ICC DevCon 2020

3D Printing spatially varying color and translucency

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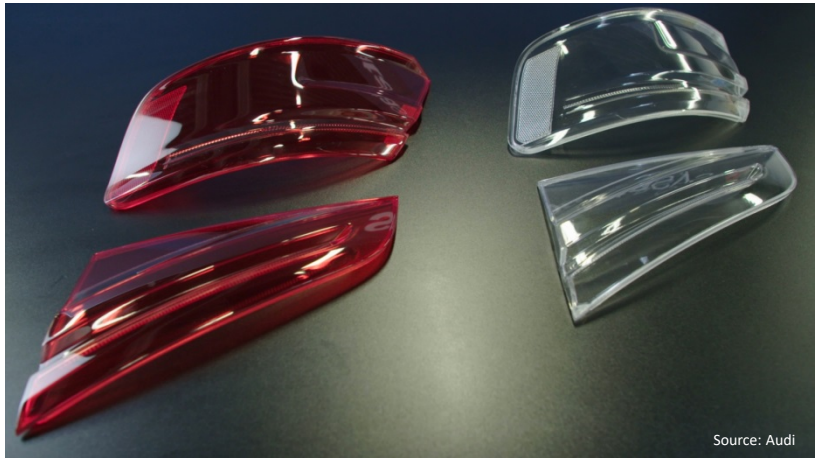
Application areas



Design prototypes

Replacements parts fitting into existing visual environment

Cultural heritage

Entertainment

3D printers available

Stratasys J750

Mimaki 3DUJ-553

Materials:

Cyan

Magenta

Yellow

Black

White

Transparent

Hi-Resolution Multimaterial 3D Printers (Polyjet)

Related work

Color 3D Printing (examples)

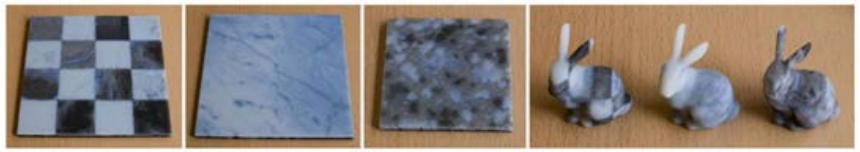
Joint

color + translucency

Translucency 3D Printing (examples)

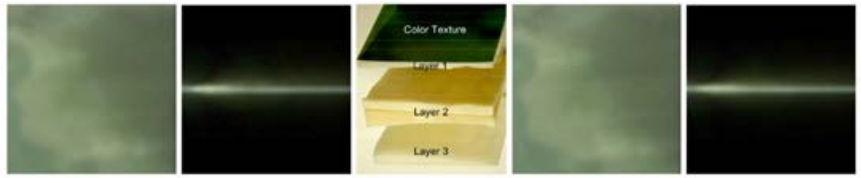
Brunton et al. 2015

Hašan et al. 2010



Babaei et al. 2017

Dong et al. 2010



Reproducing perceptual attributes

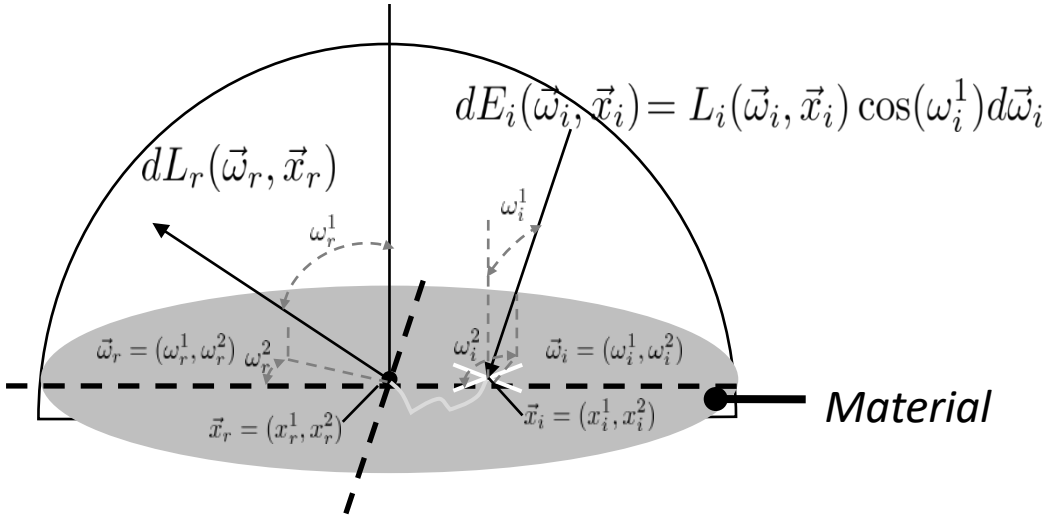
?

Reproducing physical quantities

Reproducing Physical Quantities?

Why not using BSSRDFs?

- High dimensionality
  - High memory consumption
- Measurement effort
  - Instruments not available
  - Time consuming
- No perceptual metric



Can we reproduce given BSSRDFs?

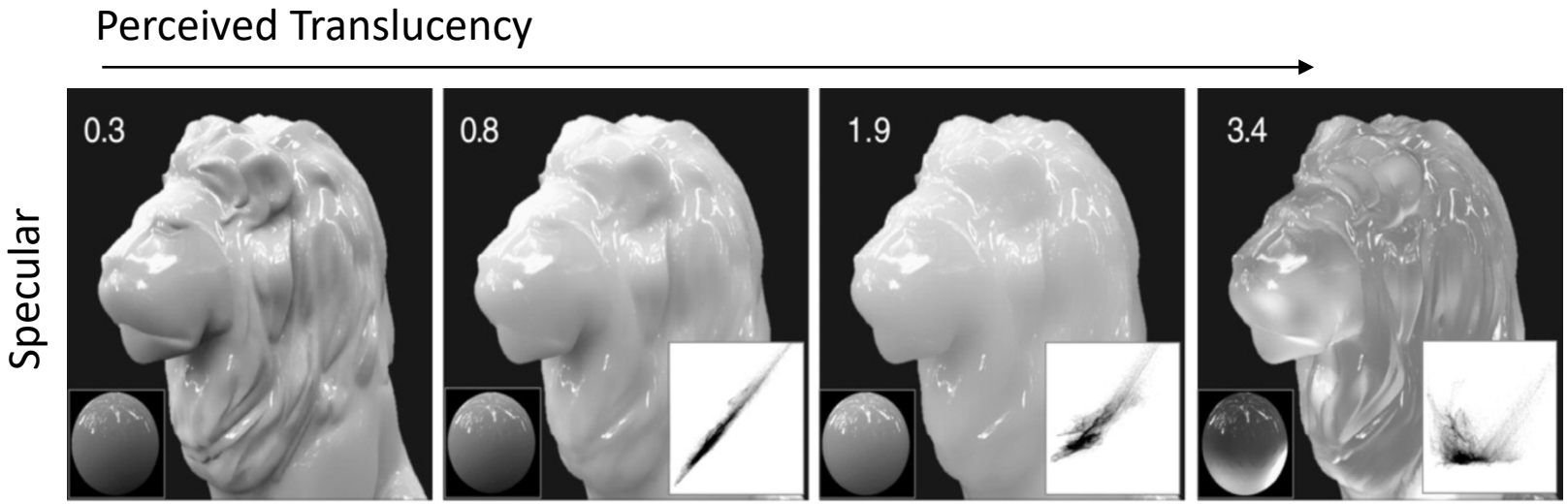
Mostly impossible due to printing systems limits:

- Absorption (factor)
- Scattering (factor / function)
- Refractive index
- Resolution (surface roughness)

$$S(\vec{\omega}_i, \vec{x}_i, \vec{\omega}_r, \vec{x}_r) = \frac{dL_r(\vec{\omega}_r, \vec{x}_r)}{dE_i(\vec{\omega}_i, \vec{x}_i)}$$

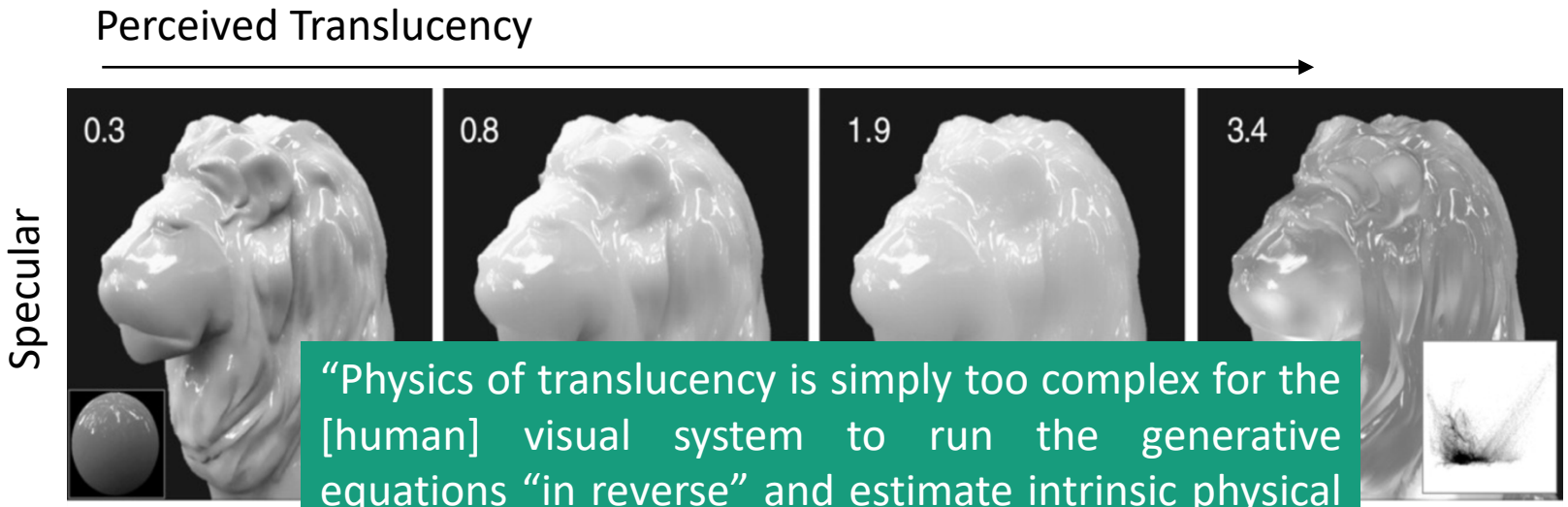
Bidirectional Surface Scattering
Reflectance Distribution Function (BSSRDF)

Perceptual attributes



Motoyoshi, 2010

Perceptual attributes



"Physics of translucency is simply too complex for the [human] visual system to run the generative equations "in reverse" and estimate intrinsic physical parameters via inverse optics.

