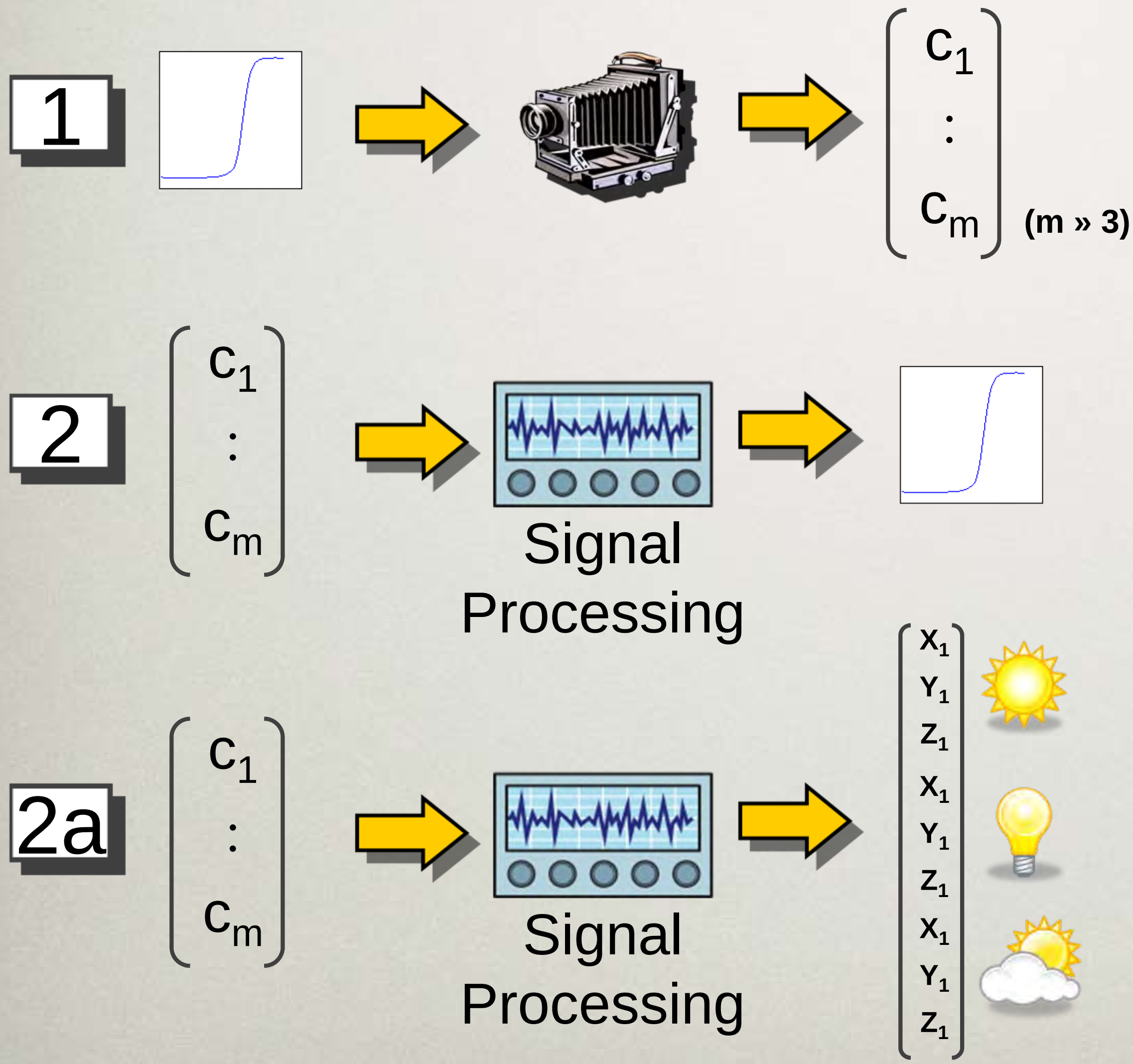
In General:
Mismatch for **different** Observer and **same** Illuminant

Typical Metameric Workflow (ICC)



What Needs to be Changed?

What Needs to be Changed?



Increase the number of camera channels

$\Rightarrow$ reduce loss of information

Estimate the reflectance spectrum instead of a tristimulus for a specific observer and illuminant

or

Estimate tristimuli for **multiple illuminants**

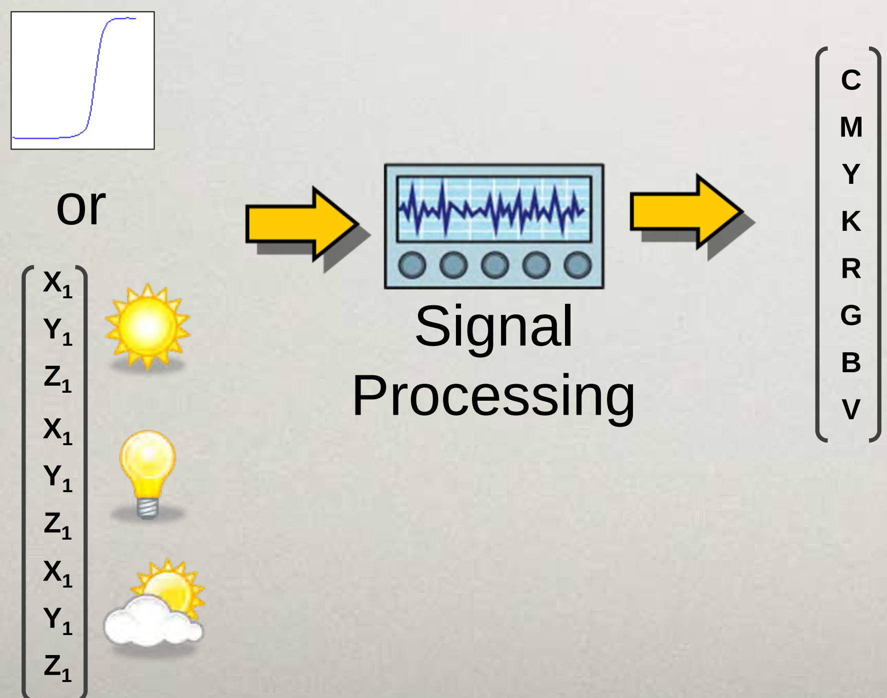
What Needs to be Changed?

3

Increase the number of colorants (inks)

