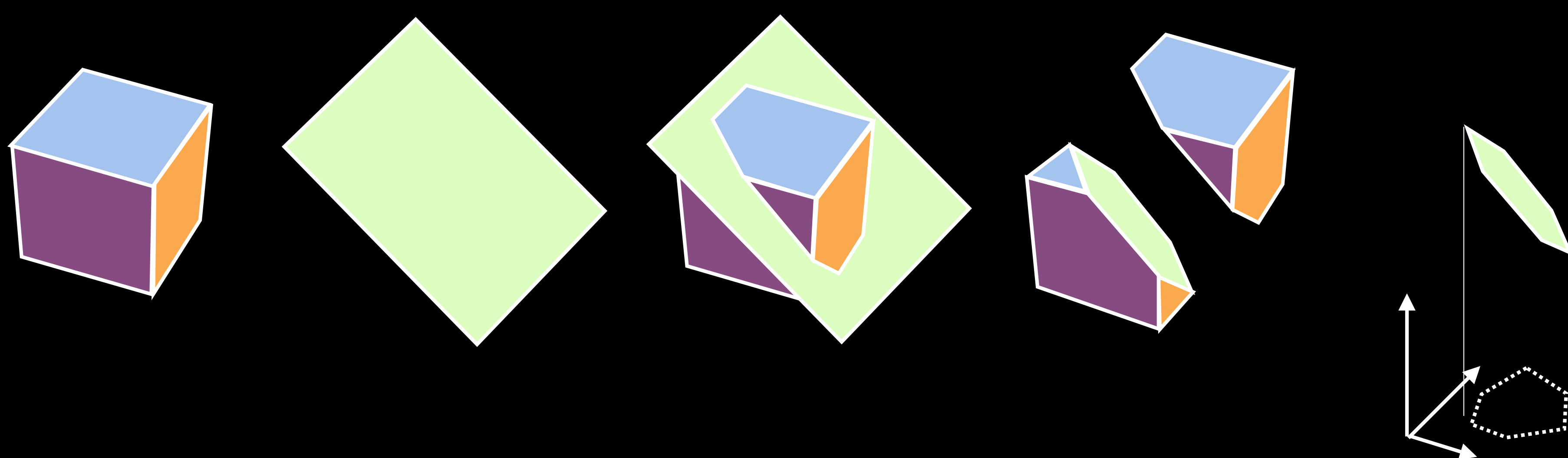
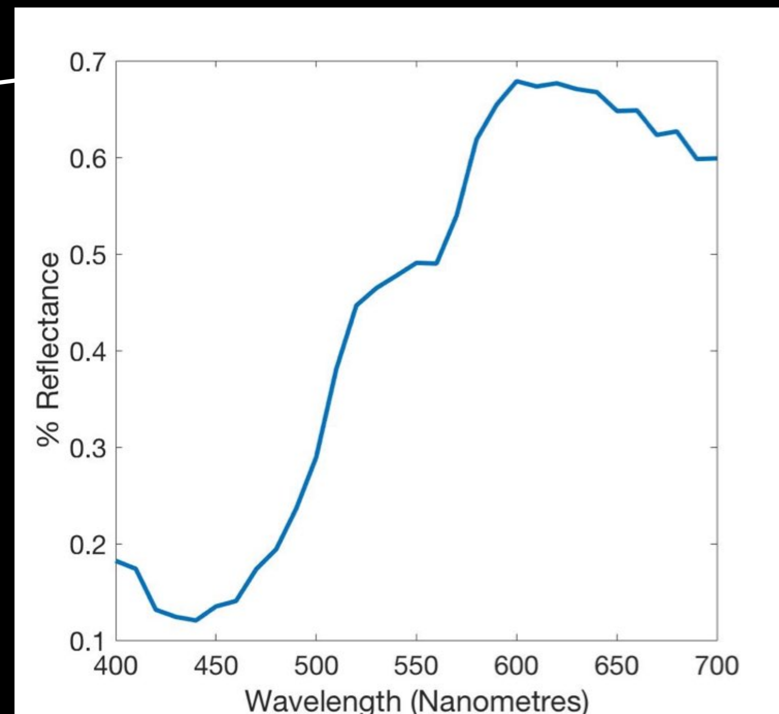
Metamer Sets