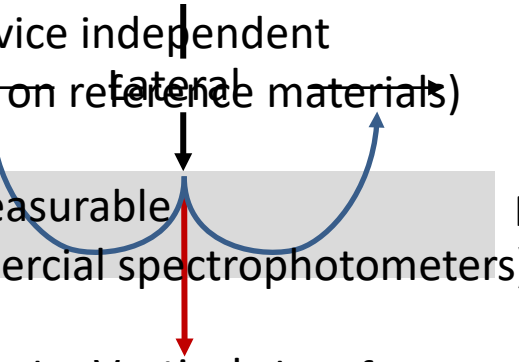
… instead the visual system relies on simple image heuristics [cues] that correlate with translucency."

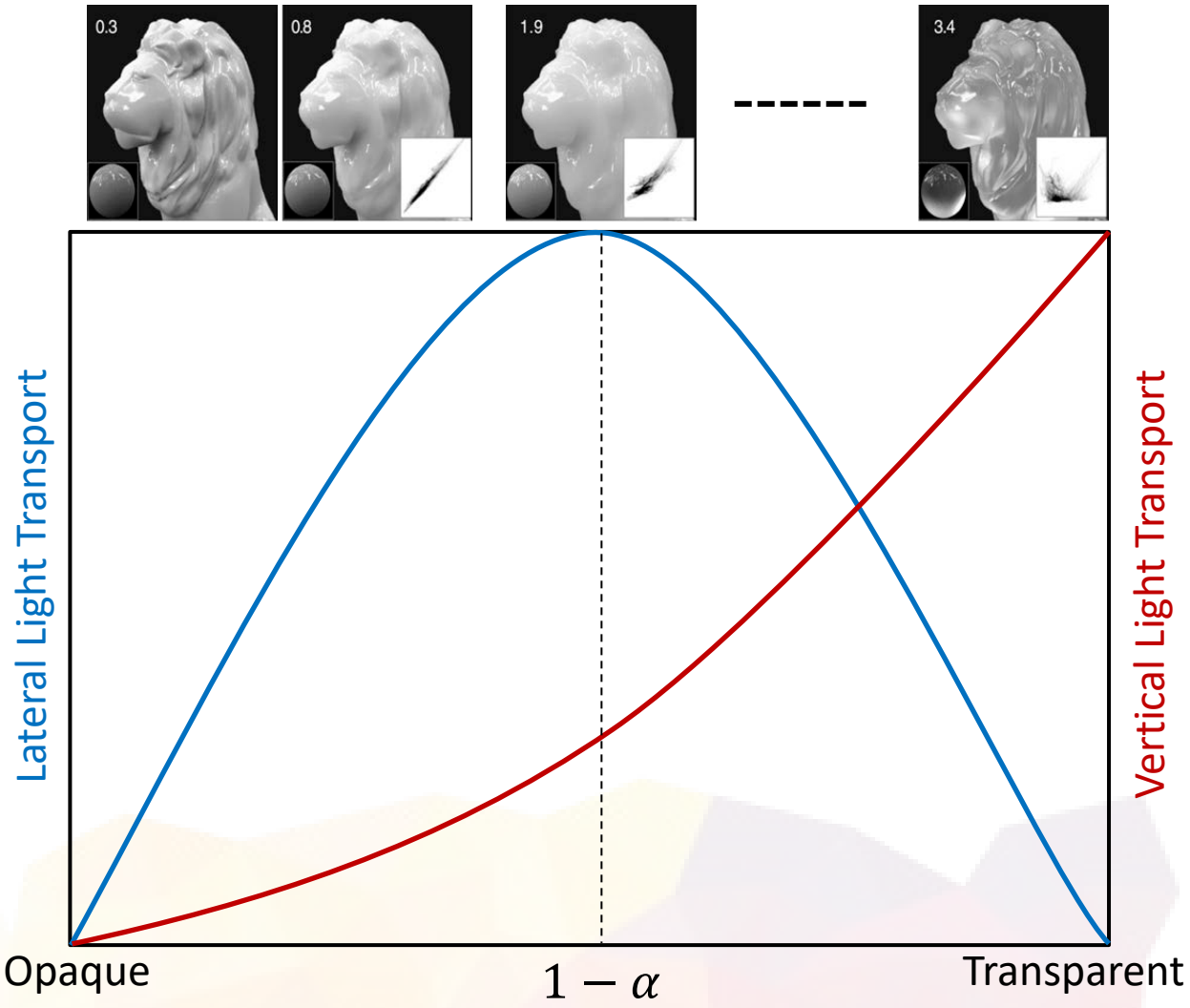
Fleming and Bülthoff, 2005

Motoyoshi, 2010

Visual cues induced by light transport

- is device independent
(based on reference materials)
- is measurable Material
(commercial spectrophotometers)
- is nearly perceptual uniform
(for reference materials)
- Add to RGB reproduce RGBA





Urban et al., 2017

Benefits of reproducing RGBA

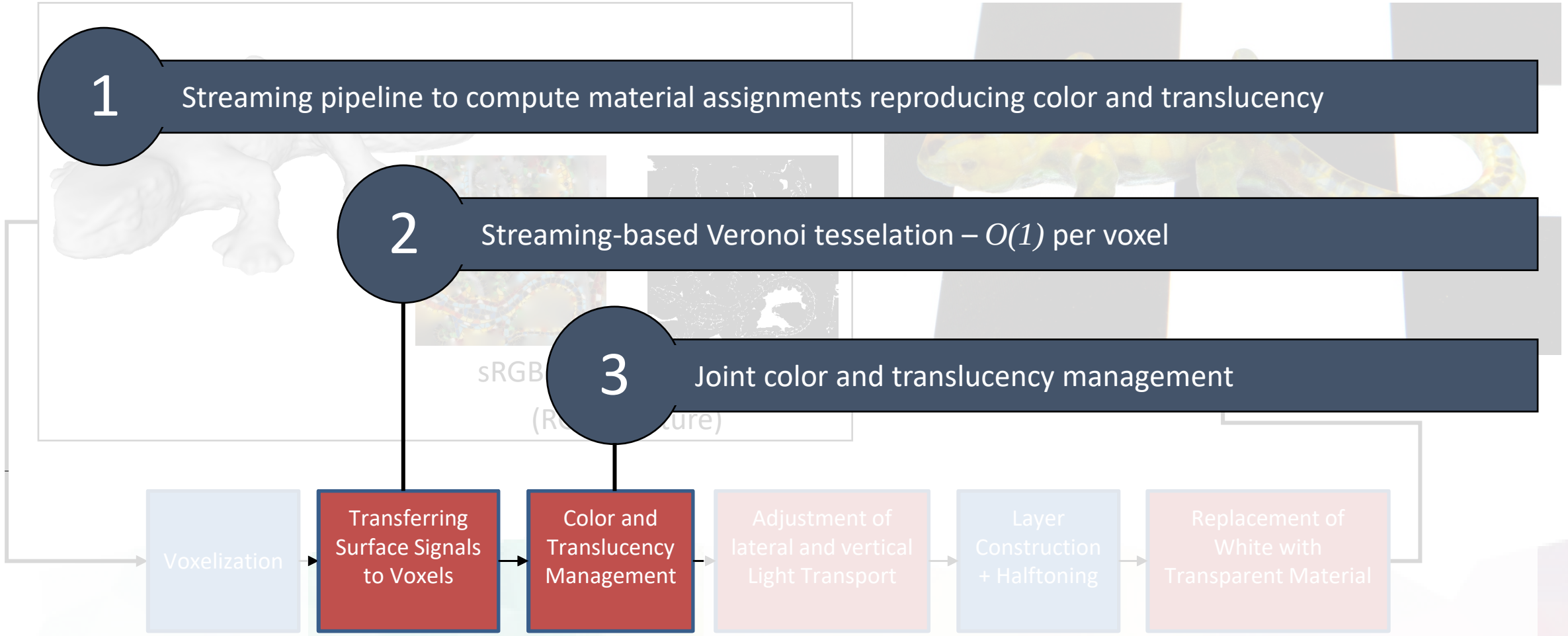
RGBA textured 3D models are

- supported by various 3D file formats

- can be created and modified by various 3D modeling tools

- RGBA textures can be modified by image processing tools

Streaming voxel-based pipeline



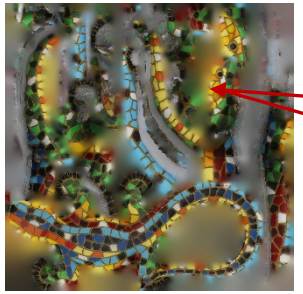
Approach: Minimize translucency error while preserving relative color