$\Rightarrow$ maximize spectral printer gamut

4

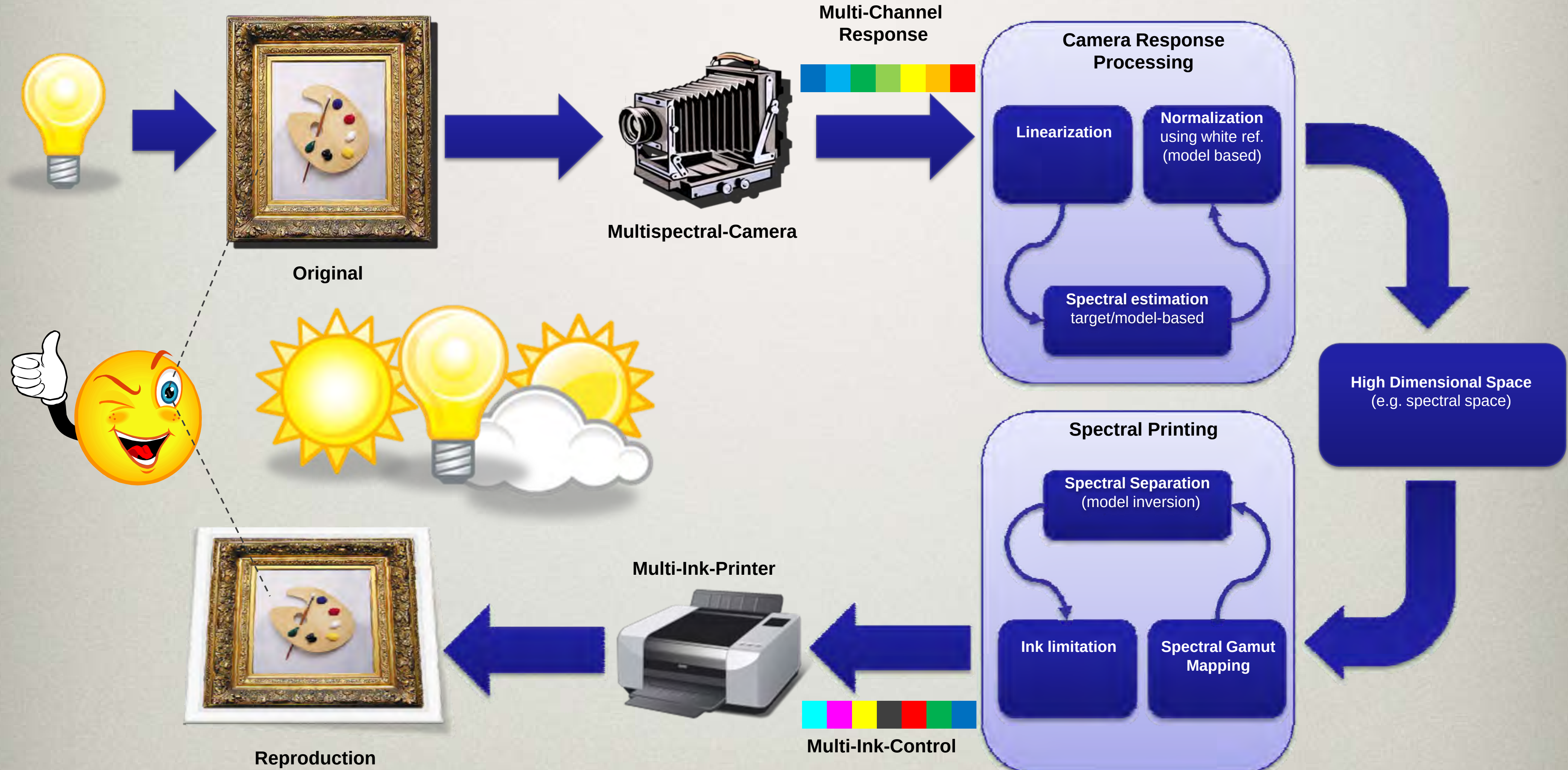


Separate colors based on spectral or multi-illuminant information

$\Rightarrow$ minimize metamerism

The Spectral End-to-End Reproduction Workflow

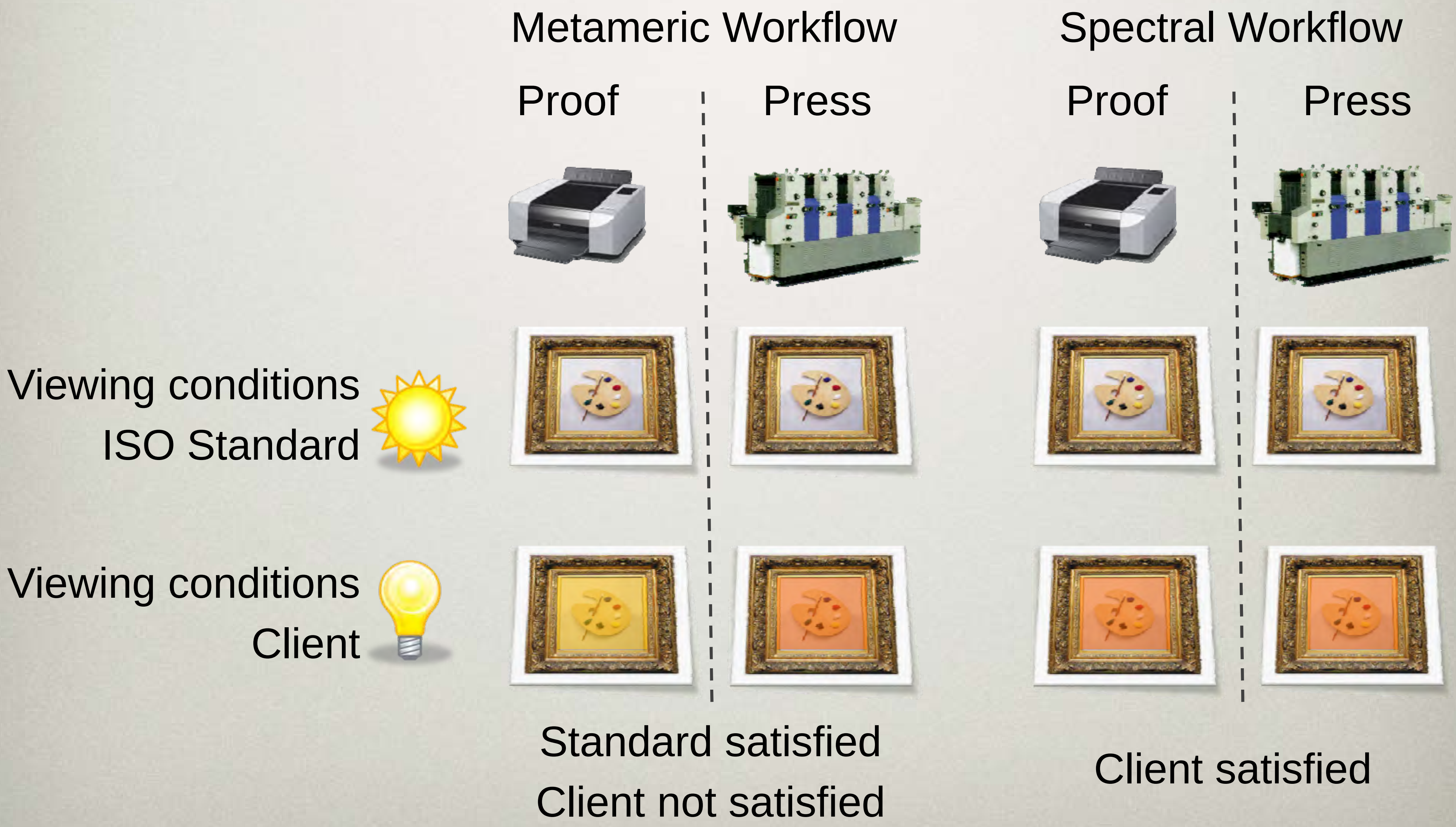
Spectral End-to-End Reproduction Workflow



Where is a Spectral Workflow useful?

Where are the Applications?

Highly Accurate Proofing of Offset-Press-Prints



Cultural Heritage

Van Gogh's ***The Starry Night*** (what are the real colors?)

- Reproducing artwork

  Bring the real color appearance of a van Gogh painting into the living room

- Support and document restoration work

Highly Accurate Industrial Color Communication

Today

Color Communication (swatches, samples…)

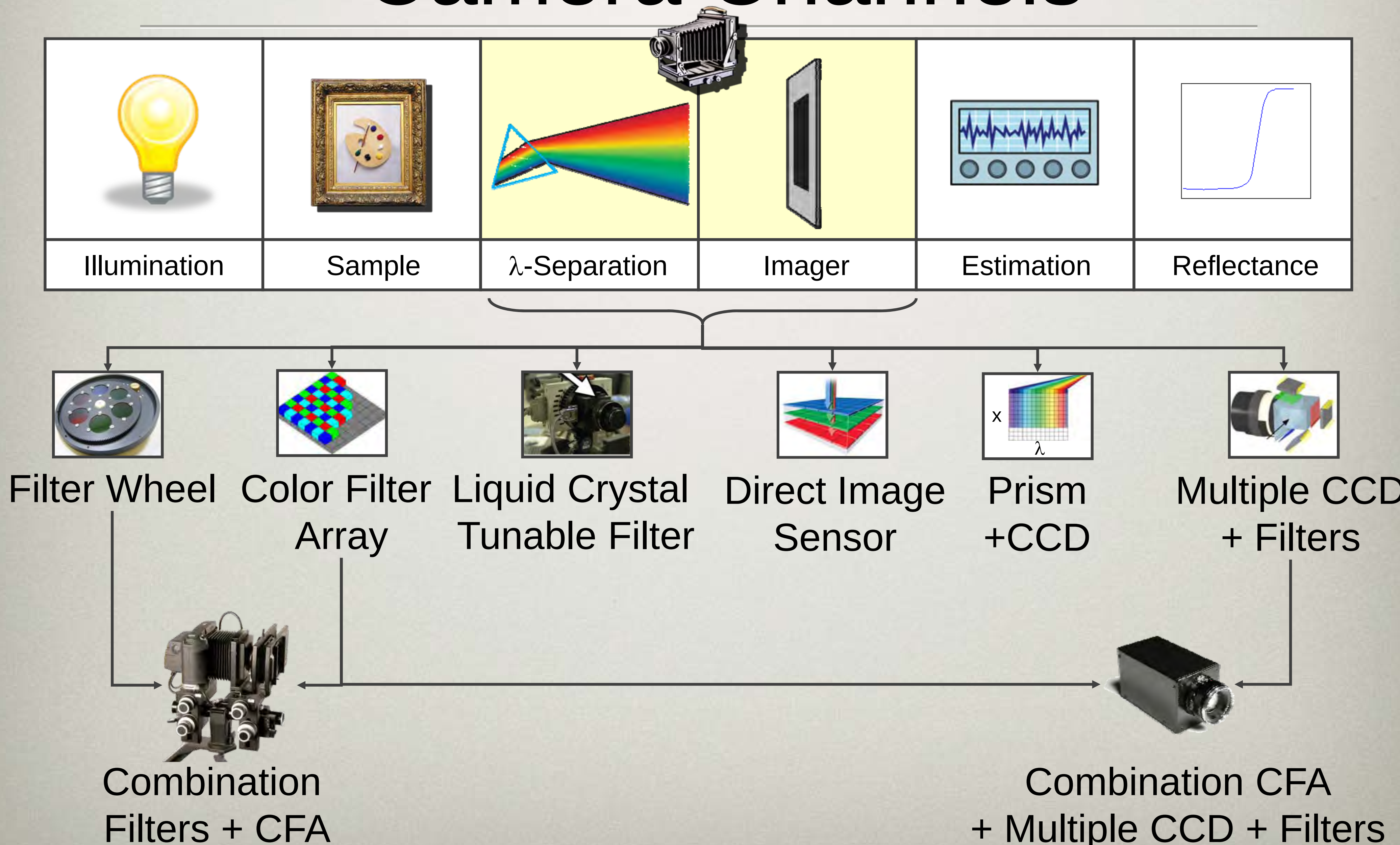
Highly Accurate Industrial Color Communication

Tomorrow?

Color Communication (swatches, samples…)

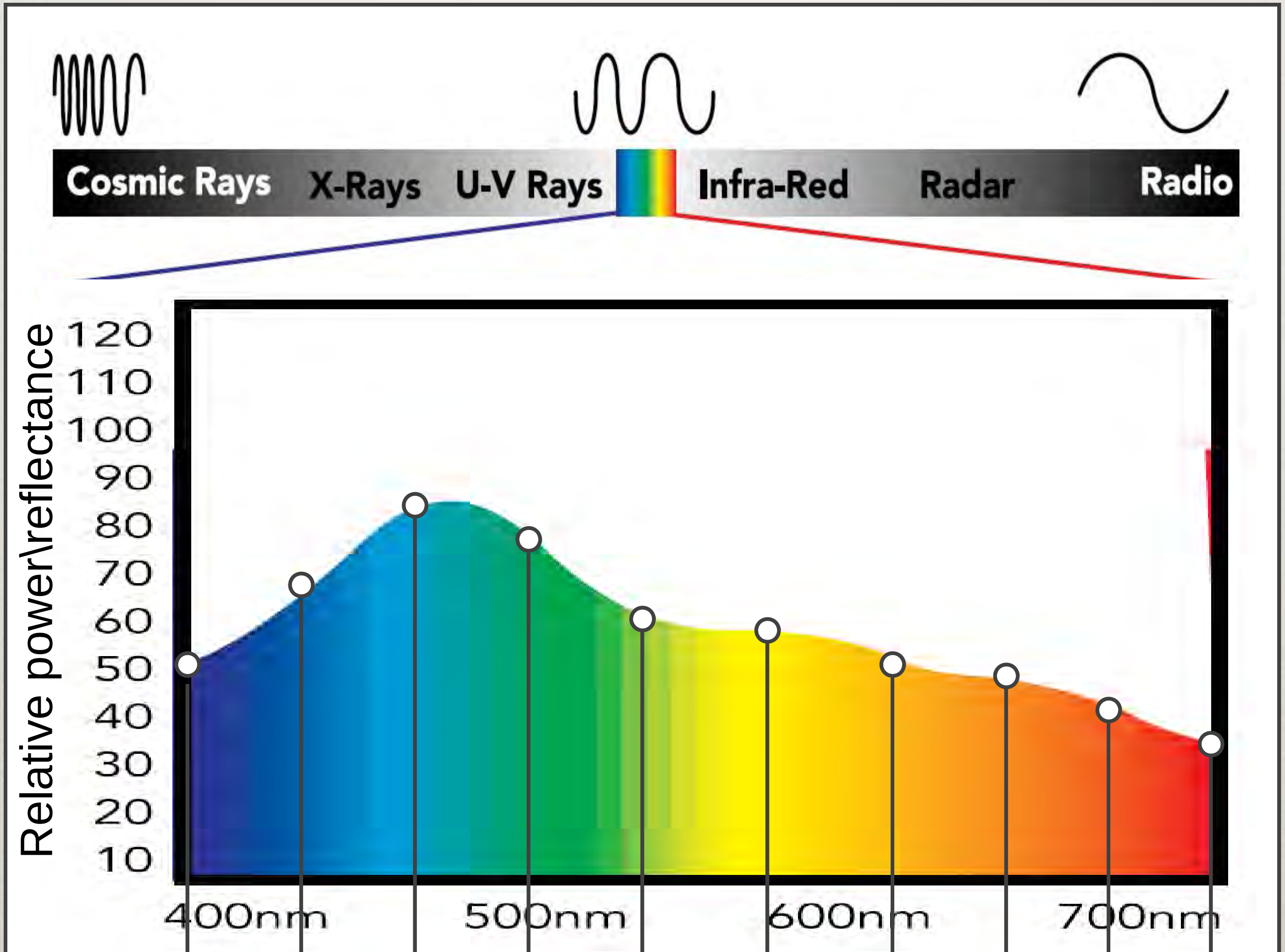
Multispectral Cameras

Ways to Increase the Number of Camera Channels



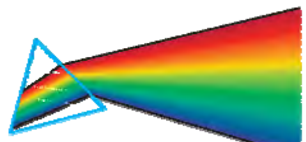
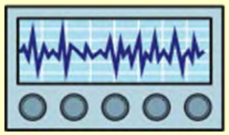
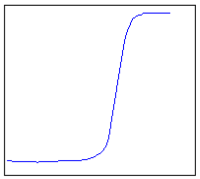
Camera Response Processing

Vector Representation of Spectra

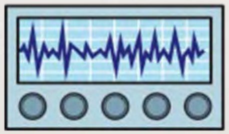


$$S = [50 \quad 65 \quad 85 \quad 80 \quad 60 \quad 58 \quad 55 \quad 50 \quad 45 \quad 40]^T$$