Graham D. Finlayson
University of East Anglia



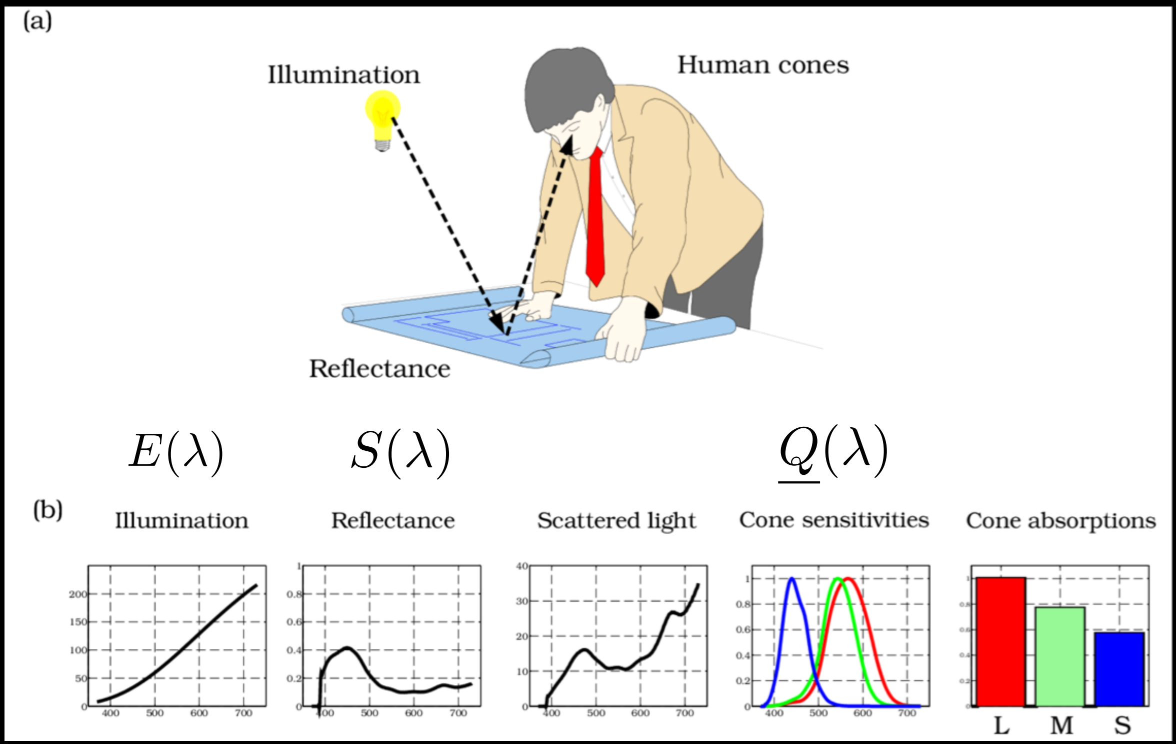
RGB to Spectra



Nitre Challenge

Metamerism

Simple Image Formation



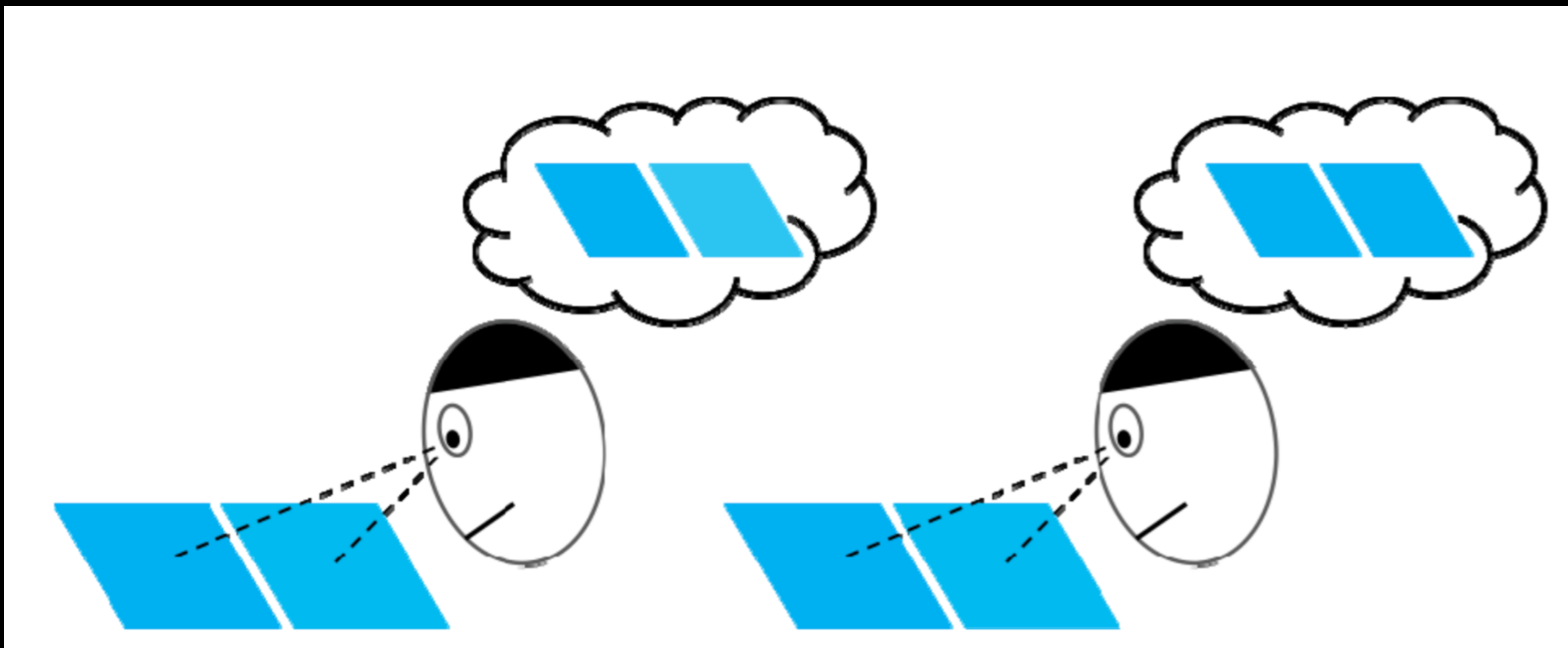
$$\int_{\omega} \underline{Q}(\lambda)E(\lambda)S(\lambda)d\lambda$$