Precomputation: Conversion to voxels

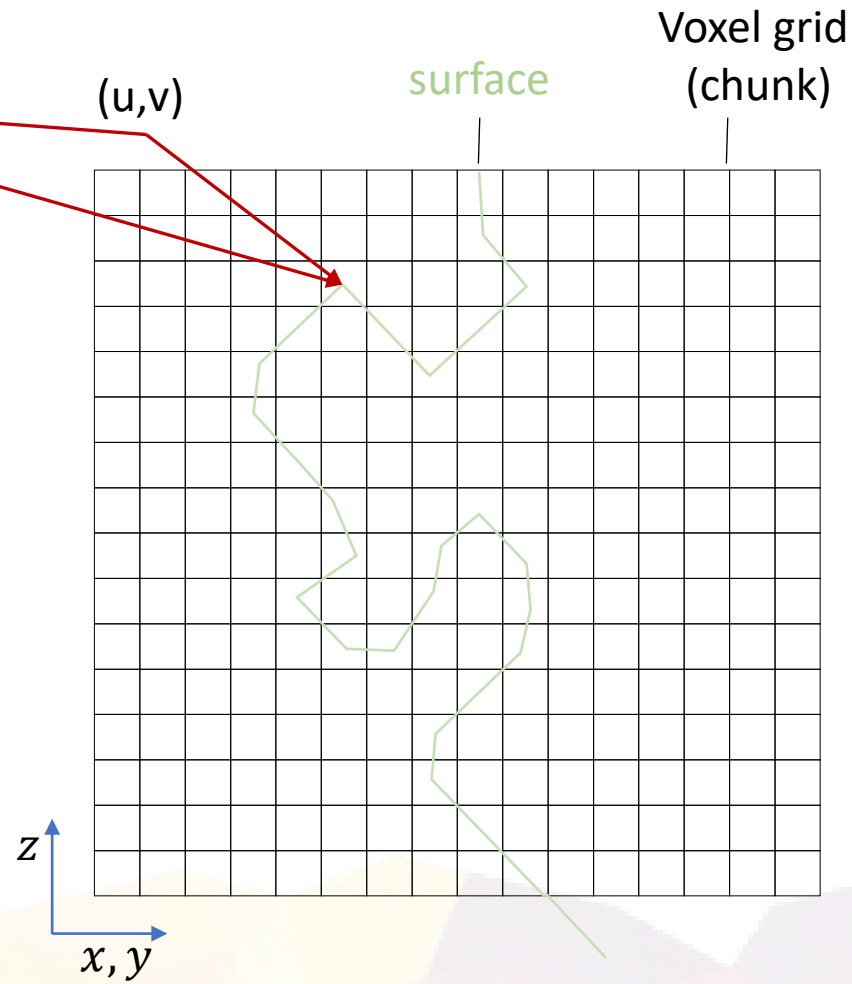
Per chunk (const. # slices):

6-separating surface voxelization + rasterization of RGBA values:

- Interpolate texture coordinates
- Sample texture
- Write RGBA to surface voxel



sRGBA

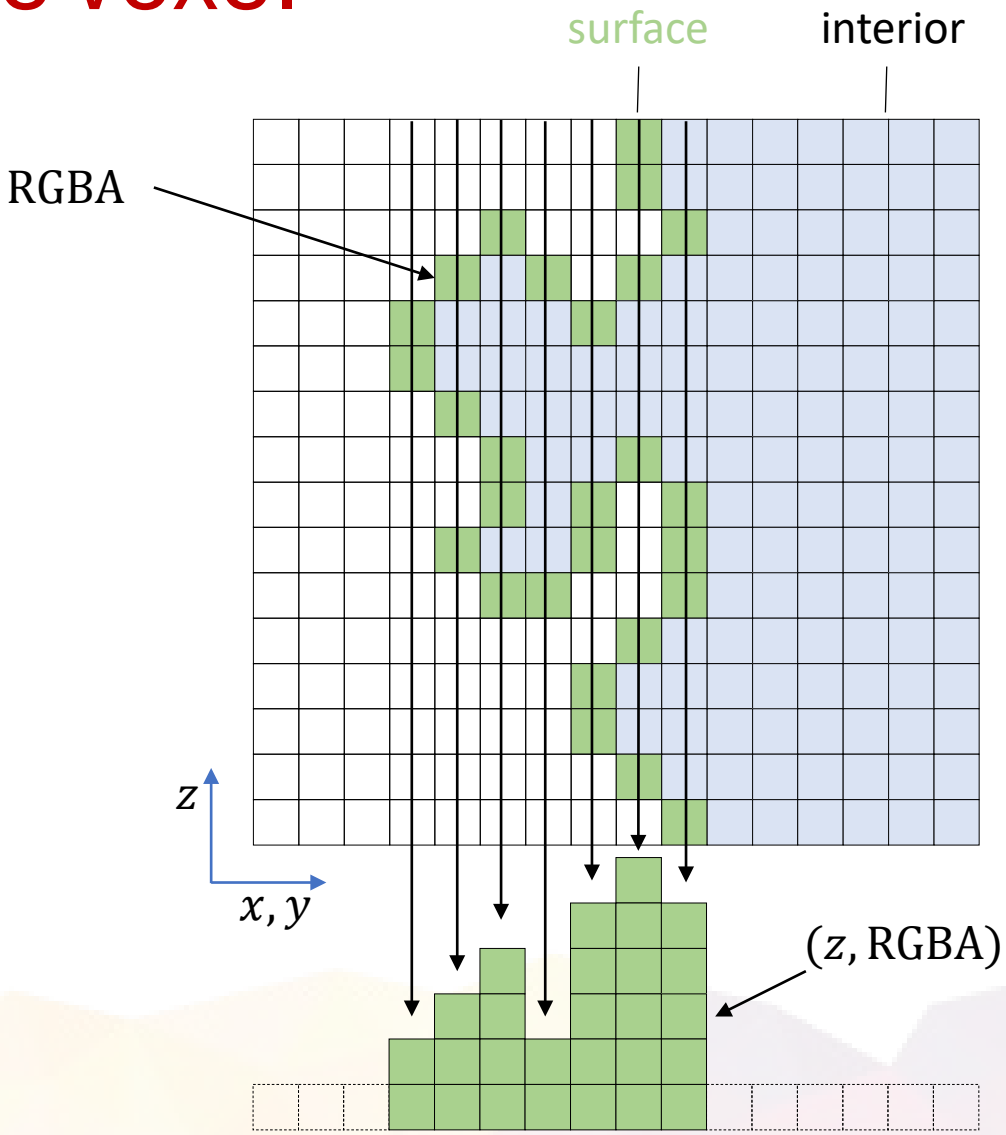


Precomputation: Sparse surface voxel representation

Per chunk:

From surface voxels, construct ordered lists of (z, RGBA) pairs

Construction in linear time w.r.t. # surface voxels



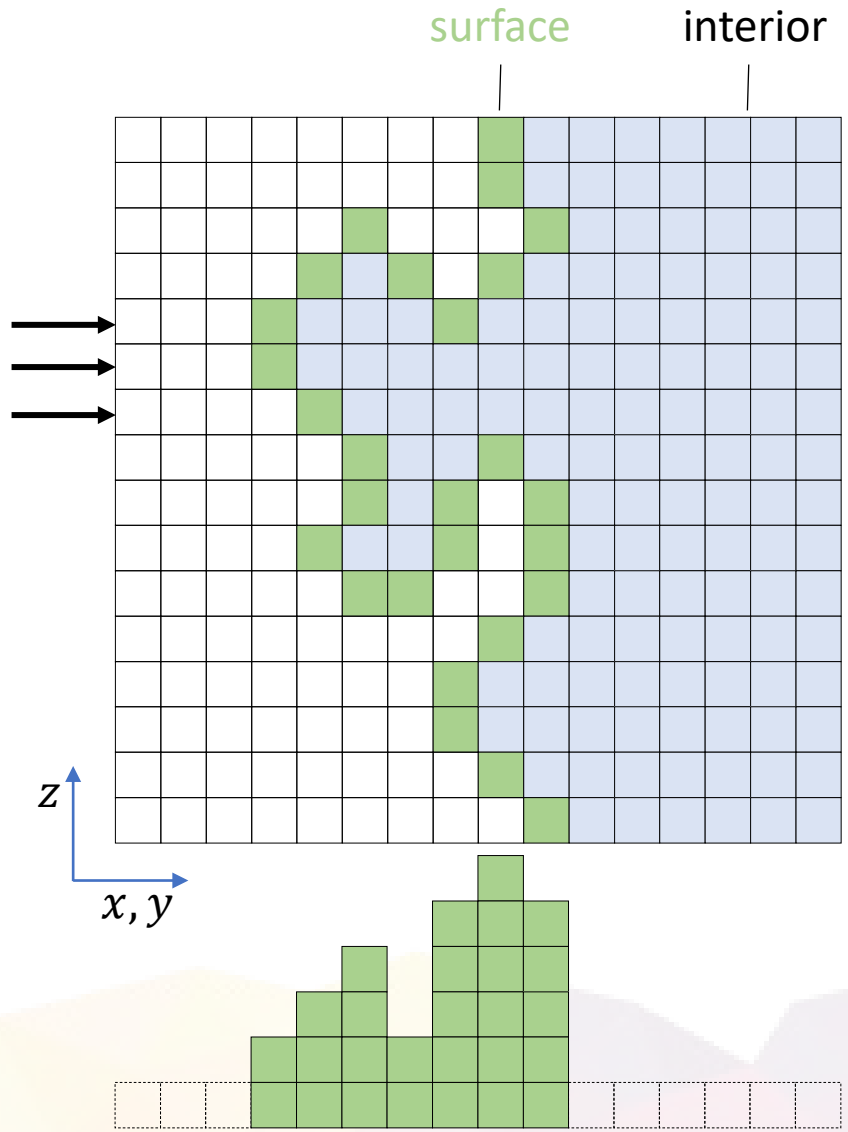
Transfer RGBA to all voxels

We need the following at **all** voxels:

- RGBA
- Distance to nearest surface voxel

Discrete Voronoi tesselation

- slice-wise computation in $O(1)$ time per voxel
- Incremental look-up of nearest voxel + distance in z
- 2D distance transform in (x, y)
  Felzenzwalb and Huttenlocher, 2012

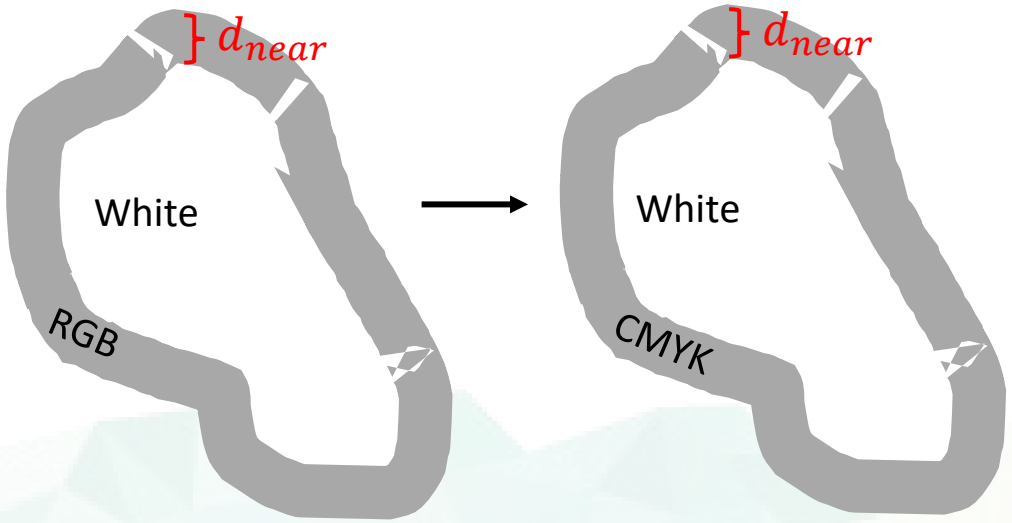


$$DT(\Delta z^2)(x,y) = \min_{x',y'} \left(\Delta z(x',y')^2 + (x'-x)^2 + (y'-y)^2\right)$$