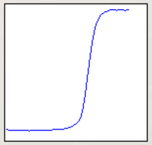
Reflectance Estimation

					
Illumination	Sample	λ-Separation	Imager	Estimation	Reflectance

$$\begin{bmatrix} c_1 \\ : \\ c_m \end{bmatrix}$$



Signal Processing

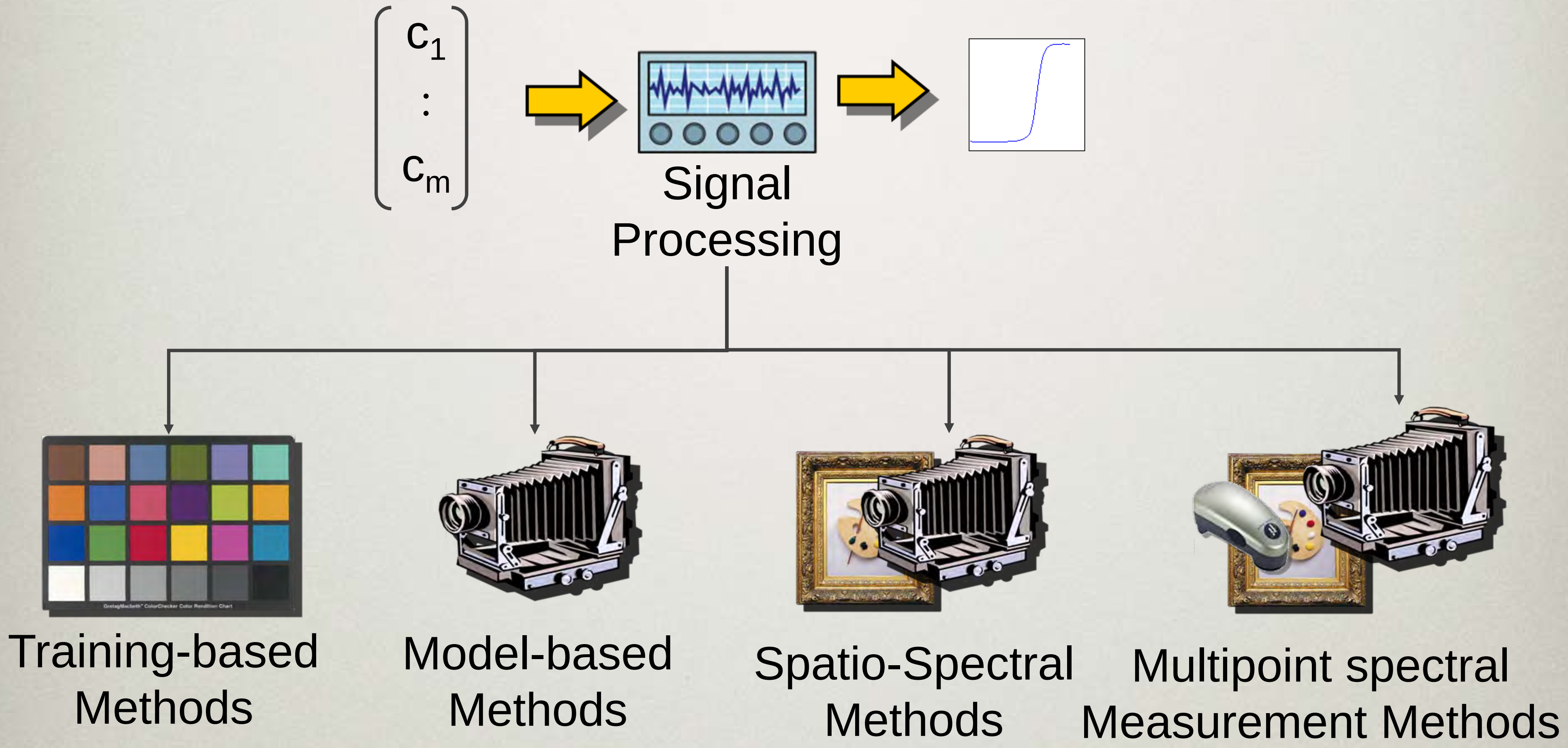


Problem is under-determined (ill-posed)

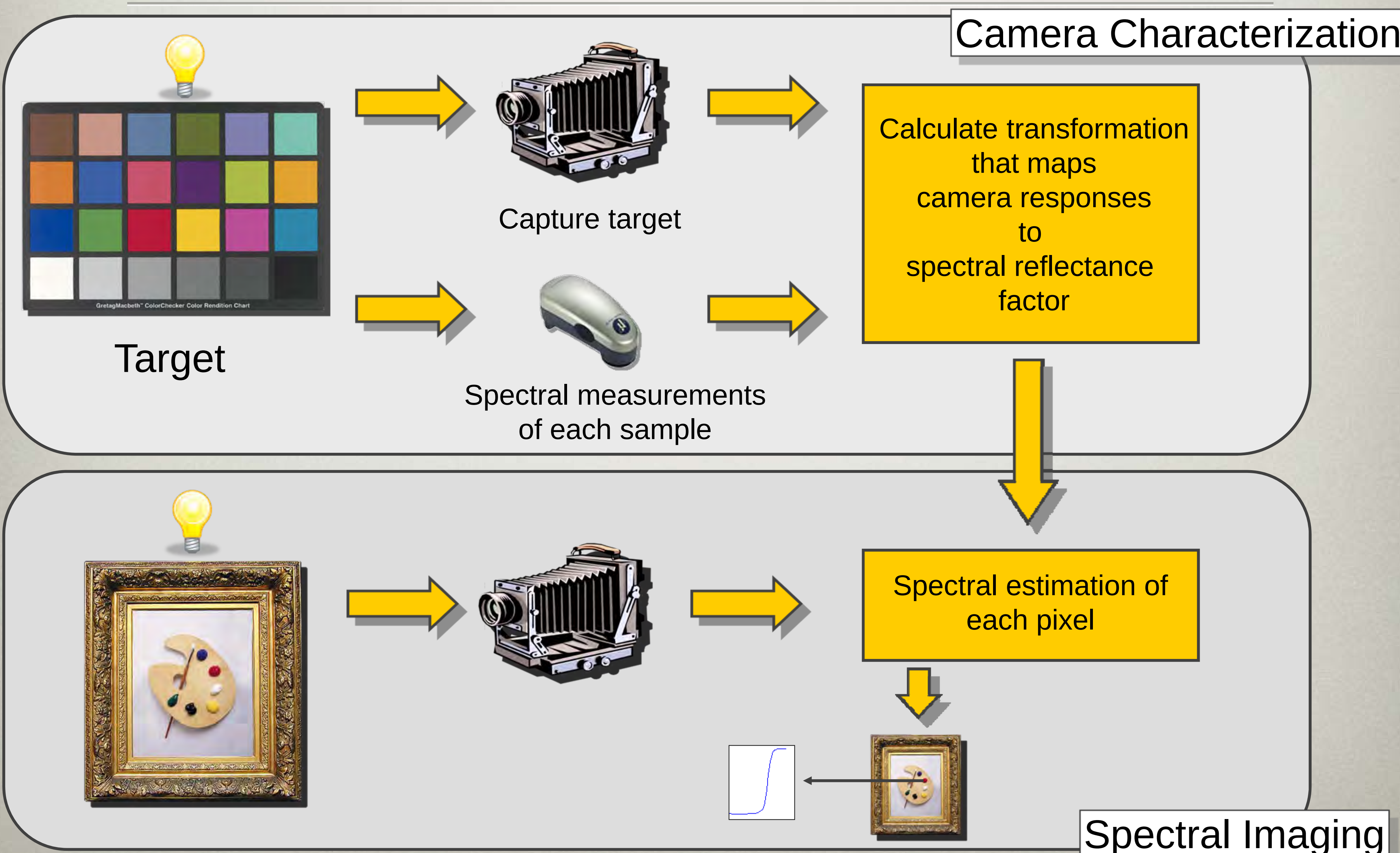
General Approach:

Utilize as much information as possible

Reflectance Estimation



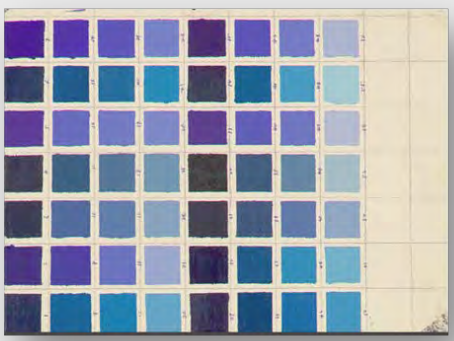
Reflectance Estimation [Training-based Methods]



Training-based Methods
General Problem

Necessary Condition:

Spectral agreement between training colors and original



Training Target

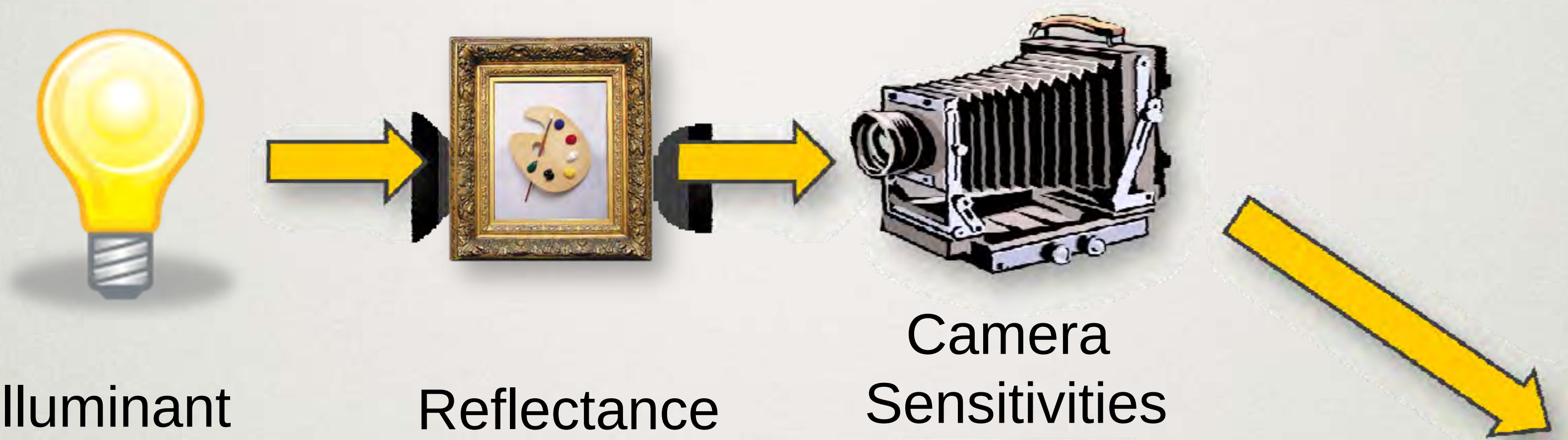
Original

It is unlikely that the spectrum of the red-pigments can be accurately estimated

The spectral estimation quality depends strongly on the selected target.

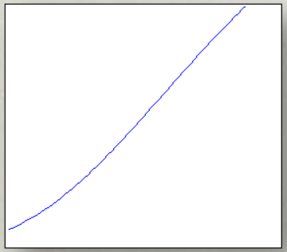
Multipoint spectral measurement methods
“Target is the Original”

Sensor Response of a Linear Imaging Device



$\int$

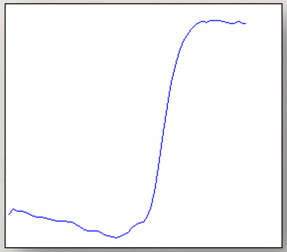
Illuminant



i

x

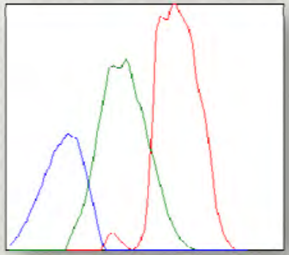
Reflectance



r

x

Camera Sensitivities



$[s_1 \ldots s_m]^T$

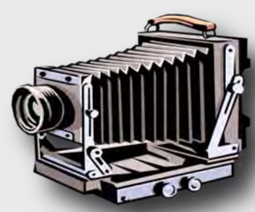
$$d\lambda = \begin{pmatrix} c_1 \\ : \\ c_m \end{pmatrix}$$

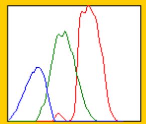
Vector representation:

$$\underbrace{\begin{pmatrix} s_{11}i_1 \ldots s_{1n}i_n \\ : \qquad\qquad : \\ s_{m1}i_1 \ldots s_{mn}i_n \end{pmatrix}}_{\textbf{L}\text{ (Lighting Matrix)}} \begin{pmatrix} r_1 \\ : \\ r_n \end{pmatrix} = \mathbf{L}\cdot r = \begin{pmatrix} c_1 \\ : \\ c_m \end{pmatrix}$$