$$\underline{R}(\lambda) = \underline{Q}(\lambda)E(\lambda)$$

$$\int_{\omega} \underline{R}(\lambda)S(\lambda)d\lambda$$

Wandell, BA. “Foundations of Vision”

Observer Metamerism



Emissive chart for imager calibration

Jeffrey M. DiCarlo, Glen Eric Montgomery and Steven W. Trovinger
Hewlett-Packard Laboratories
Palo Alto, California

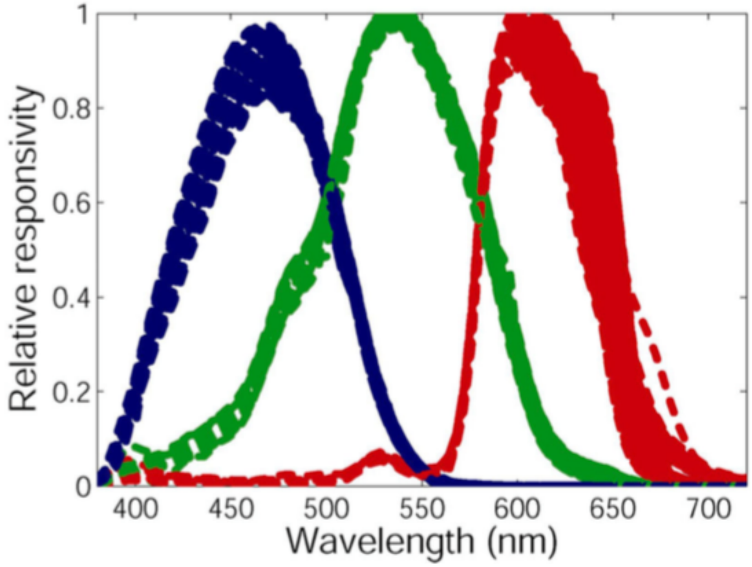


Figure 1. *Responsivity functions for two hundred instances of a consumer camera plotted on top of one another. The widths of the lines indicate the responsivity variations across camera instances.*

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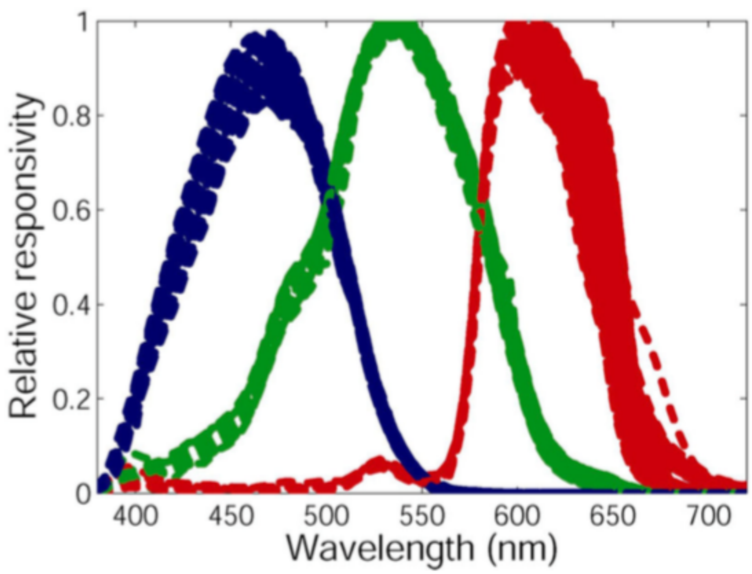


Figure 1. *Responsivity functions for two hundred instances of a consumer camera plotted on top of one another. The widths of the lines indicate the responsivity variations across camera instances.*