RGBA → material assignments

Transferring Surface Signals to Voxels

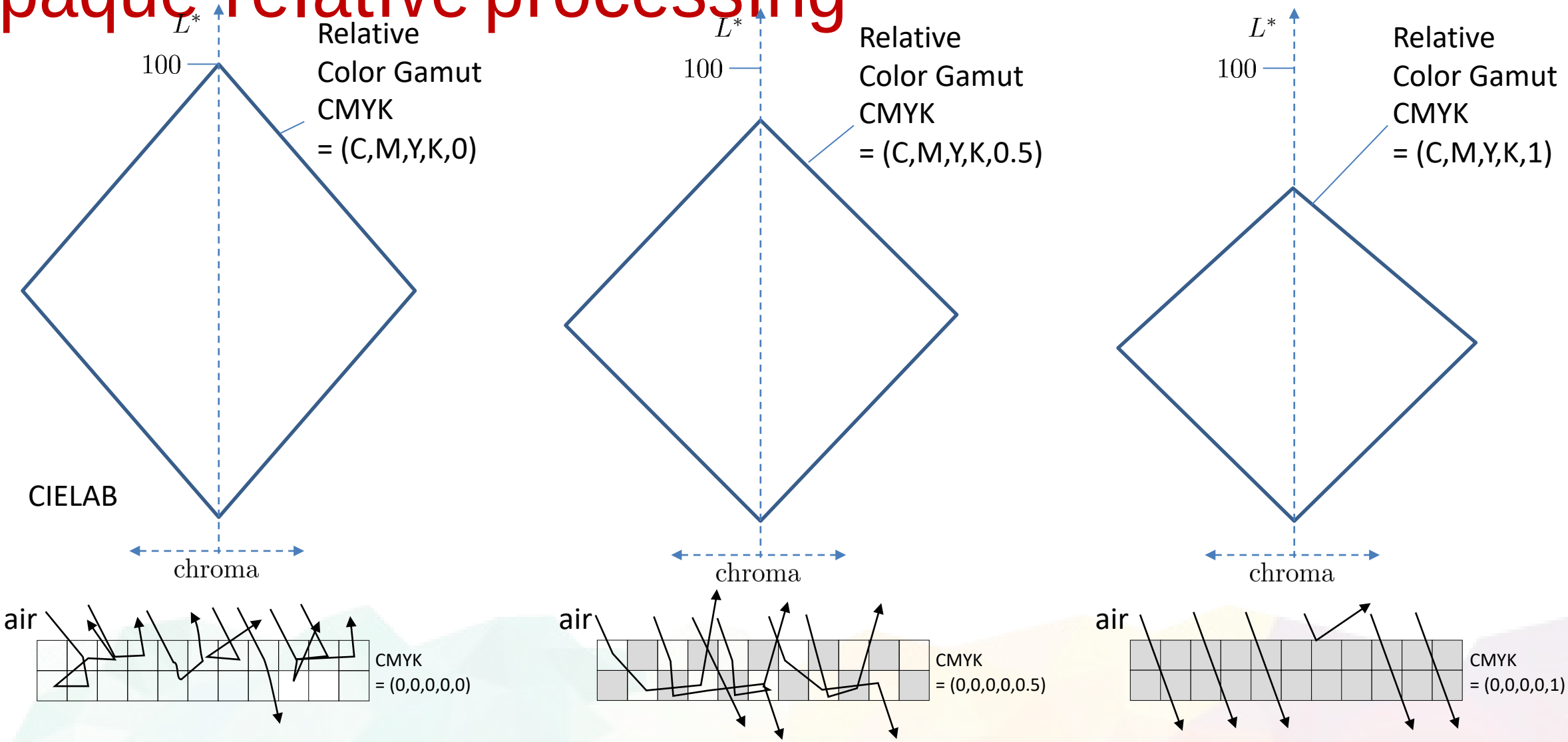
Beyond distance d_{near} look-up tables to convert RGBA to CMYK with (1,1,1,)



ratio of white and clear material:

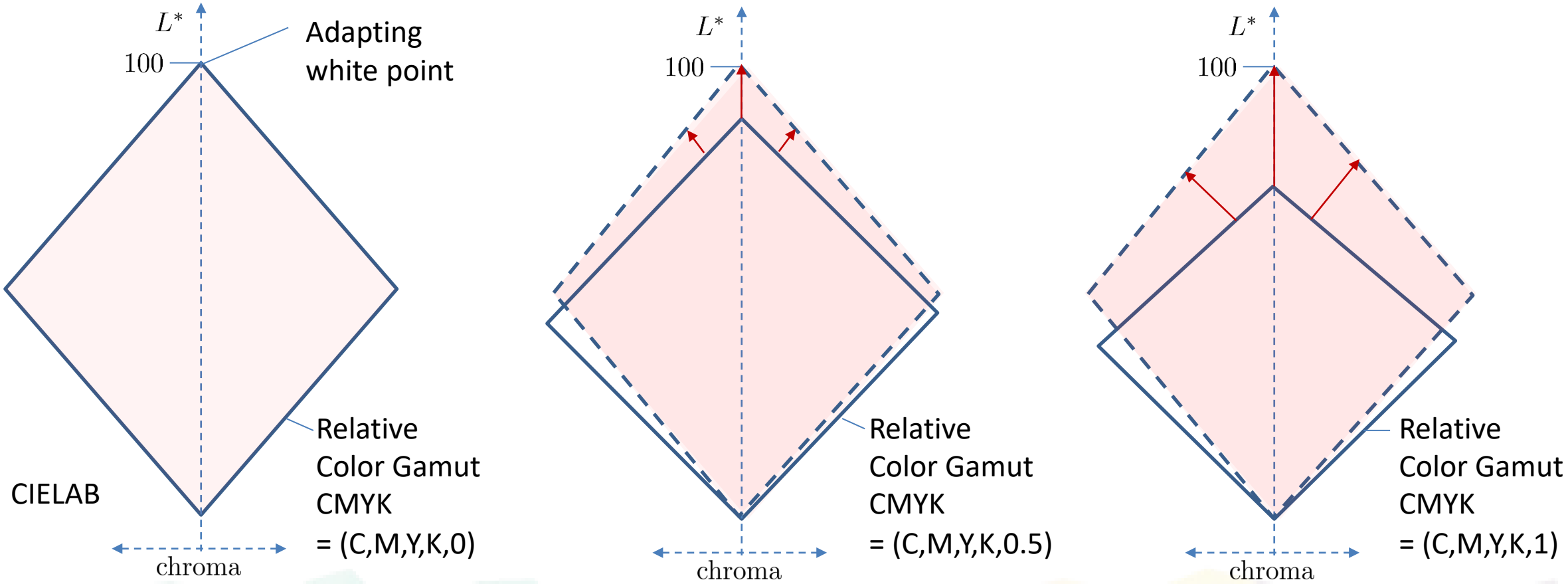
= 0 only white material
= 0.5 50% white / 50% clear material
= 1 only clear material

Opaque-relative processing



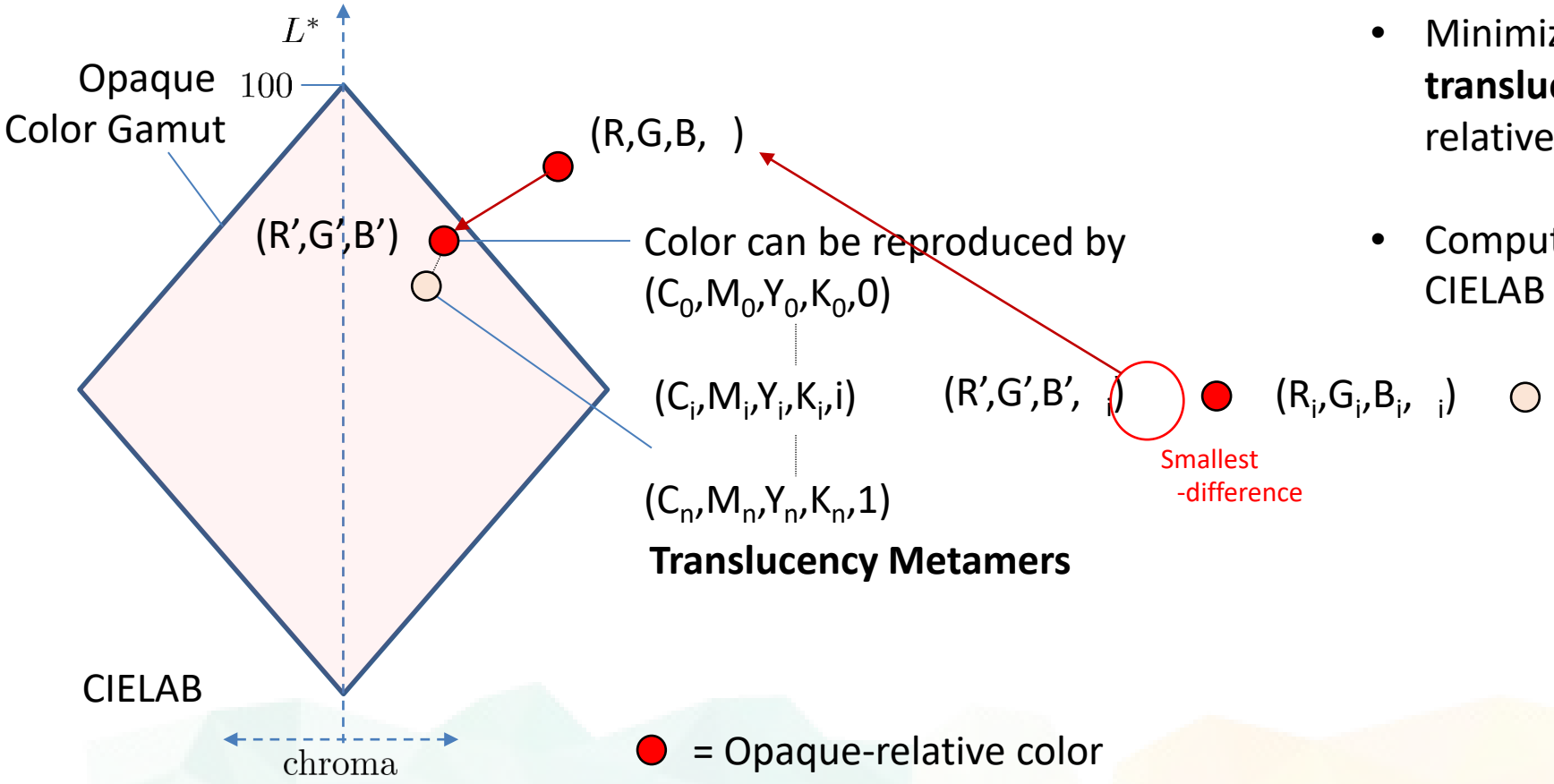
Voxelization → Transferring Surface Signals to Voxels → **Color and Translucency Management** → Adjustment of lateral and vertical Light Transport → Layer Construction + Halftoning → Replacement of White with Transparent Material