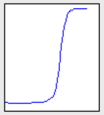
Reflectance Estimation [Model-based Methods]

Calculate colorimetric transform



 x  = **L**

Use lighting matrix **L**
and additional information
to calculate
spectral reflectance factor
from
camera responses



The camera model:

$$\underbrace{c}_{\substack{\text{camera response} \\ \text{(known)}}} = \underbrace{\mathbf{L}}_{\substack{\text{lighting matrix} \\ \text{(known)}}} \cdot \underbrace{r}_{\substack{\text{reflectance} \\ \text{(unknown)}}}$$

Solve underdetermined equation with respect to r:

$$f(\mathbf{L},c) = r$$

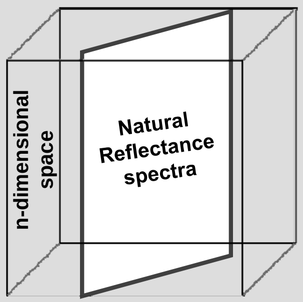
The Mathematics

Reflectance Estimation [Model-based Methods]

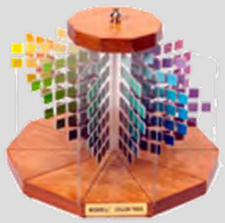
Pseudoinverse

- Simple mathematical solution
- Does not minimize the spectral RMS error
- Sensitive to noise

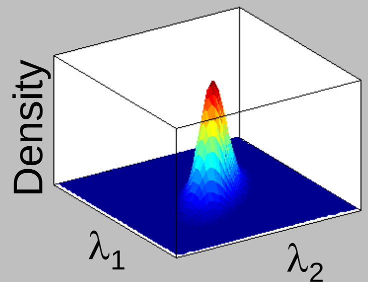
Principle Component Method



- Additional assumption:
  Natural reflectances can be described by a low-dimensional linear model
- Model parameter (principle components) can be calculated using a spectral database



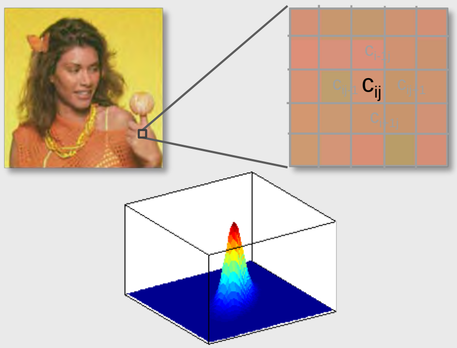
Wiener Inverse



- Additional assumption:
  Natural reflectances and noise are normally distributed
- Determine covariance matrices from spectral database
- Optimal linear filter for reflectance estimation

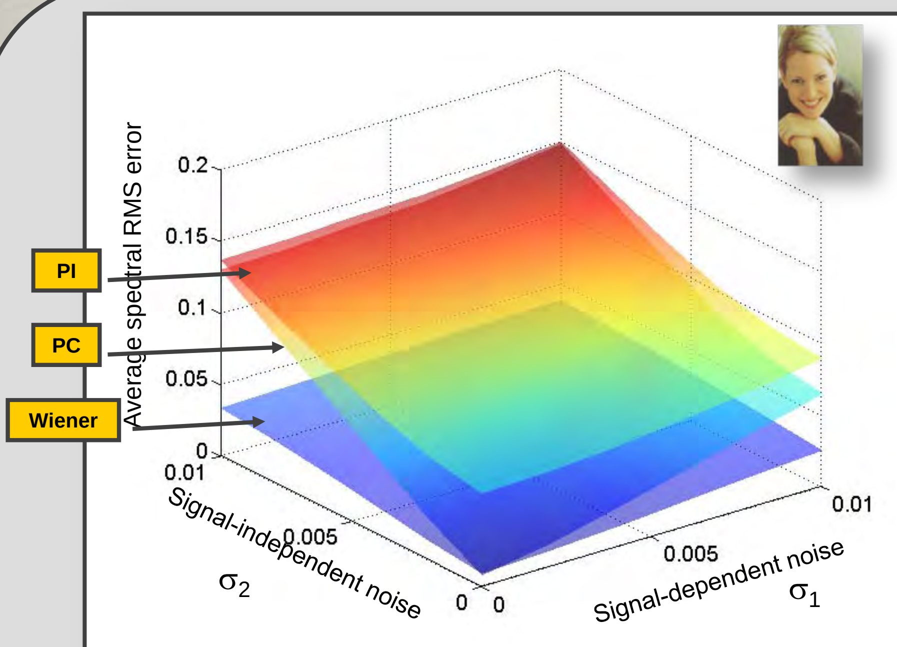
Reflectance Estimation [Model-based Methods]

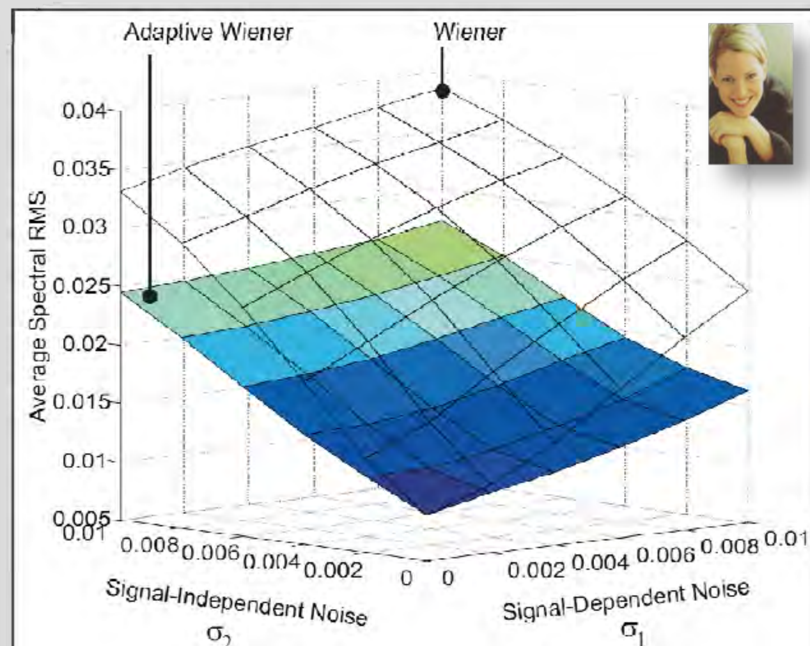
Spatially Adaptive Wiener Inverse



- Combining noise reducing and reflectance estimating Wiener filter

Urban et al. 2008





Results: Six channel Sinar camera

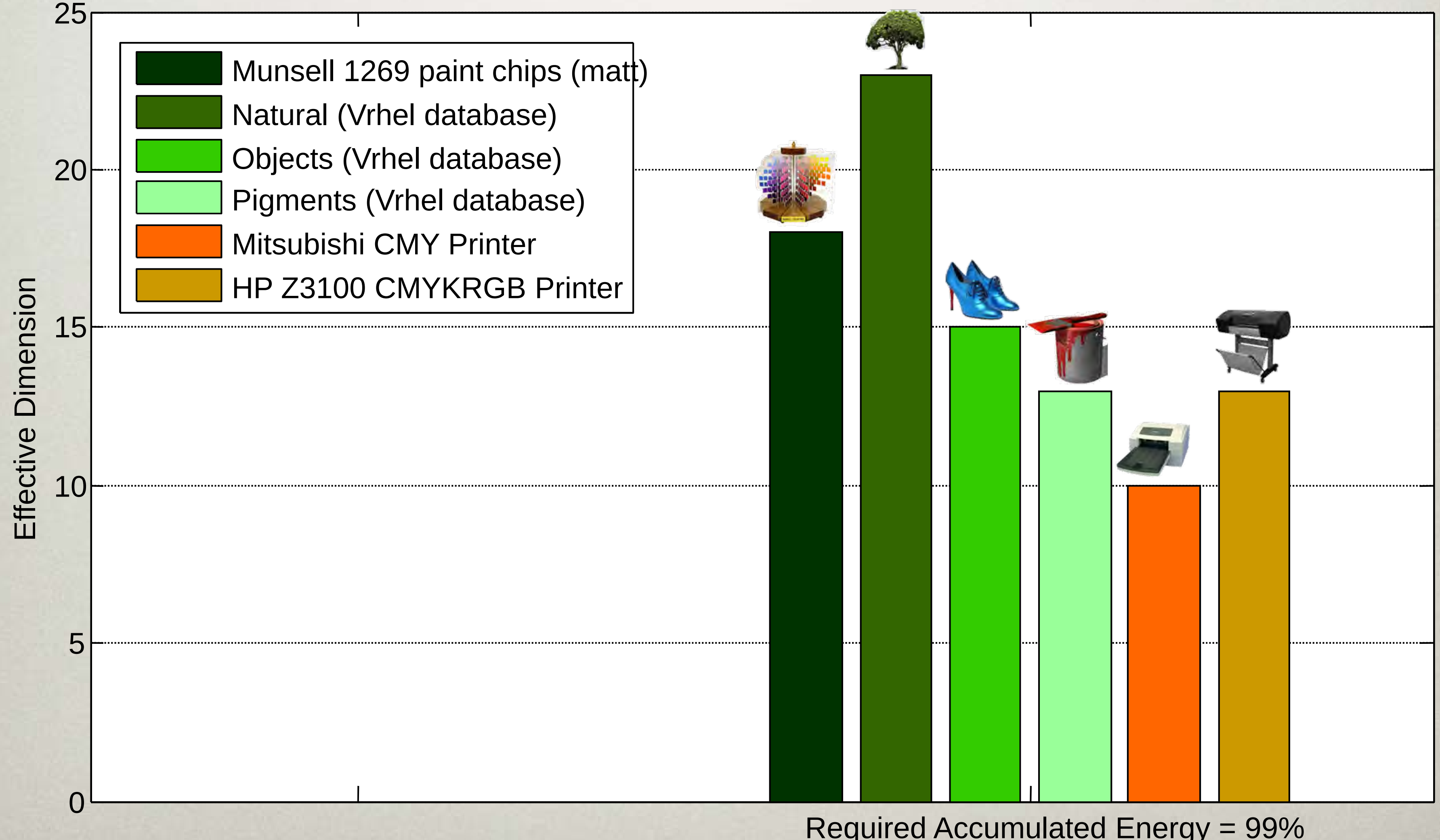
Spectral Printing

Are all Natural Spectra Printable?

A look at the effective spectral dimension

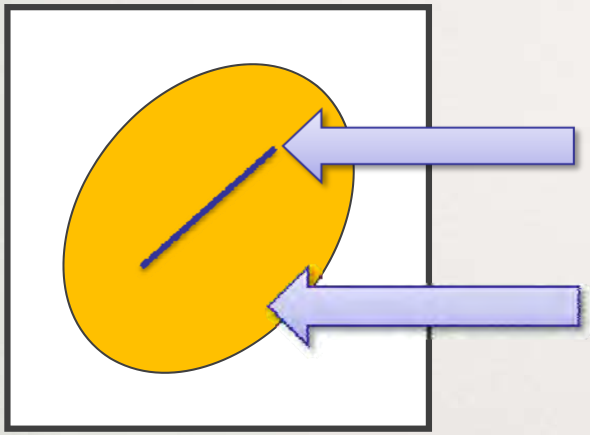
Effective dimension ~ minimal number of characteristic spectra that sufficiently represent the spectral dataset

Are all Natural Spectra Printable?



Hardeberg 2002

Are all Natural Spectra Printable?