Figure 6. *The first prototype of the emissive calibration chart.*

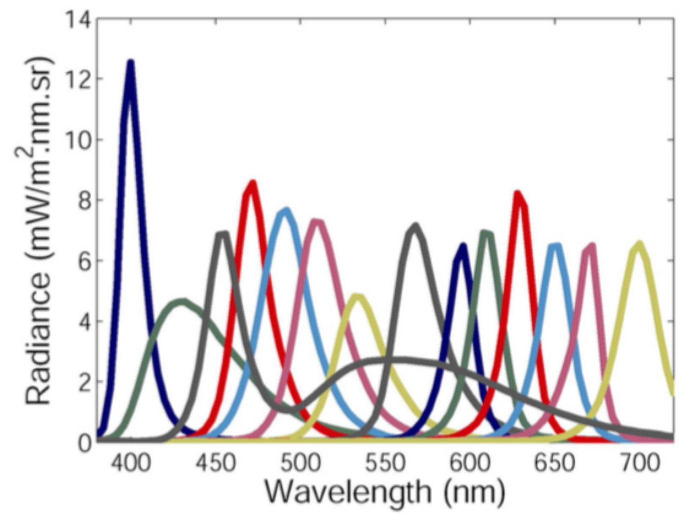
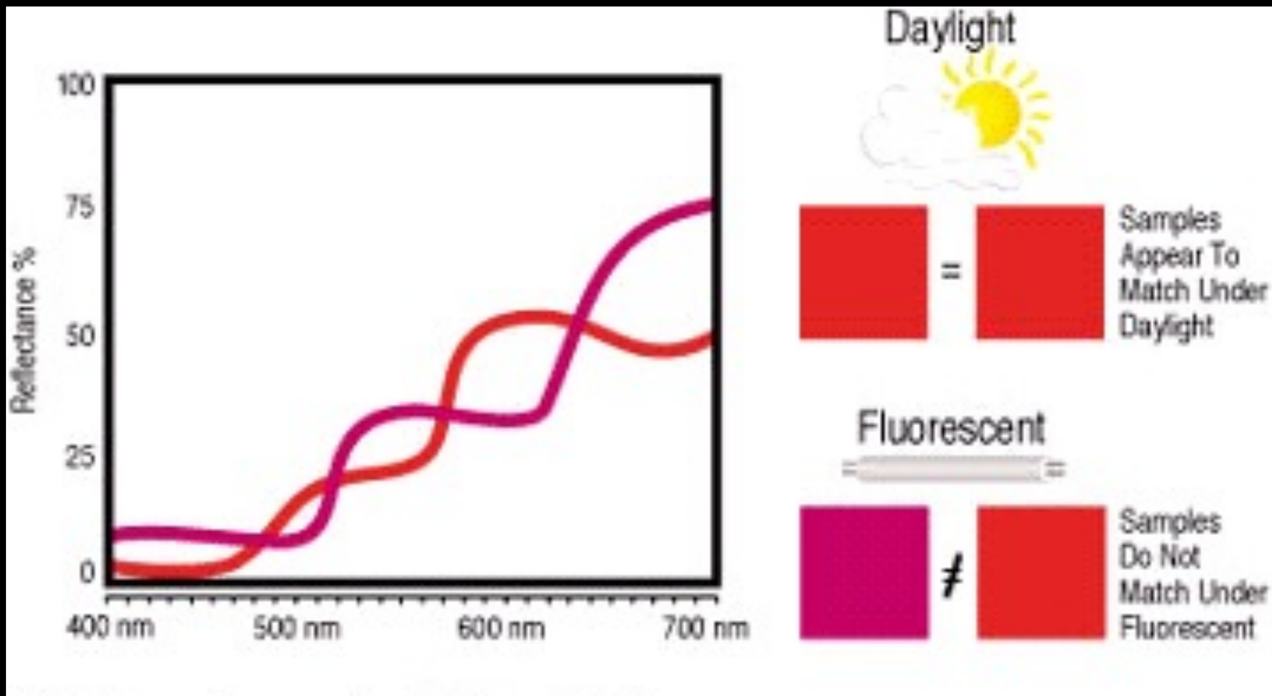


Figure 7. *The spectral power distributions of the LED light sources used in the emissive calibration chart.*