Opaque-relative processing



- Perform hue-preserving gamut expansion towards the opaque gamut [CMYK = (C,M,Y,K,0)]

Strategy for joint color and translucency reproduction



- Gamut mapping (hue-preserving)
- Minimize translucency difference within all **translucency metamers** for opaque-relative (R',G',B')
- Compute multi-dimensional look-up table CIELAB CMYK

= Opaque-relative color

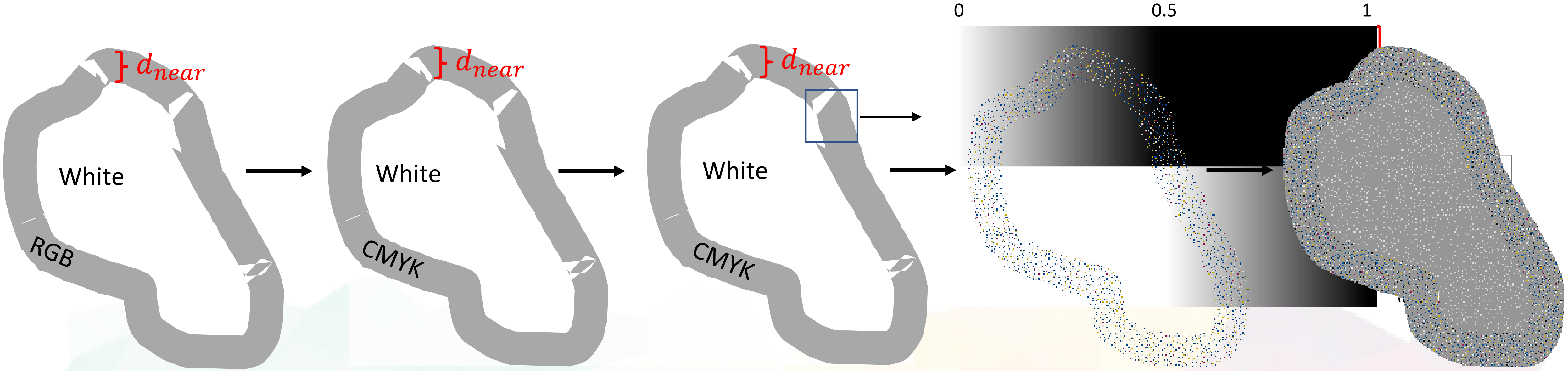
= Absolute color (same hue)

RGBA → material assignments

Layer Construction + Halftoning

…t of …h …aterial

Within d_{near} of the surface, … transport gamut (several overlapping lines printed on top of one another: "Replace white voxels …", "… d_{near} …", "… halftoning … CMYK … light transport gamut")

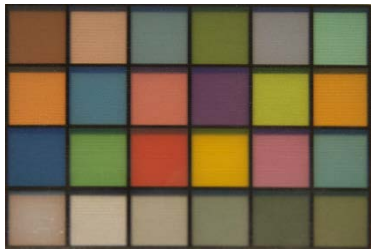
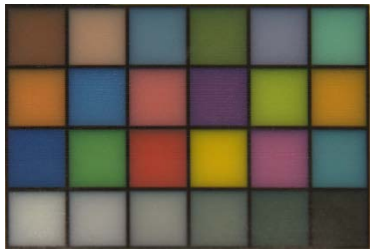
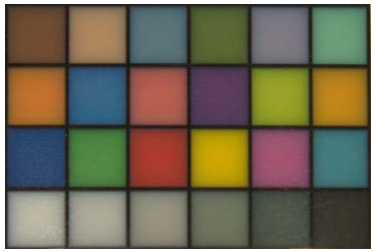
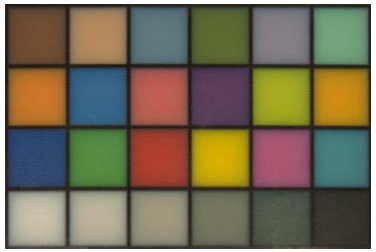
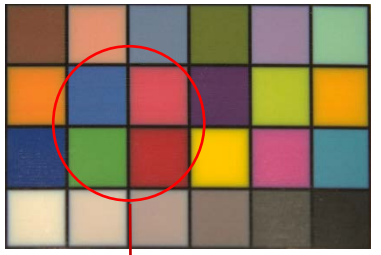


Adjustment of lateral and vertical Light Transport

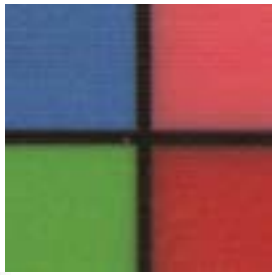
Layer Construction + Halftoning

Replacement of White with Transparent Material

Evaluation (Color Checker – Frontlit)

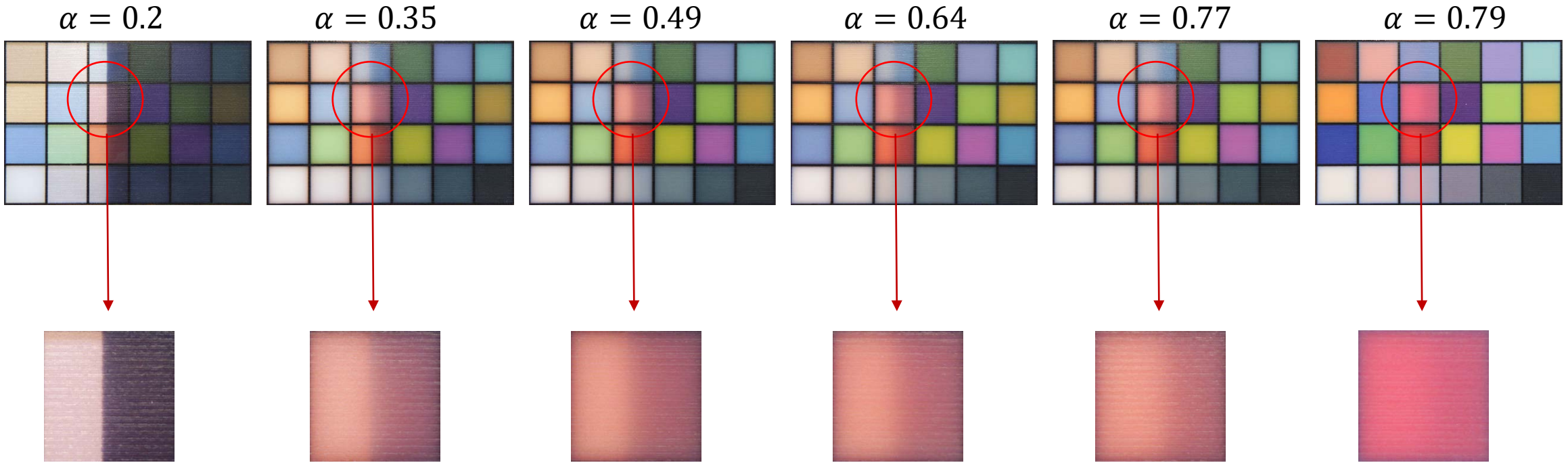
	$\alpha = 0.2$	$\alpha = 0.35$	$\alpha = 0.49$	$\alpha = 0.64$	$\alpha = 0.77$	$\alpha = 0.79$
						
E_{00}	5.5	3.7	3.7	3.0	3.2	2.3
a	0.7	0.23	0.15	0.06	0.02	0.06

Median errors: input vs. print



- Printer: Stratasys J750
- Optical Printer Model: Broadband cellular Neugebauer model
- Performance: Computation faster than printing

Evaluation (Color Checker – Backlit)



Evaluation (Color + Transparency)