Spectral printer gamut

All natural reflectances

Dimension difference $\Rightarrow$ Nearly every given spectrum is out-of-gamut

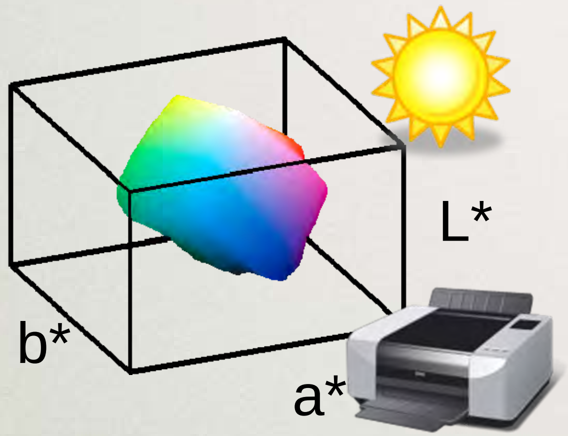
$\Rightarrow$ Spectral Gamut Mapping necessary

Colorimetric Gamut Warning

Spectral Gamut Warning

Spectral Gamut Mapping

- How to calculate the spectral gamut?



Colorimetric Gamut

Spectral Gamut

- How to gamut map spectral images? What are the objectives?

  - Minimizing a spectral distance metric related to human color vision

Or

  - For one illuminant as visual correct as a colorimetric reproduction
  - For other illuminants superior

Printer Model

- What spectral printer model should be used?

Control values
(e.g. CMYKRGB)

Model

Reflectance

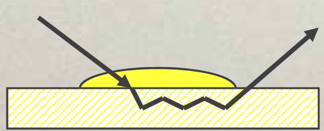
- Printer model needs to be inverted

Control values
(e.g. CMYKRGB)

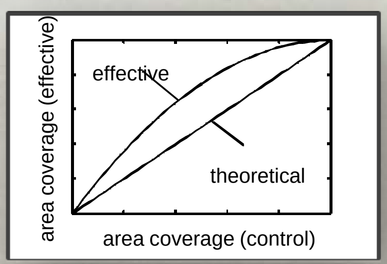
Model Inversion

Reflectance

- Problems:

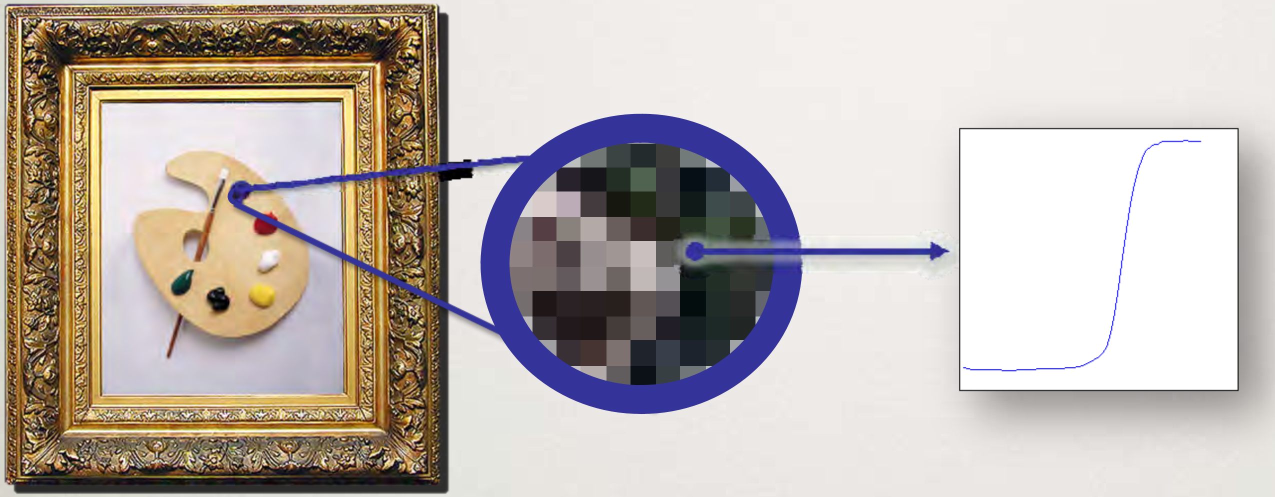


Optical dot gain



Non-linear

Printer Model Inversion



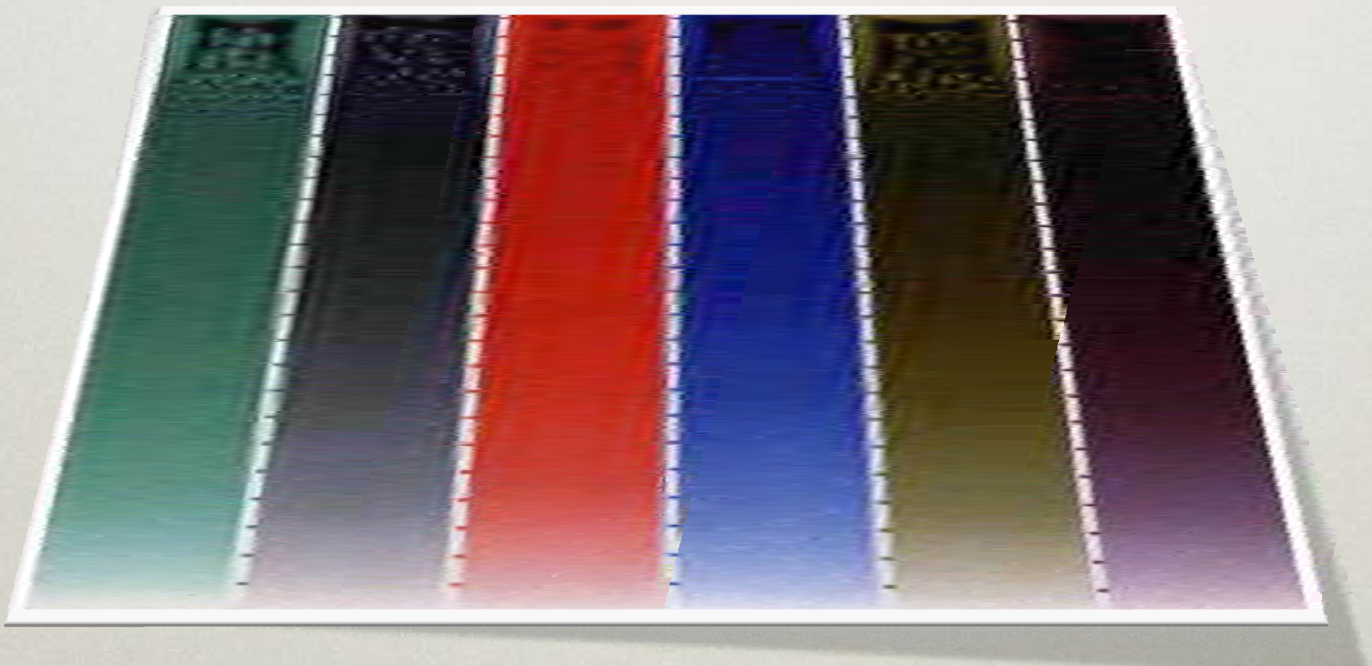
- Model inversion on a Pixel by Pixel Basis

$\Rightarrow$ very fast algorithm and implementation

Ink Limitation

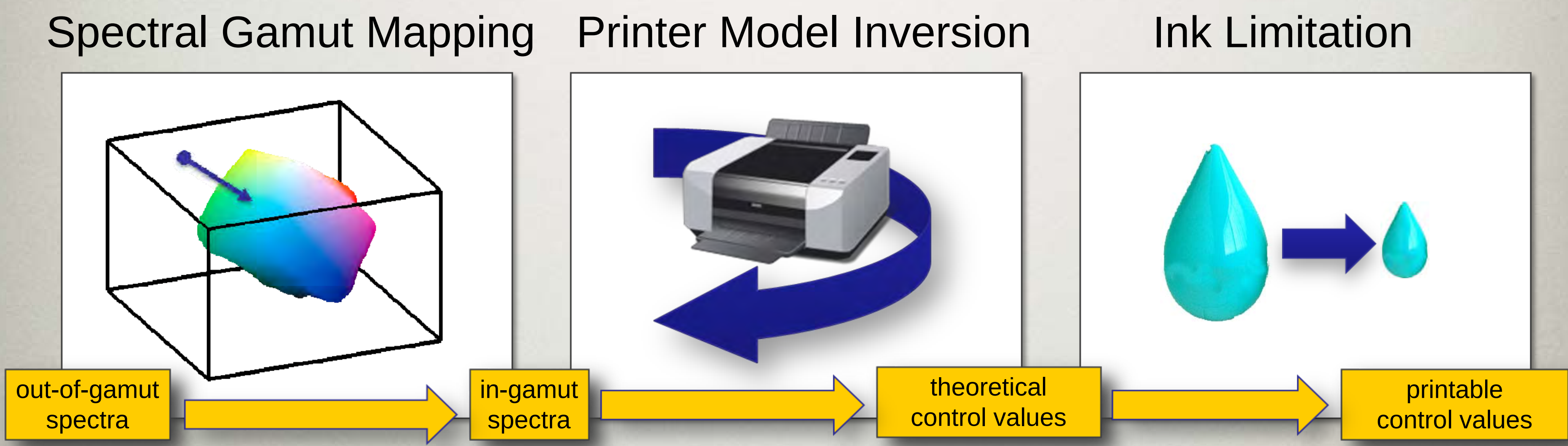
Limited mechanical colorant-absorption of media

$\Rightarrow$ ink limitation necessary



Secondary and tertiary colors (Chen 2006)

Spectral Printing Workflow



Spectral Printer Model

Printer Model

- What spectral printer model should be used?

- Many different models have been developed:

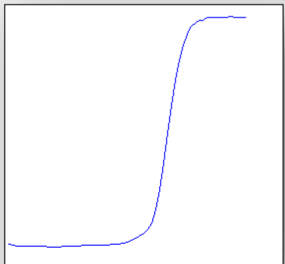
  Pure empirical, physical and hybrid models.
  [see Wyble and Berns 2000 for a comparison]

- The Cellular Yule Nielsen Spectral Neugebauer (CYNSN) model is widely used (good compromise between simplicity and accuracy)

Spectral Gamut Mapping

Spectral Gamut Mapping

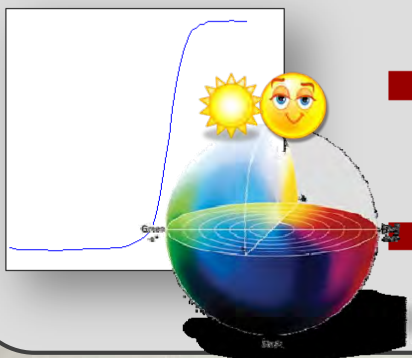
Within Spectral Space



- Minimizing spectral RMS differences
- Minimizing spectral metrics related to human color vision (Color Matching Functions)

Imai et al. 2002, Viggiano 2004

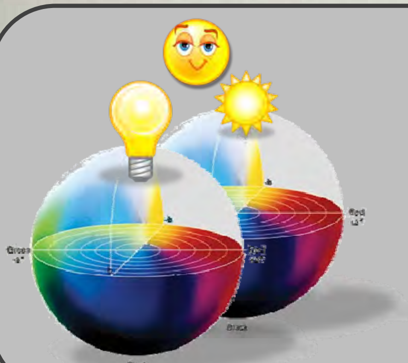
Perceptual and Spectral Space, e.g. LABPQR



- Perceptual space (e.g. CIELAB) – first 3 dim.: Perform traditional gamut mapping
- Remaining dimension – metameric black space: minimize RMS distance