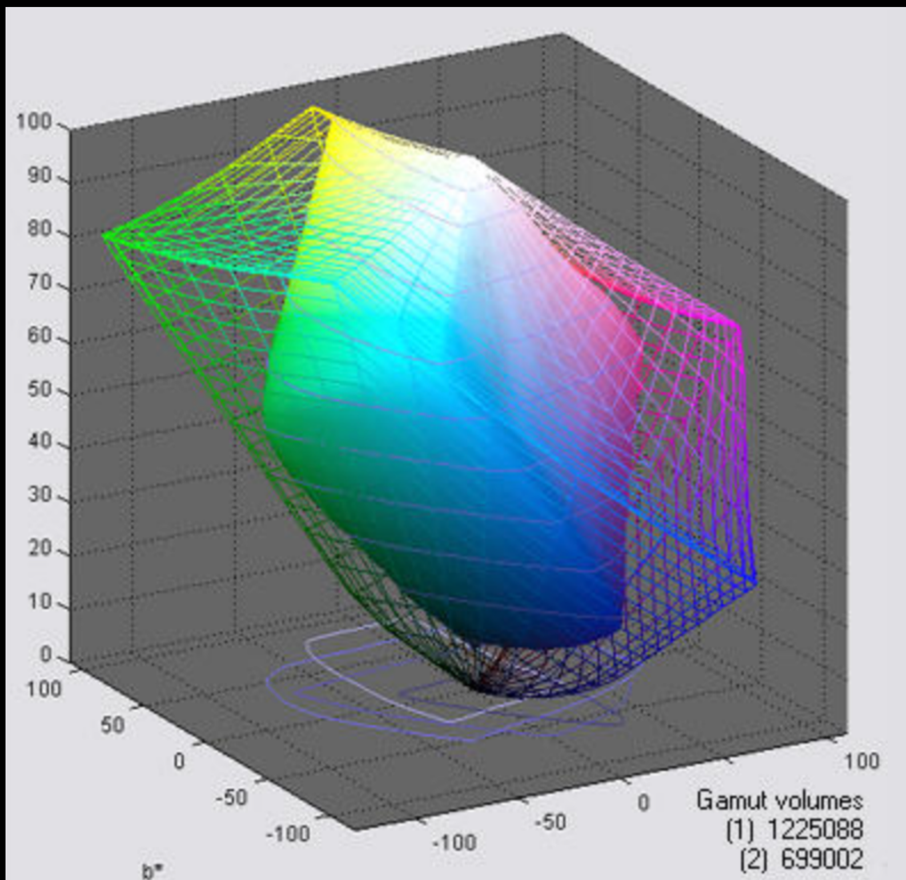
Illuminant Metamerism



Reflectance Curves of a Metameric Pair

Idea of Gamuts:

A stepping stone to thinking about metamers

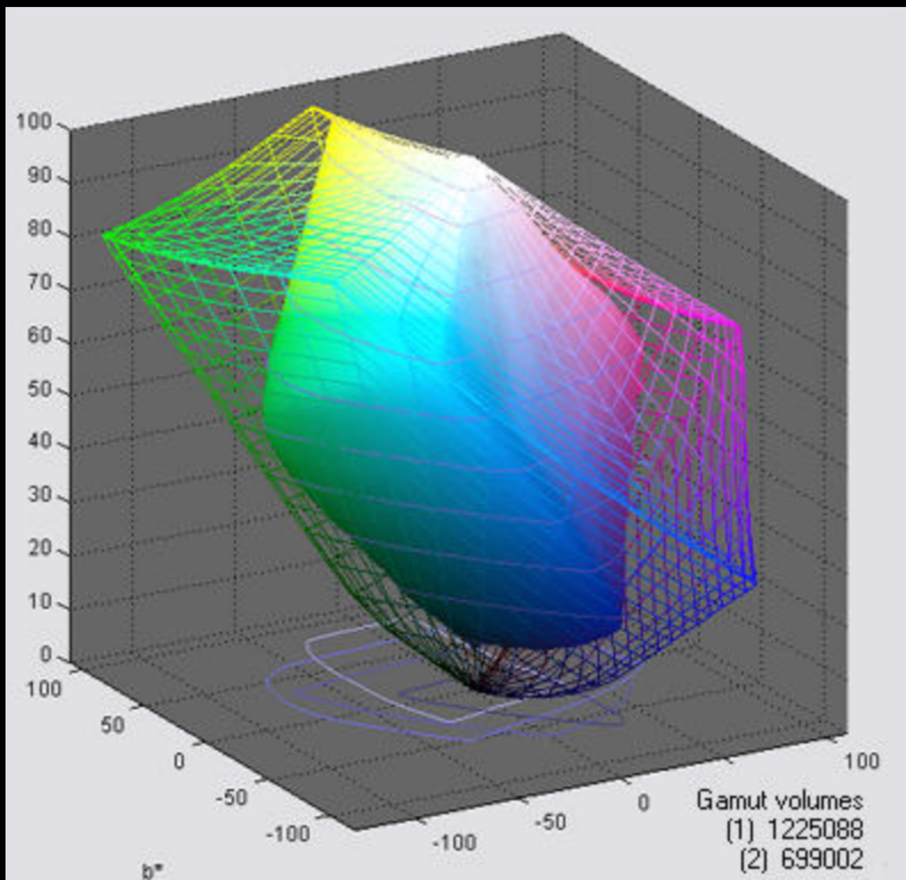


Wire Frame: Adobe RGB

Solid: Epson Printer

Idea of Gamuts:

A stepping stone to thinking about metamers



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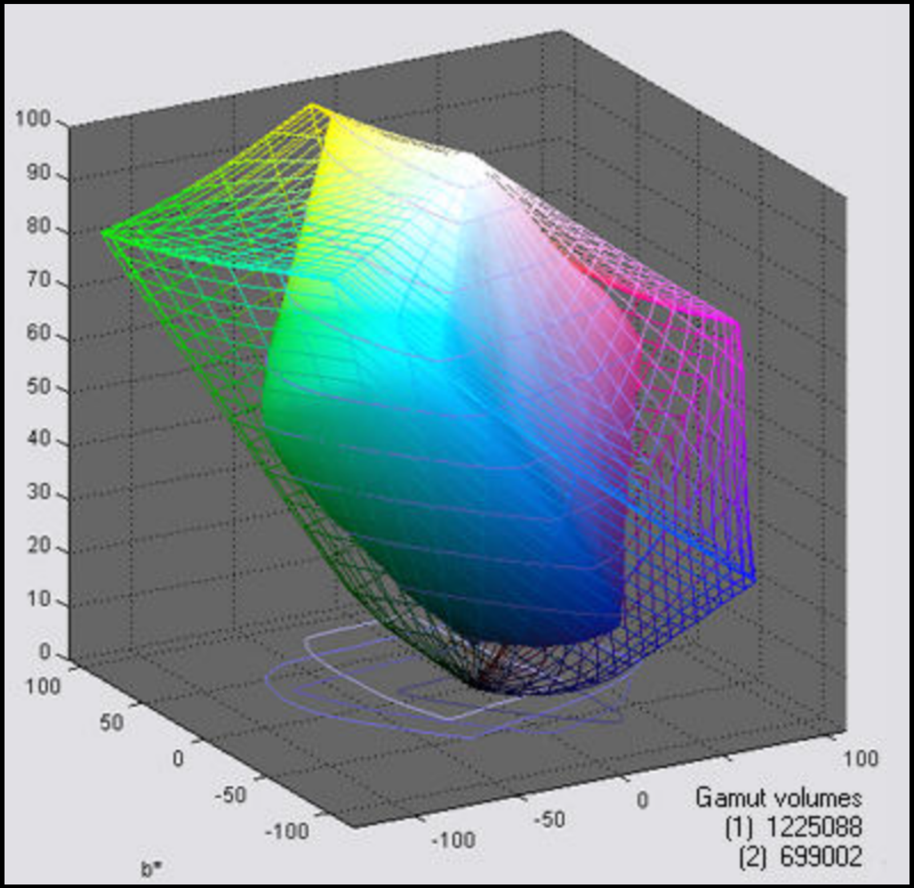
i) If we could manufacture any reflectance (theoretically possible), what would be the gamut of colours?

Idea of Gamuts:

A stepping stone to thinking about metamers



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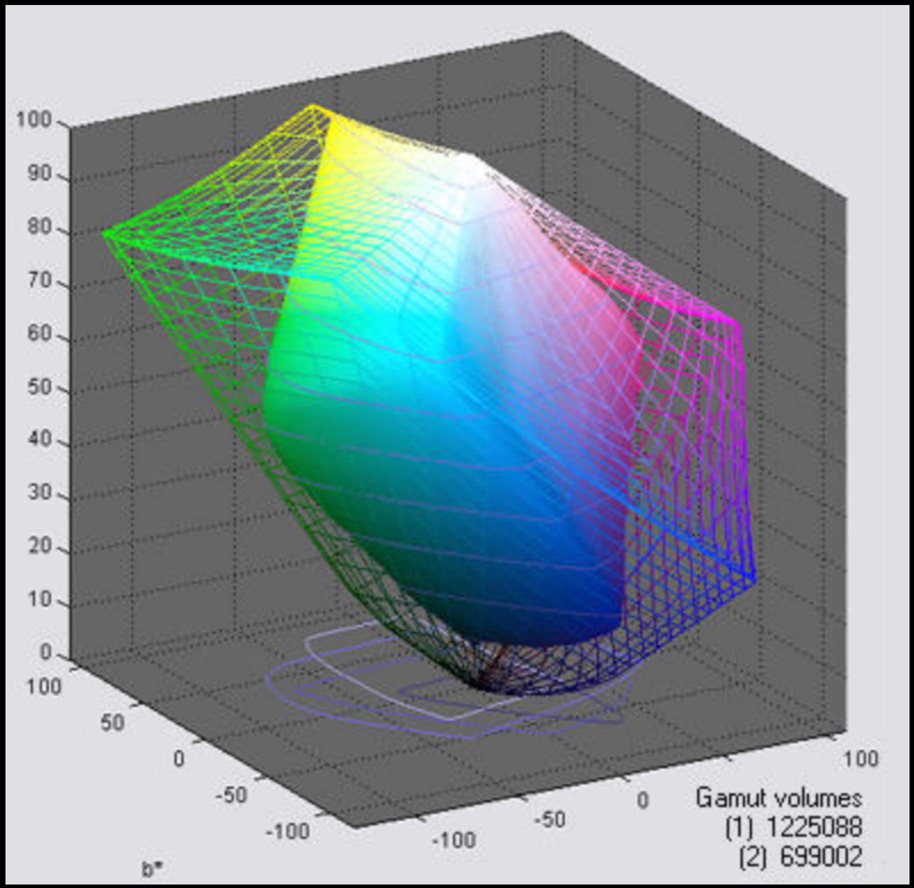
i) If we could manufacture any reflectance (theoretically possible), what would be the gamut of colours?