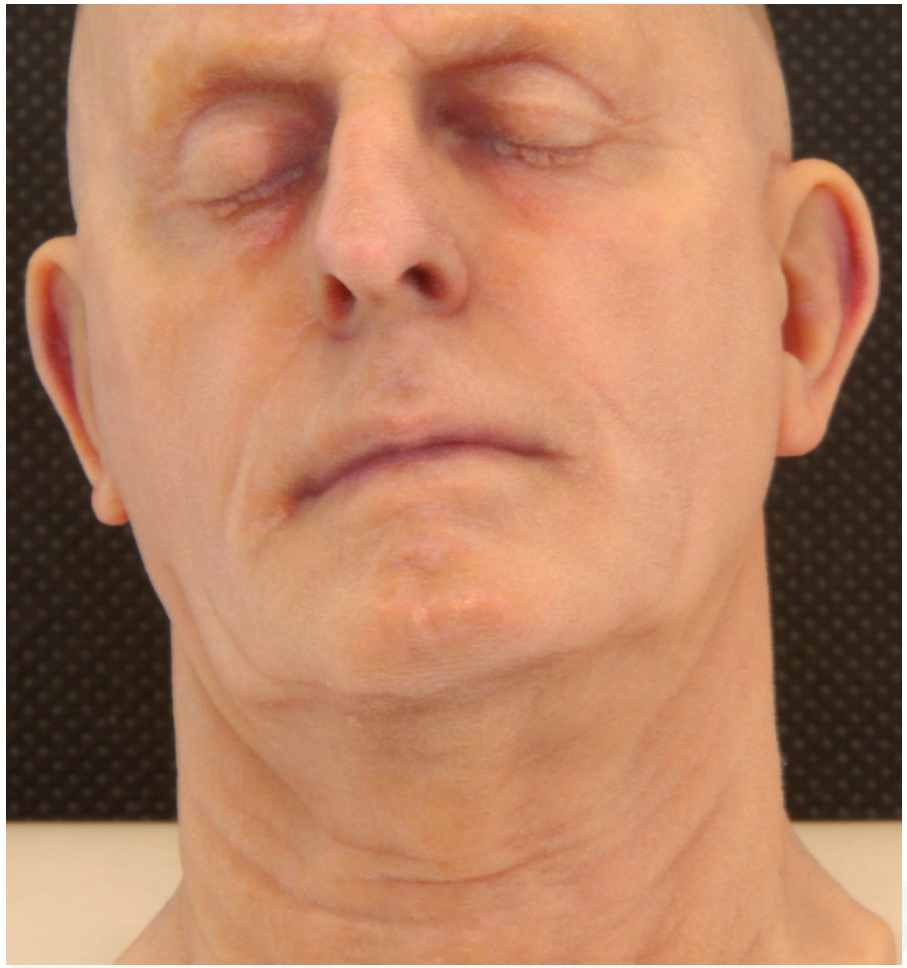
This and next slides:
Pictures of 3D prints,
not renderings

0.7mm (polished)

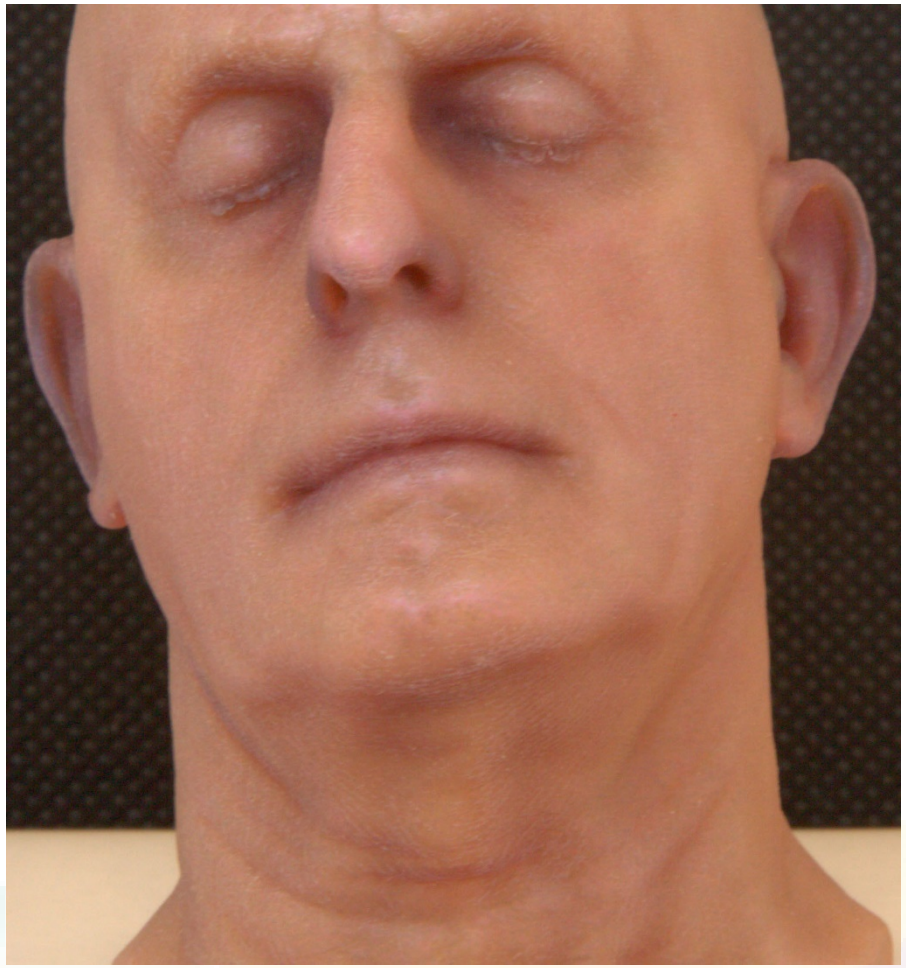
Revealing internal structures of complex models (28 sub-part). [skin: RGBA = (1,1,1,0)]