Rosen and Derhak 2006

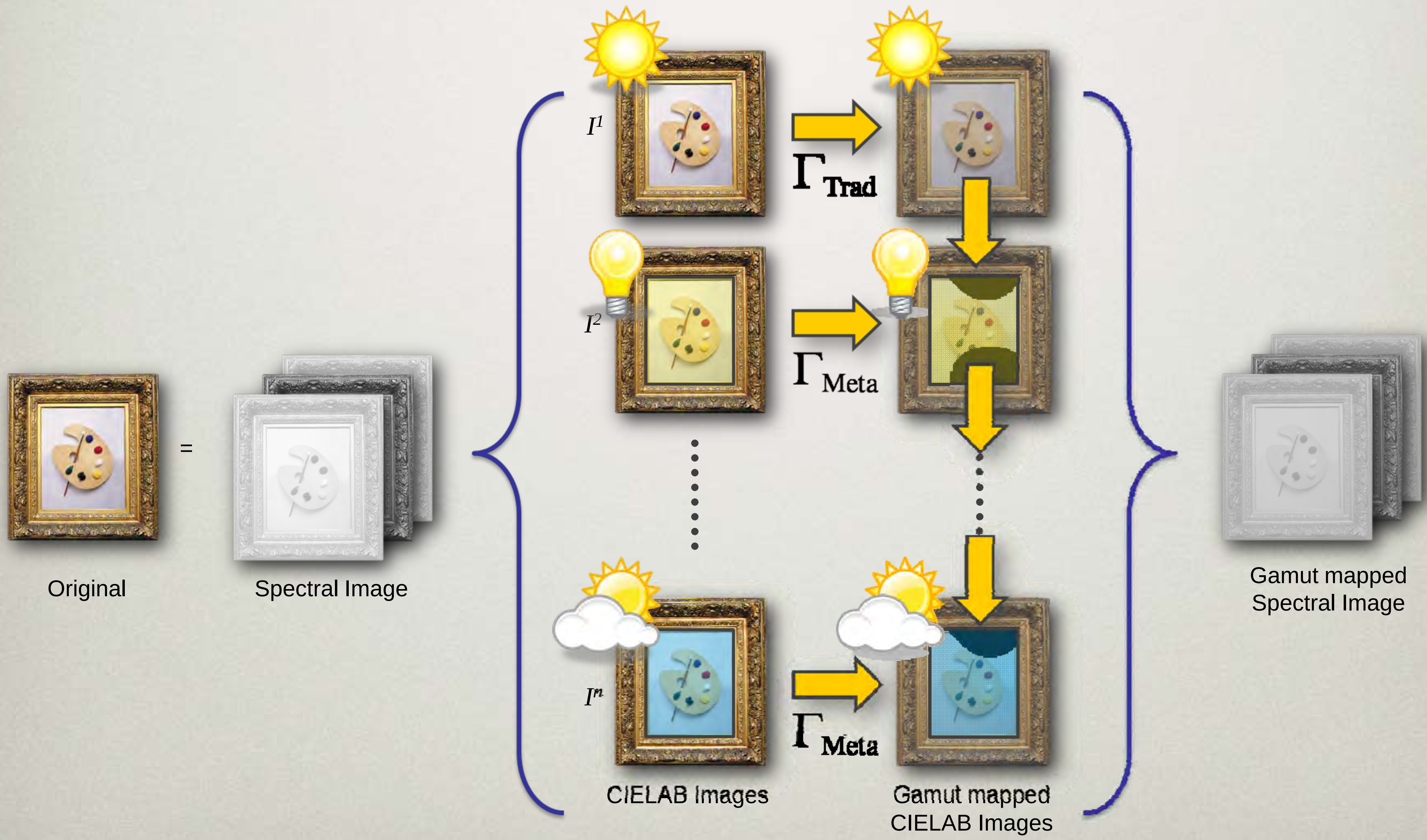
Multi-illuminant Perceptual Spaces



- Perceptual space (e.g. CIELAB) for most important illuminant: traditional gamut mapping
- All other spaces: metamer mismatch-based mapping

Urban et al. 2008

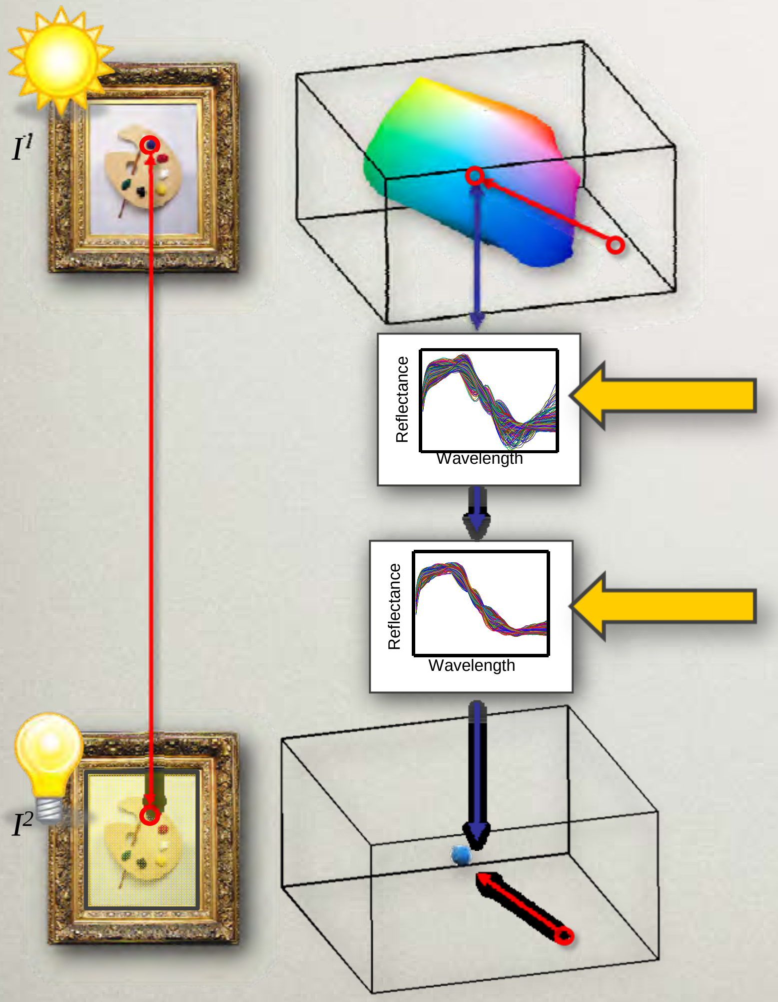
Metamer Mismatch-based Spectral Gamut Mapping



Reproduction has to match the original under a set of illuminants

Metamer Mismatch-based Spectral Gamut Mapping

Spectral printer gamut mapping in color spaces related to human color vision



Most important illuminant:
Traditional metameric gamut mapping

Metameric Reflectances

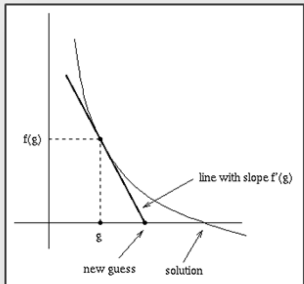
Metameric Reflectances
within spectral printer gamut

Next illuminant:
Mapping onto the metamer mismatch gamut
(e.g. minimize color difference)

Spectral Printer Model Inversion

Spectral Printer Model Inversion

Standard Mathematical Methods



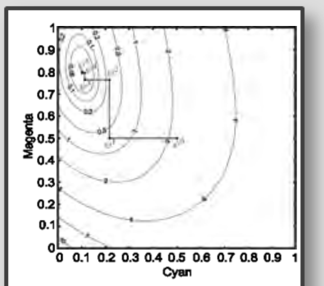
- Solve $\left\| R(\psi) - r \right\|_2 = \min$

$$\psi \in [0,1]^m$$

- Newton-based methods

Taplin 2001, Zuffi and Schettini 2002

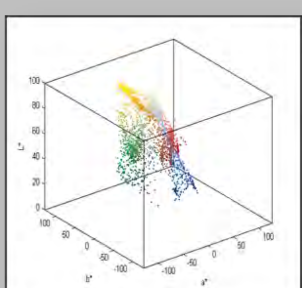
Cellular Subspace Linear Regression Iteration

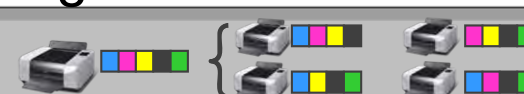


- Use special properties of the CYNSN model
- Accelerate processing within a low-dimensional subspace

Urban et al. 2006, 2007

Gamut Mapping + Model Inversion

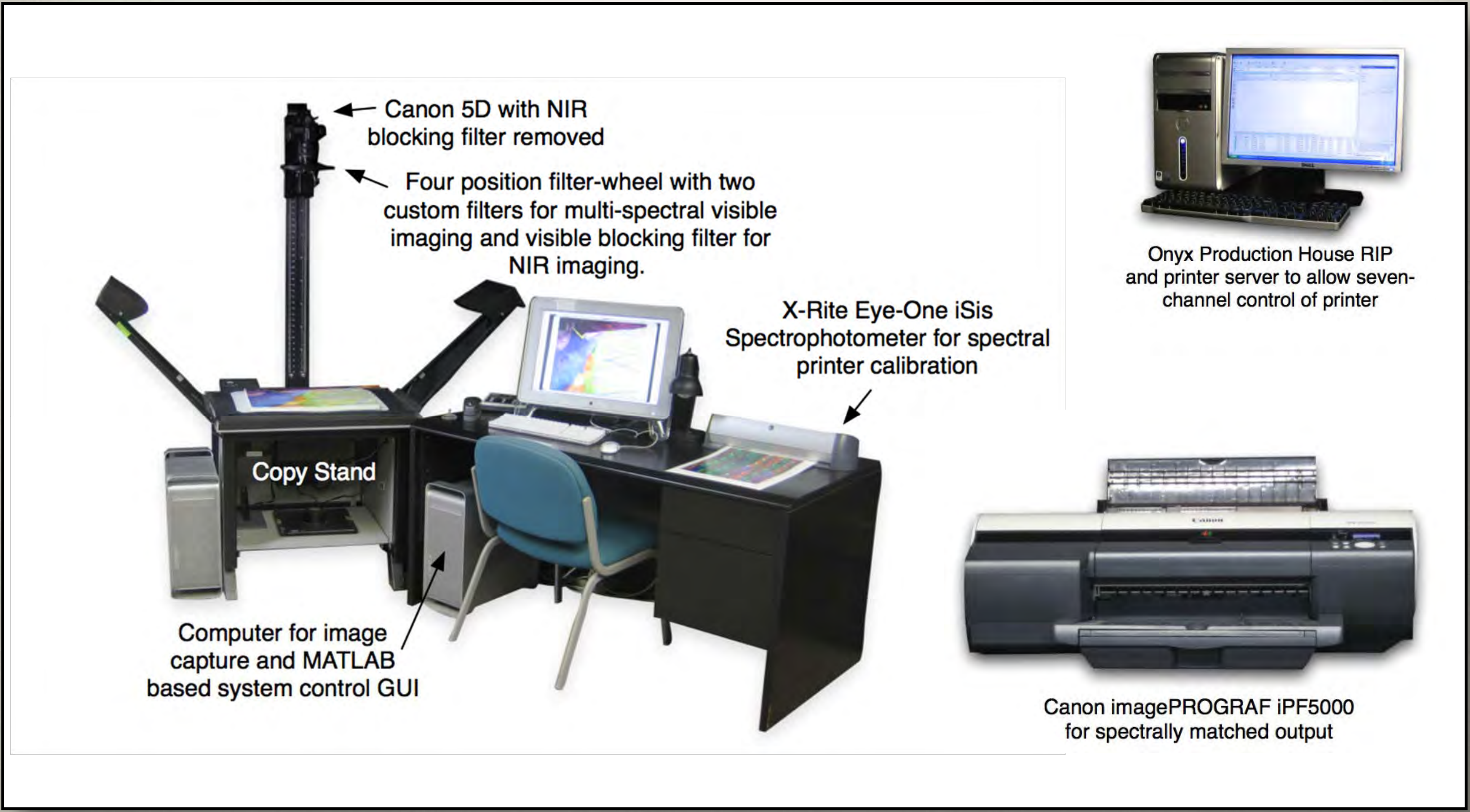


- Limit the number of overprints to four 
- Utilize JND of observer + large color quantization of printers to perform a discrete optimization within submodels
- Select inks based on multi-ill. colorimetry