ii) This theoretical gamut is called the Object Colour Solid (OCS)

How the OCS is computed (efficiently) has been the source of research

Idea of Gamuts:

A stepping stone to thinking about metamers



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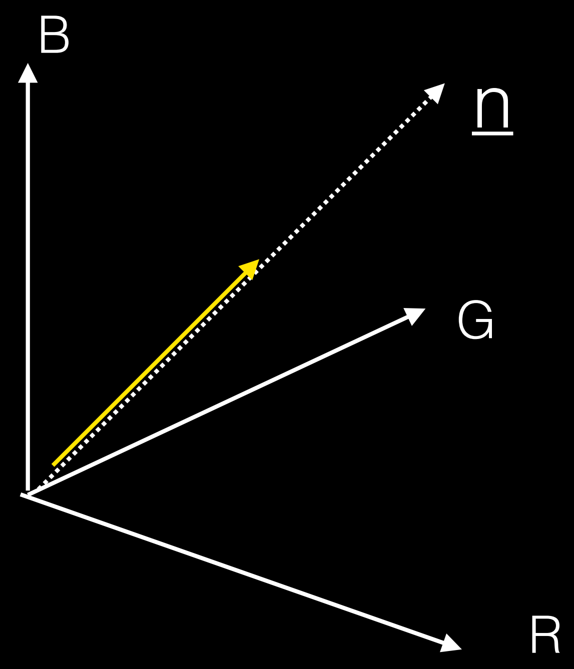
i) If we could manufacture any reflectance (theoretically possible), what would be the gamut of colours?

ii) This theoretical gamut is called the Object Colour Solid (OCS)

How the OCS is computed (efficiently) has been the source of research

iii) How we solve for the OCS can help us solve for pairs of reflectances that are metamerrs

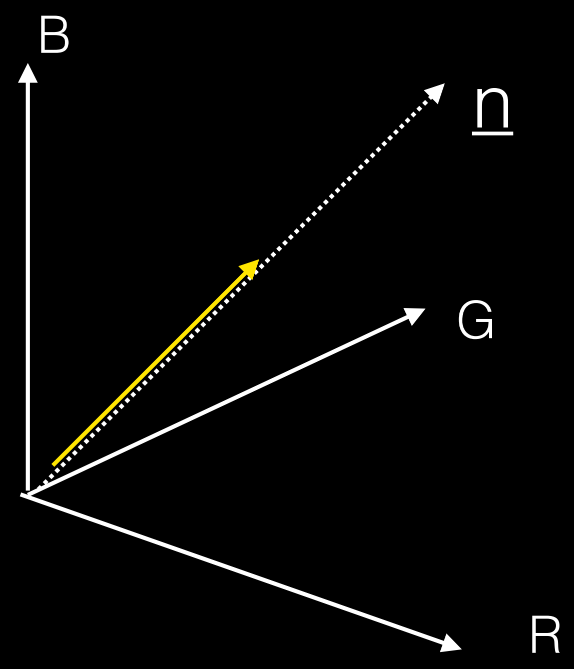
Theoretical limits: Object Colour Solid



What is the colour response $\underline{p}$ in the direction $\underline{n}$ which has maximum length?

$$\max_{S(\lambda)} ||\underline{n}.\underline{p}|| \ s.t. \ \begin{cases} 0 <= S(\lambda) <= 1 \\ \underline{p} = \int_\omega \underline{R}(\lambda) S(\lambda) d\lambda \\ (I_{3\times 3} - \underline{nn}^t)\underline{p} = \underline{0} \end{cases}$$