Translucency transitions

Control over translucent appearance



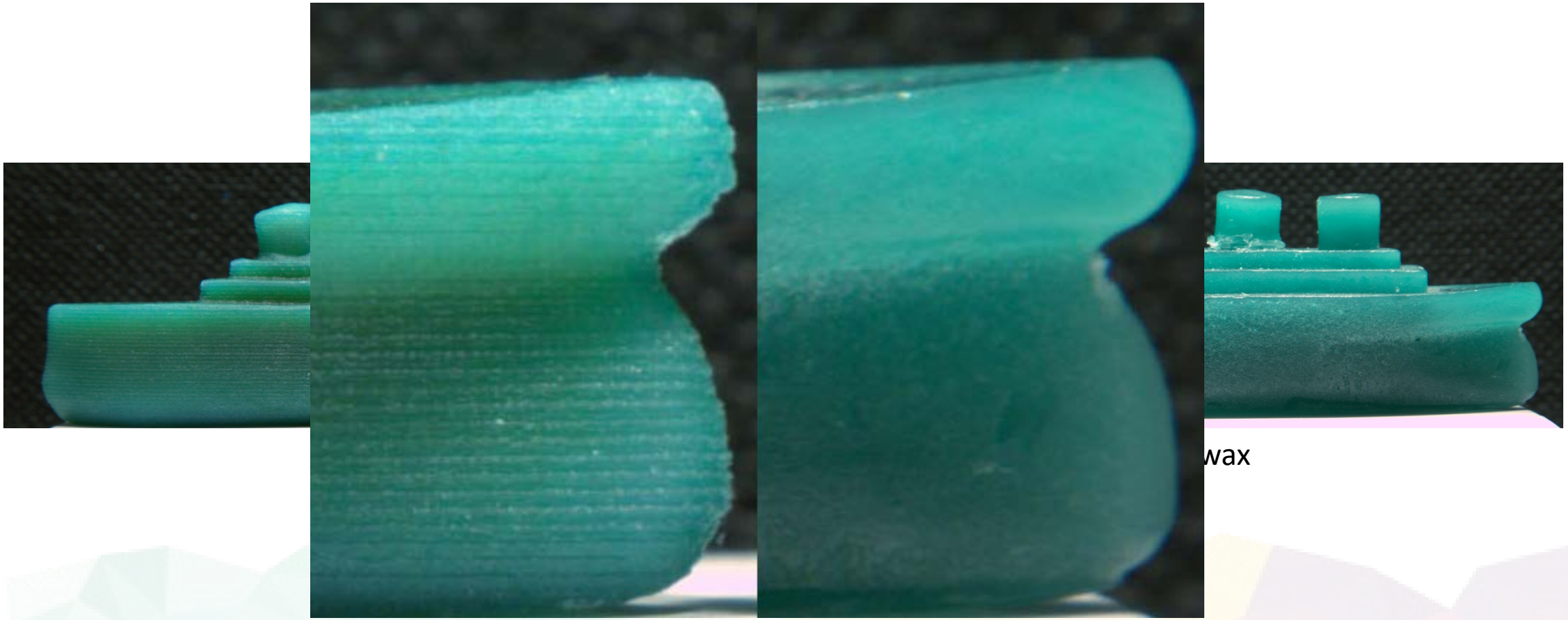
relative $\alpha = 1$



relative $\alpha = 0.54$

10 cm

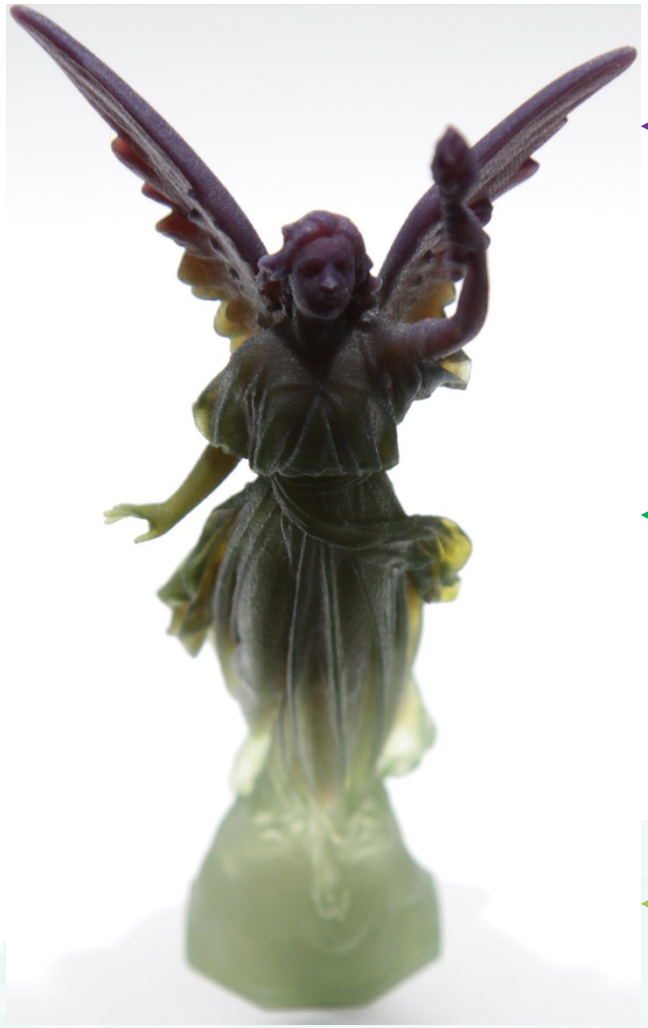
Reproducing translucent appearance

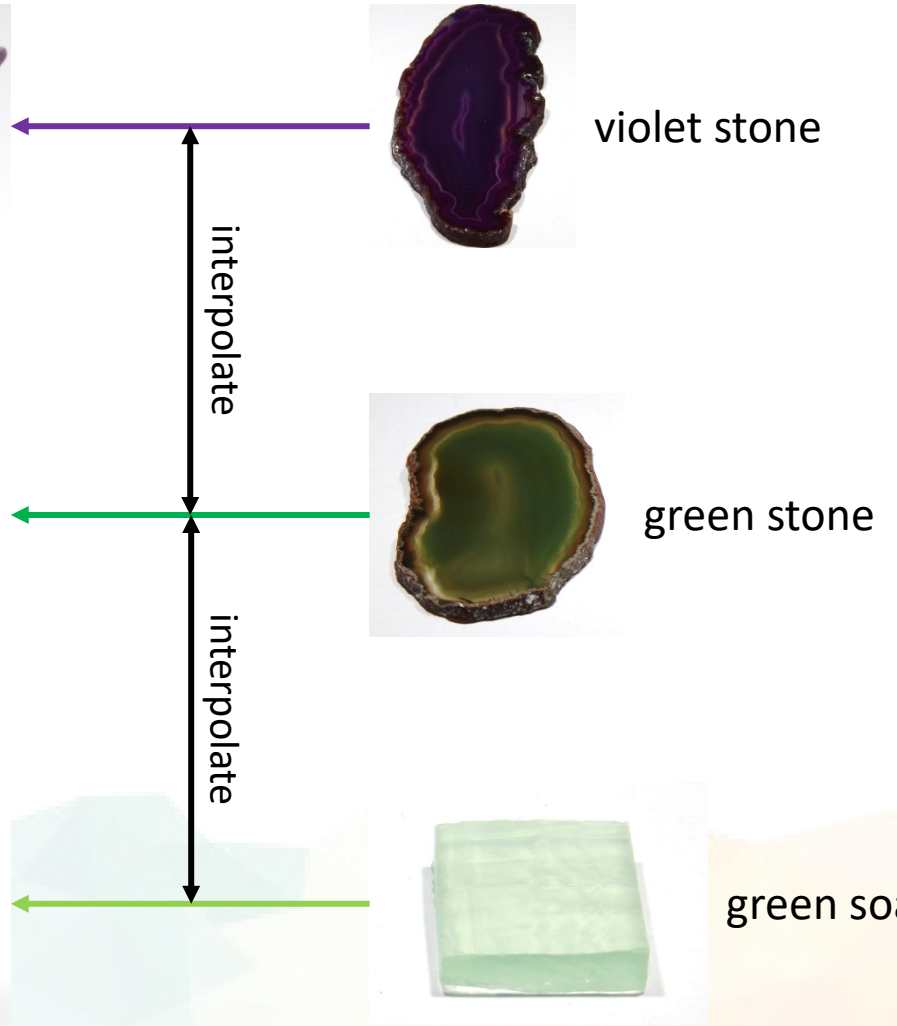


wax

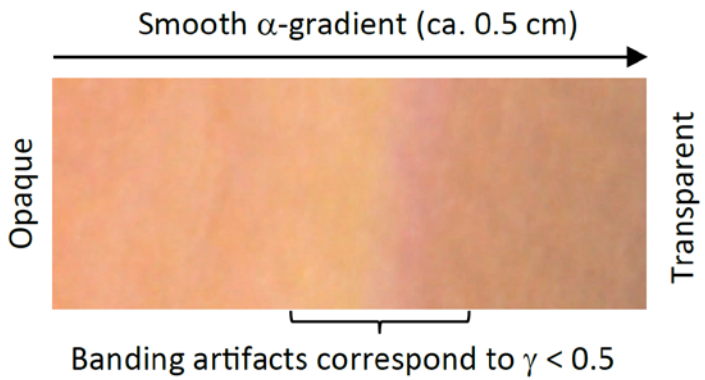
Increasing design space

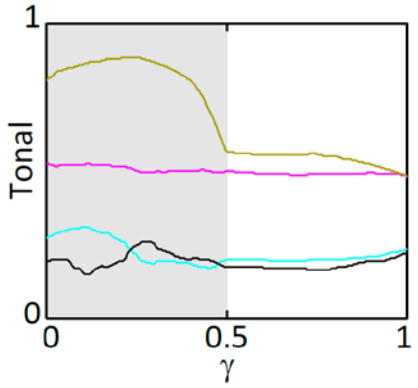
Reproducing translucent appearance





Limitations



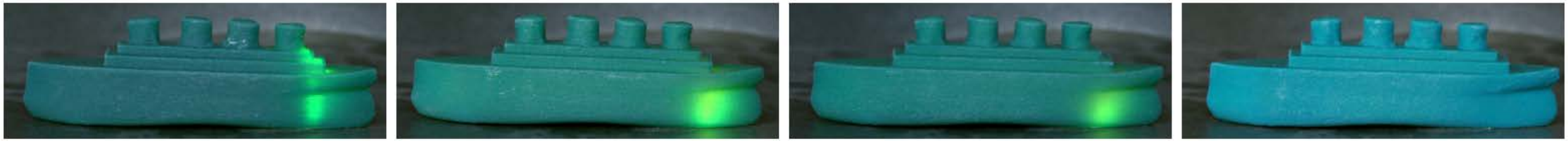


- Banding artifacts for gradients cover full range of α
- 1D translucency space: no directional dependencies
- Translucency as surface attribute: reduced degrees of freedom

Conclusions

- Fabrication of joint color and translucency
  - Efficient streaming algorithm to compute material assignments
  - Efficient streaming algorithm to compute Veronoi tesselations in *O(1)* time per voxel
  - Combined color and translucency management via translucency metamers (Opaque-relative Processing)

More information:
www.cuttlefish.de



Acknowledgements

Marco Dennstaedt and Andre Schulz (Fraunhofer IGD)

CultLab3D, Fraunhofer IGD
Hannes Urban

DIG:ED GmbH
Alphacam GmbH
Laika Studios
Stratasys

Anonymous reviewers

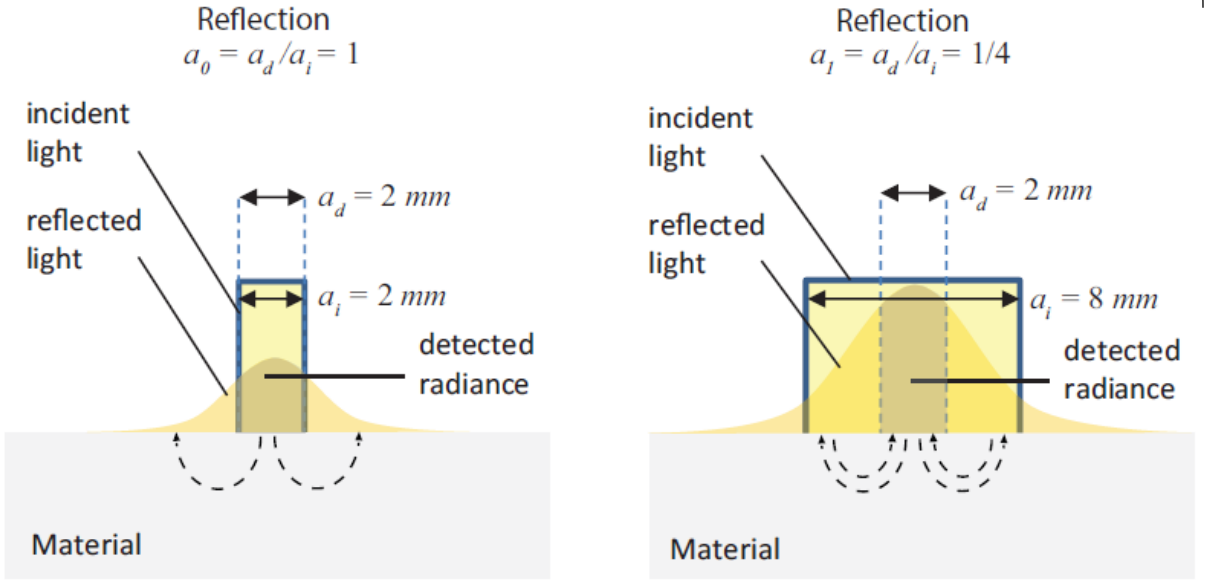
Funding:
Fraunhofer Grant Attract 008-600075,
Scan4Reco project funded by EU Horizon 2020 Framework Programme under Grant No. 665091

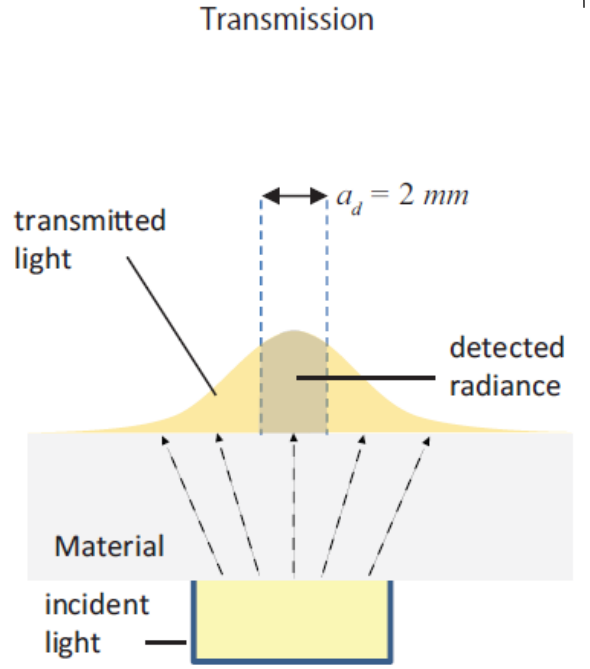
Backup Slides

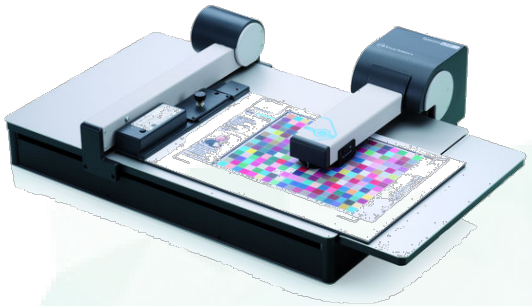
Measuring Lateral and Vertical Light Transport