Urban et al. 2008

An Example of a Spectral End-to-End Reproduction System

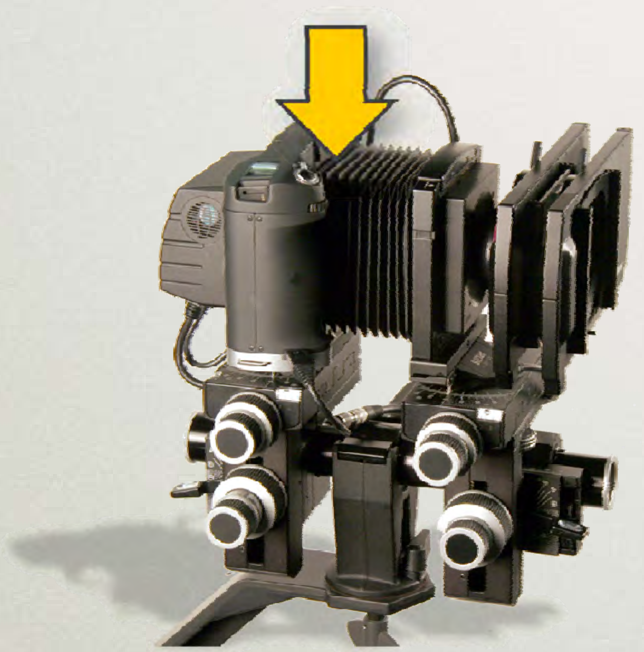
System built at the Munsell Color Science Laboratory

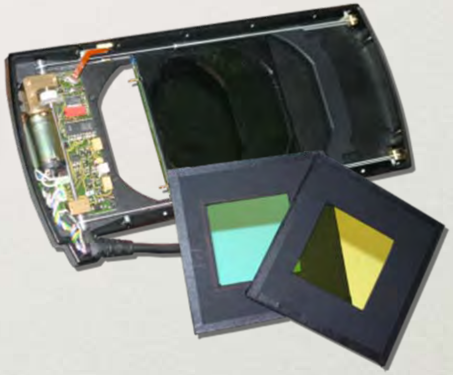


Additional Cameras

Modified Sinarback 54H digital camera

NIR blocking filter removed





Two optimized Filters

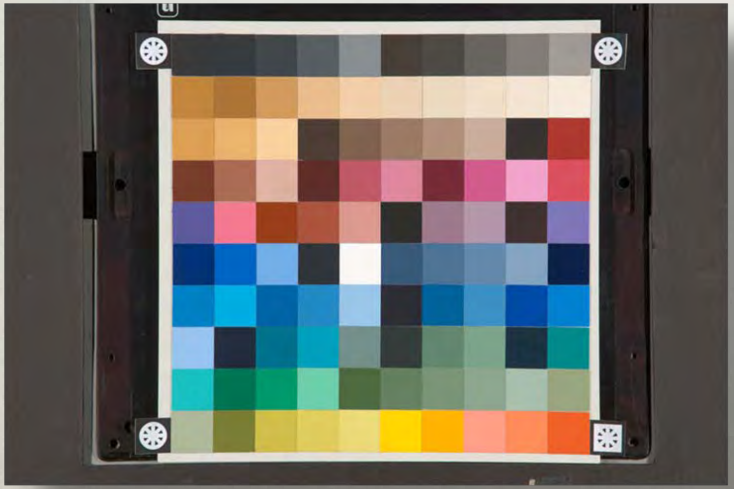
Sinarback 54H (RGB Camera)

6 Channel Camera

System Characterization

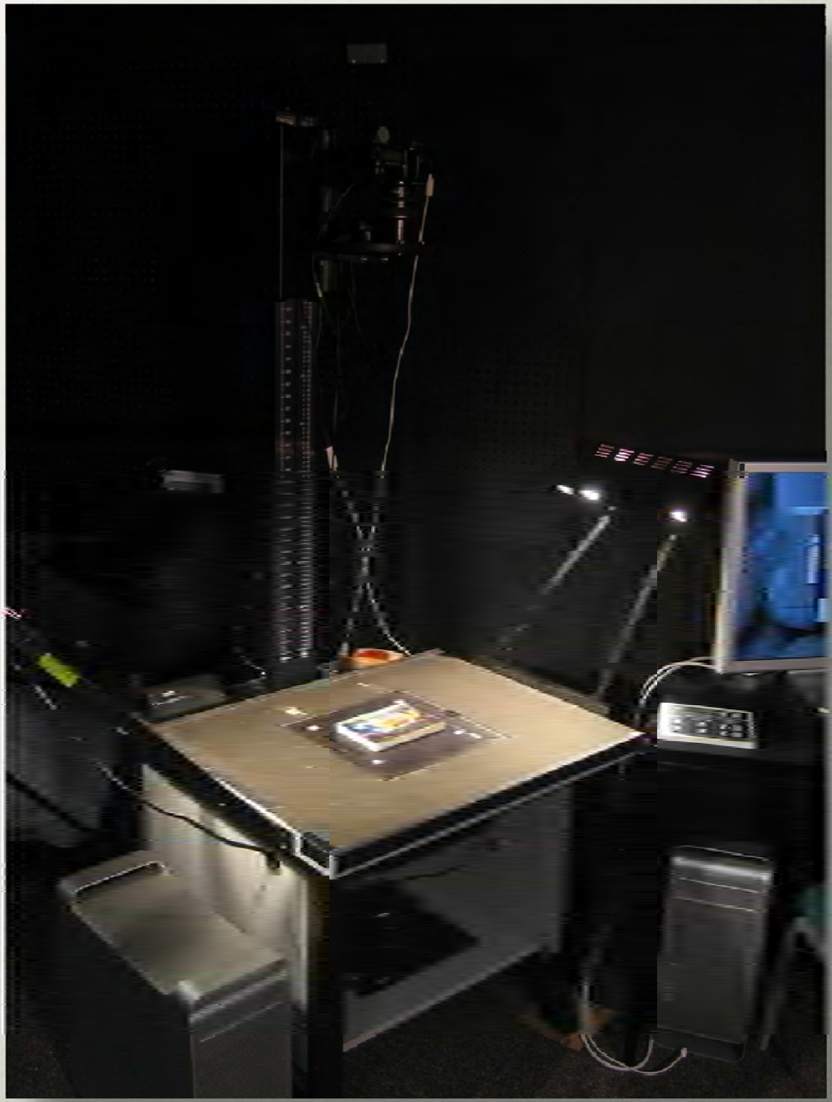
- Printer Characterization
  - 7k Patches for 7ink Printer (CMYKRGB)
  - Measured using Eye-One ISIS in ~30min

- Camera Characterization
  - White Board for Flat Fielding
  - Representative Training Target

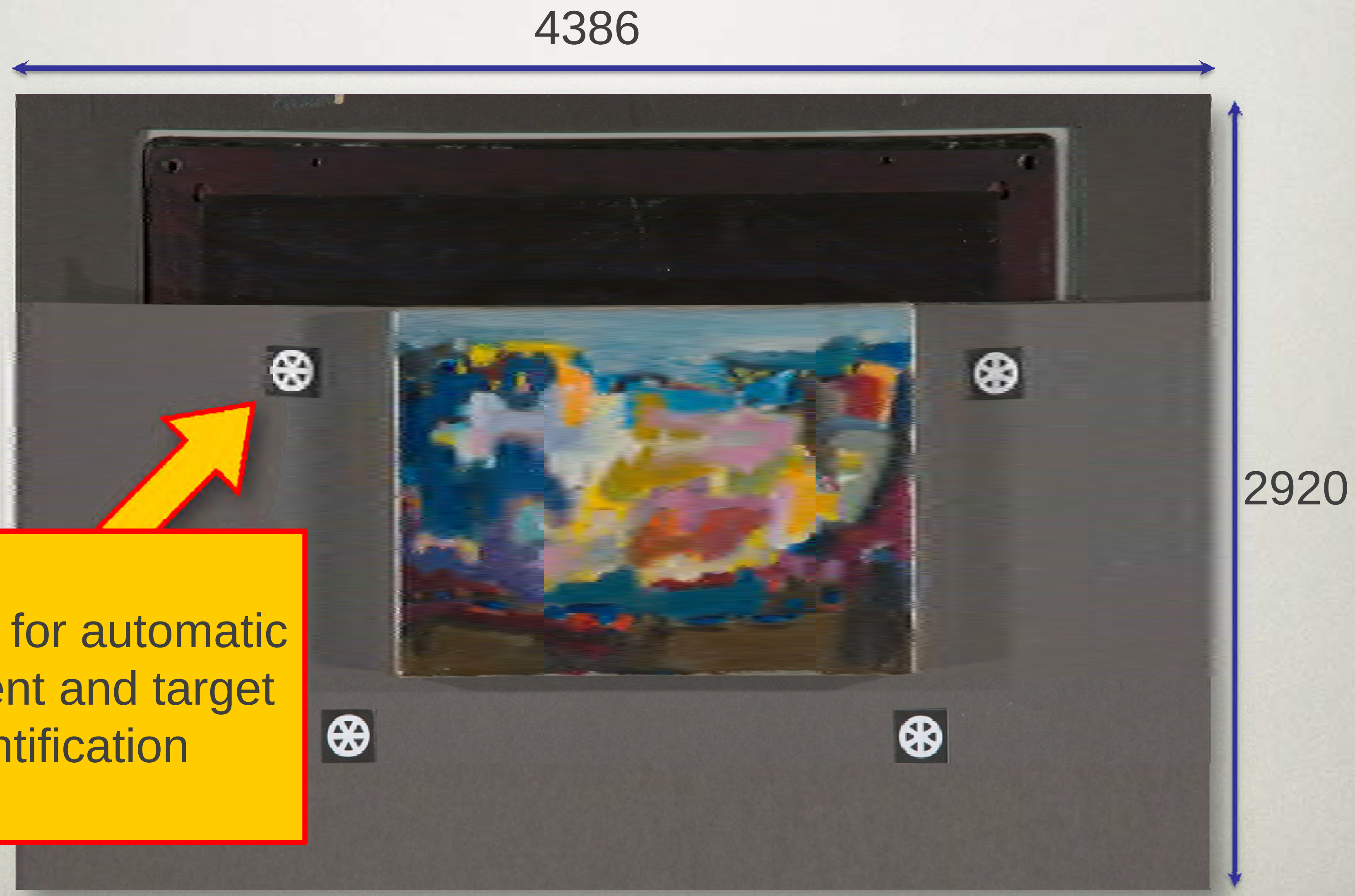


Artwork Capture

- Dedicated Motorized Copy Stand
- Quartz Halogen Lights (3200° Kelvin)
- 45-Degree Lighting Geometry
- Autofocus Camera
- 24”×30” Capture Area