Lateral light transport

Vertical light transport



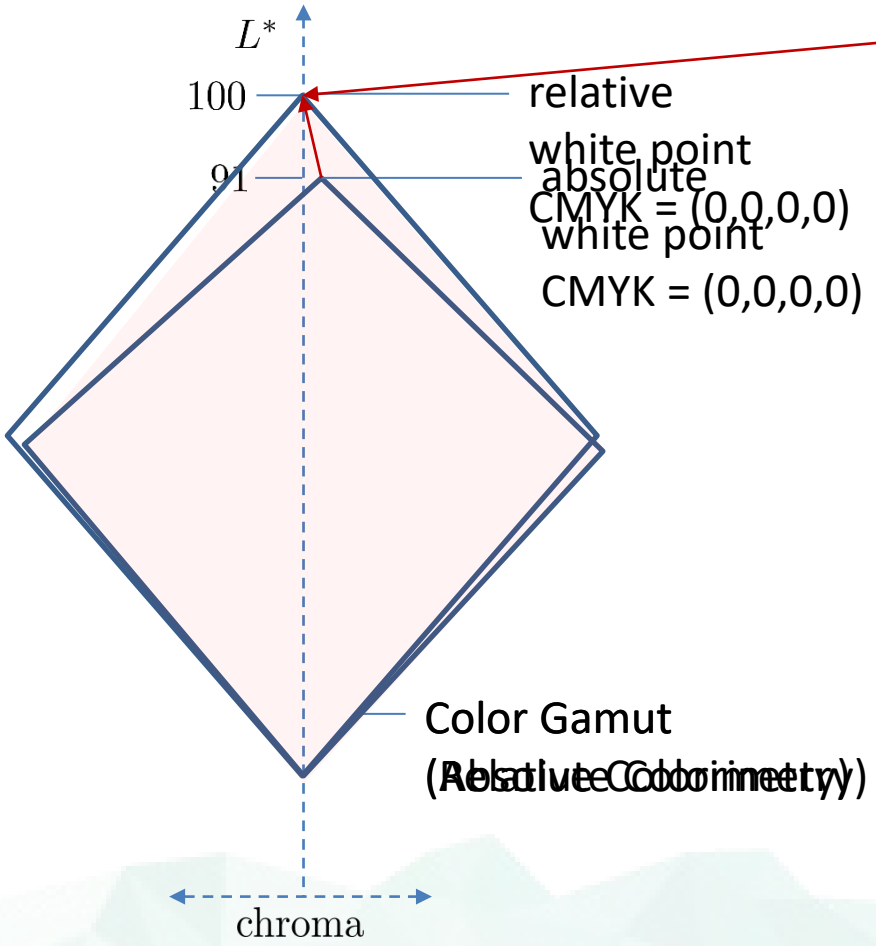




Barbieri Spectro LFP:
Commercial reflection/transmission spectrophotometer
Reflectance 45/0, Transmittance d/0

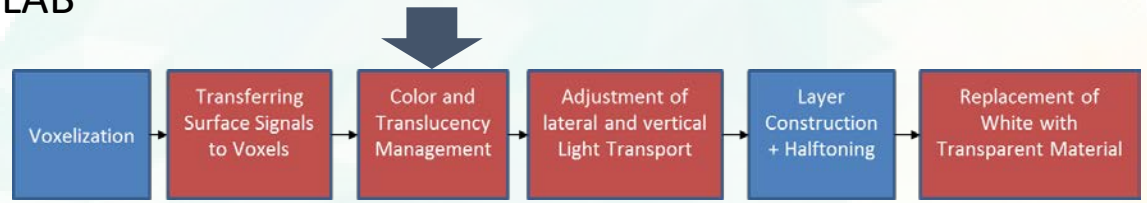
Measuring Lateral and Vertical Light Transport

Media Relative Processing



- sRGB = (1,1,1) CIELAB = (100,0,0) is not printable
- Scale colors by mapping white point to CIELAB = (100,0,0)
- Ensures that sRGB = (1,1,1) maps to CMYK = (0,0,0,0)
- Accounts for white point adaptation of the human visual system

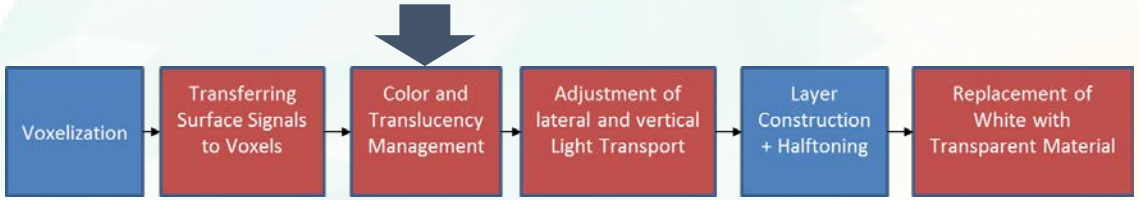
CIELAB



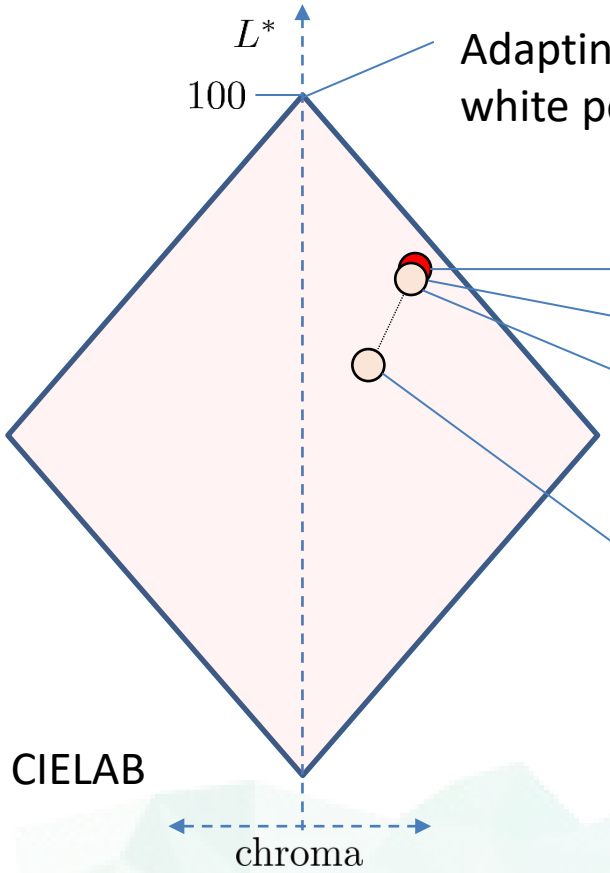
Media Relative Processing

- = 0 (fully transparent) and = 1 (fully opaque) are usually not printable for CMYK = (0,0,0,0,)

- Scale linearly to ensure that = 0 for CMYK = (0,0,0,0,1) and = 1 for CMYK = (0,0,0,0,0)



In-Gamut Colors in Opaque-Relative Representation



CIELAB

Adapting white point

Color can be reproduced by

$(C_0,M_0,Y_0,K_0,0)$ (R_0,G_0,B_0,A_0)

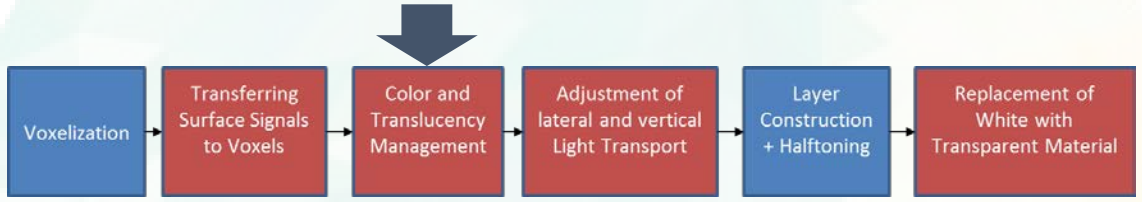
$(C_1,M_1,Y_1,K_1,1)$ (R_1,G_1,B_1,A_1)

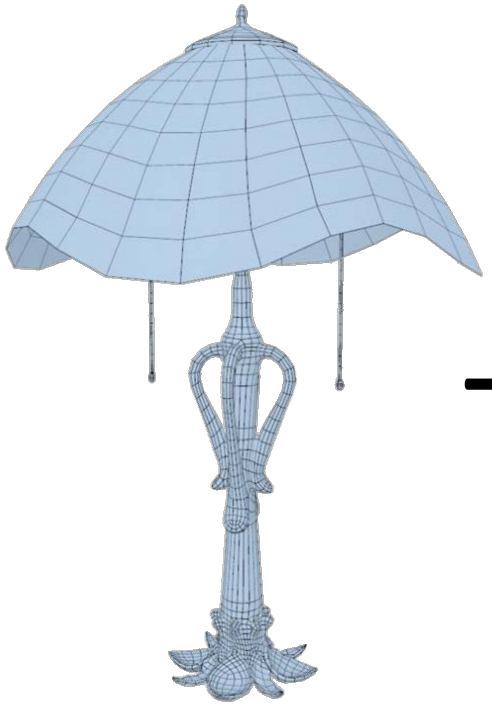
$(C_{255},M_{255},Y_{255},K_{255},255)$ $(R_{255},G_{255},B_{255},A_{255})$

Translucency metamers w.r.t. opaque-relative colors

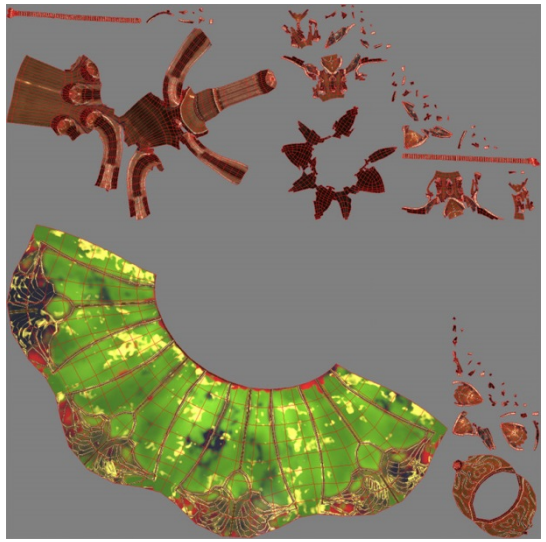
= Opaque-relative color

= Absolute color (same hue)





+



Design / modify
A in RGBA-texture

Source: turbosquid.com