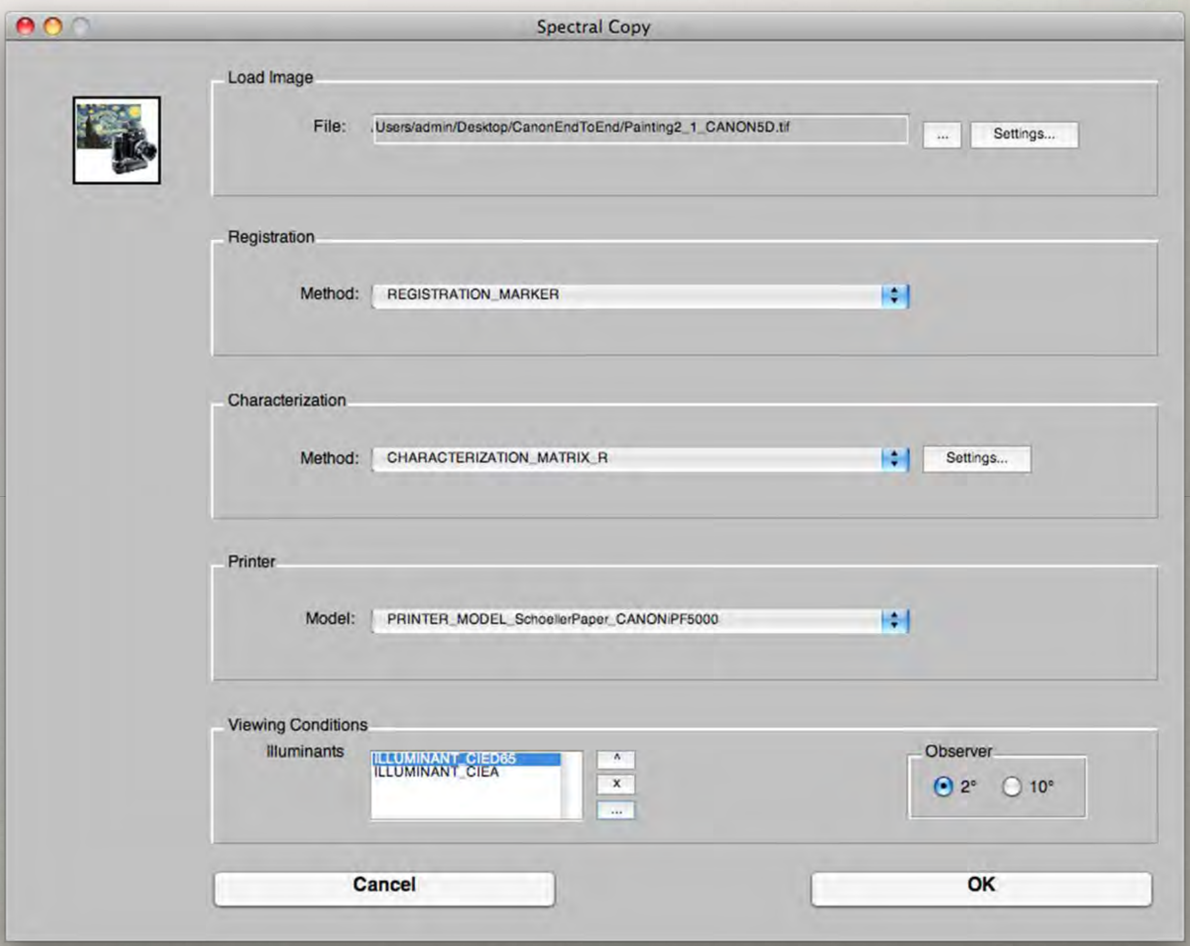
Automatic Marker-based Image Registration



Markers for automatic alignment and target identification

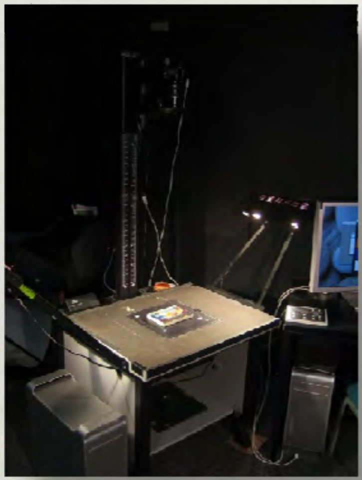
Spectral End-to-End Reproduction Software

- Simple Matlab-based user interface
- Allows non-expert users to perform all steps for spectral based capture, processing, and printer separation

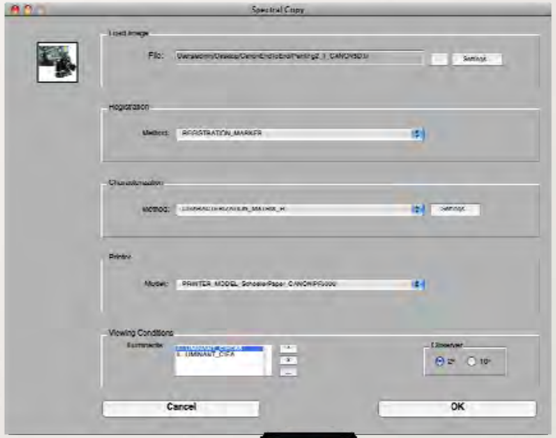


Spectral End-to-End Reproduction workflow

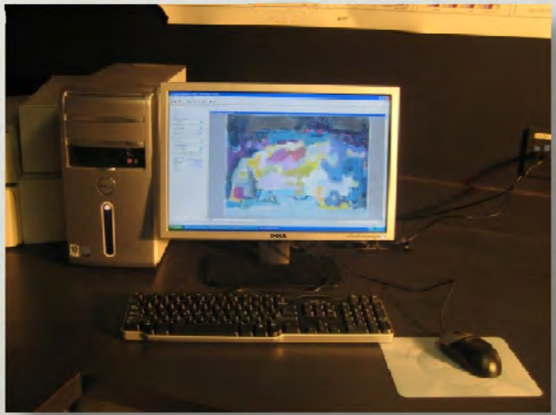
Modified Canon 5D



End-To-End Software



Canon iPF5000 12-Ink Printer



Onyx ProductionHouse RIP

Spectral End-to-End Reproduction workflow

MOMA Image Removed

Spectral End-to-End Reproduction workflow

MOMA Image Removed

Spectral End-to-End Reproduction workflow

MOMA Image Removed

Artwork Reproduction Results

Daylight

Tungsten

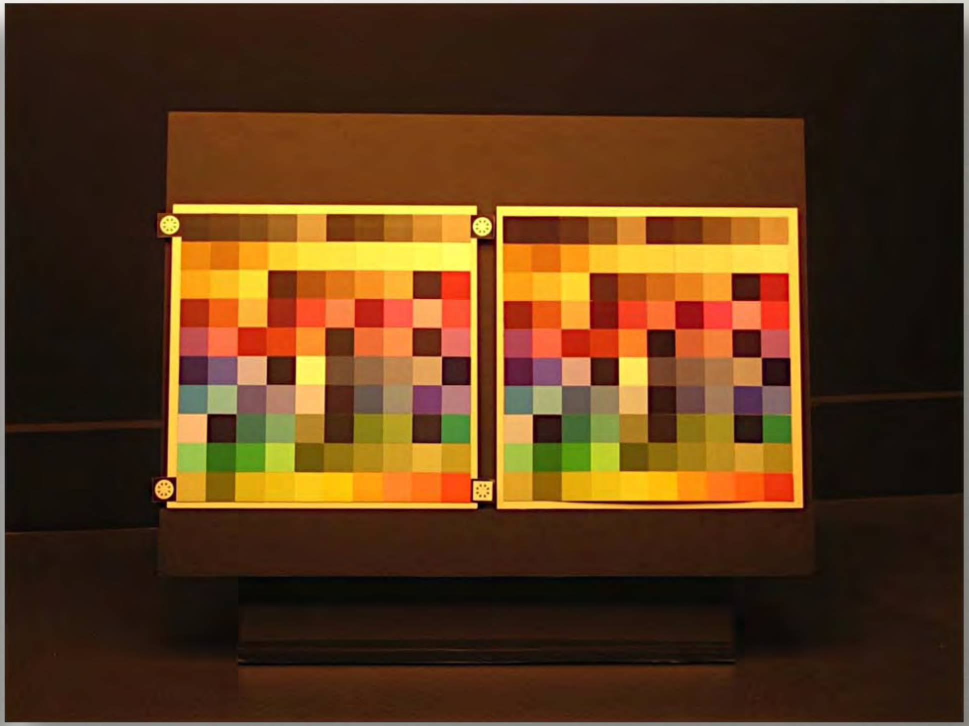
Print

Original

(Training)Target Reproduction Results

Daylight

Tungsten



Colorimetric Error:

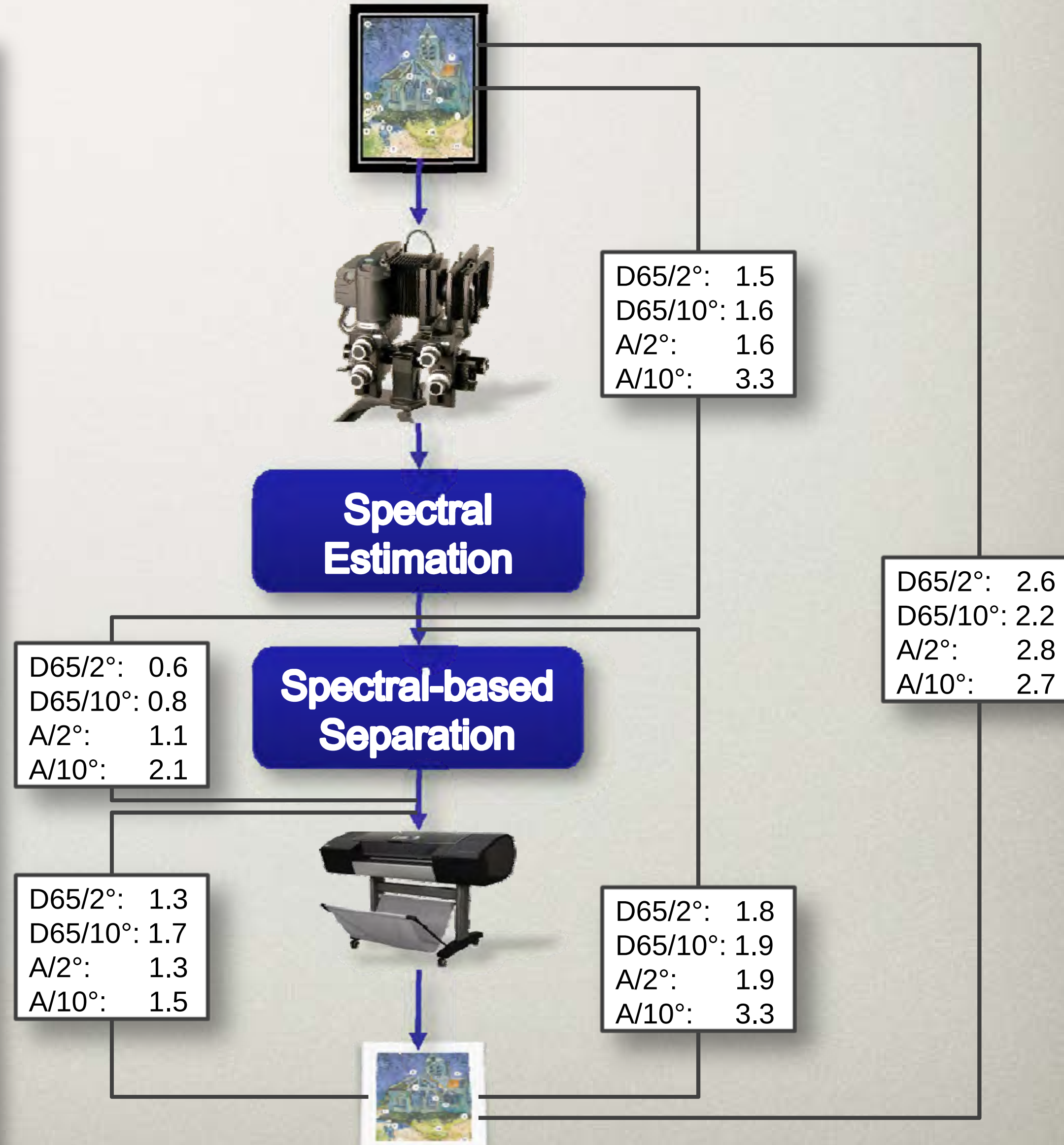
Mean:	1.7
Std:	0.8
Max:	4.1

Colorimetric Error:

Mean:	2.2
Std:	1.3
Max:	5.9

Artwork Reproduction Results

Berns et al. 2008

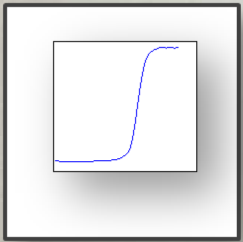


Median CIEDE2000 Errors

Conclusion

Conclusion

- Metameric Reproduction Systems have systematic limitations
  (device, illuminant and observer metamerism)
- Insufficient for special applications:
  (artwork reproduction, accurate proofing, industrial color comunication)



The solution of these problems is a spectral reproduction workflow:

- More channels throughout the whole reproduction chain
- New algorithms are necessary for characterization, separation and gamut mapping

Prototype developed at the Munsell Color Science Laboratory

- Utilized only slightly modified commercial devices
- Multiple-illuminant match

Many modules of the spectral reproduction system are still an active research field

- Improvements can be expected in future (new devices, methods and software)

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Paper

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fogra

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