Theoretical limits: Object Colour Solid

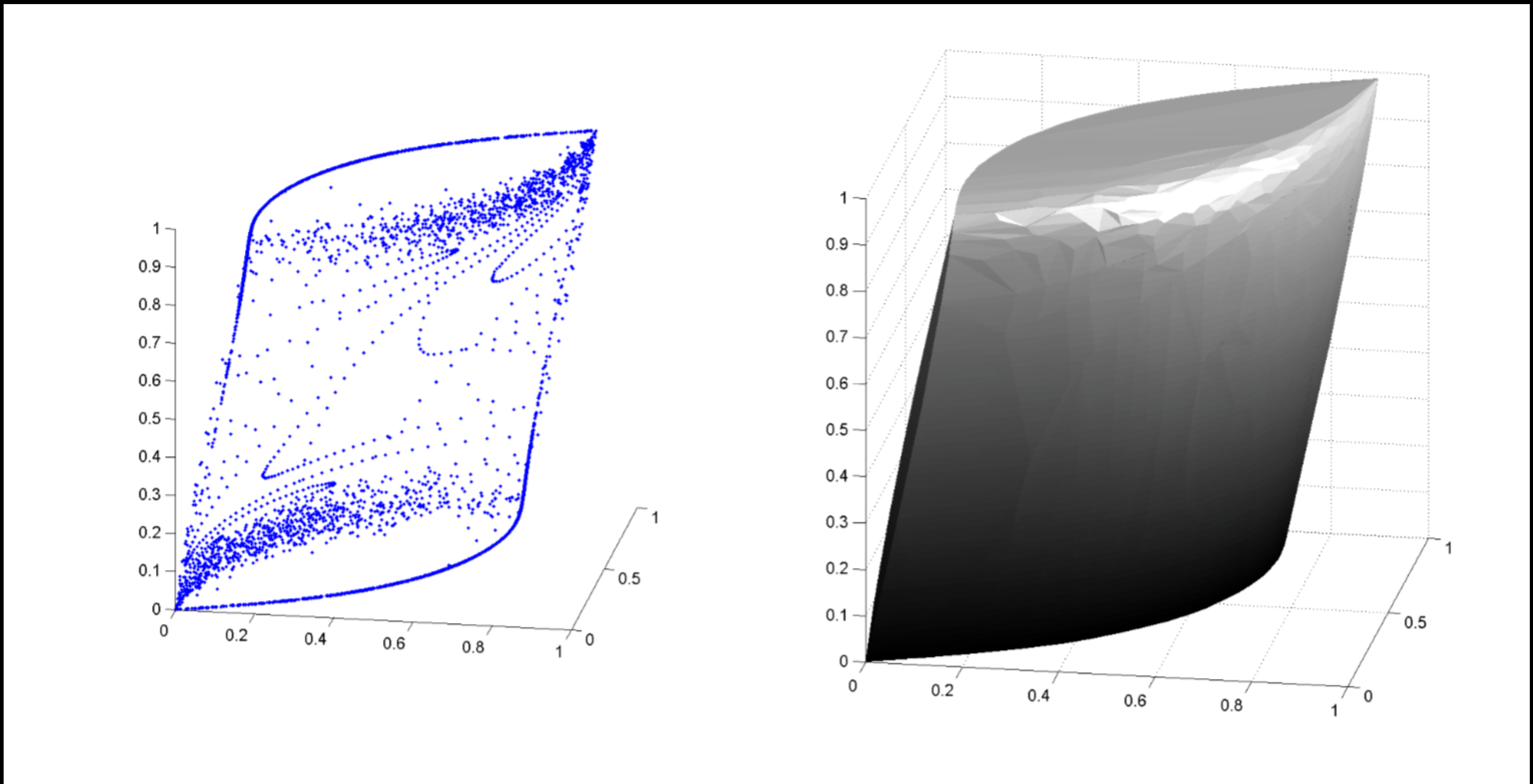


What is the colour response p in the direction n which has maximum length?

$$\max_{S(\lambda)} ||\underline{n}.\underline{p}|| \; s.t. \begin{cases} 0 <= S(\lambda) <= 1 \\ \underline{p} = \int_\omega \underline{R}(\lambda) S(\lambda) d\lambda \\ (I_{3\times 3} - \underline{nn}^t)\underline{p} = \underline{0} \end{cases}$$

In the discrete domain, this optimisation is a 'Quadratic Program'. Can be solved Efficiently. (Actually, can be further simplified as a linear program)

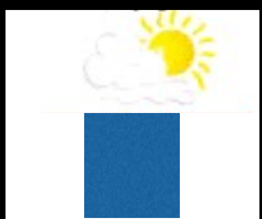
Object Colour Solid



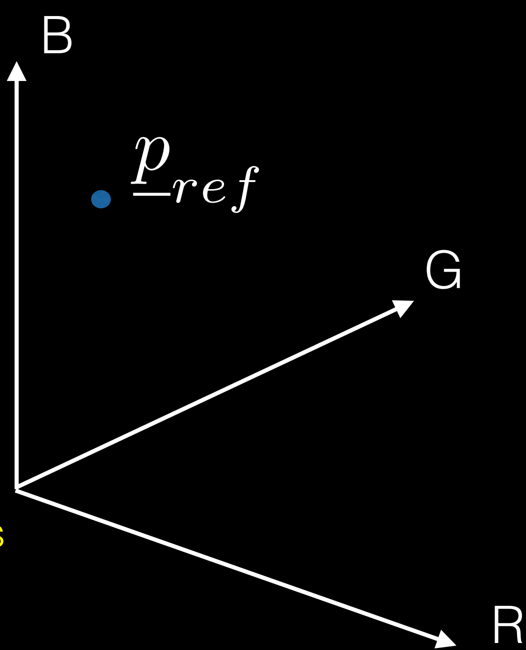
Metamer Mismatch Volume

a measure of how well spectrum is recovered

$\underline{R}(\lambda)$



Many reflectances S(λ) integrate to the same ref RGB



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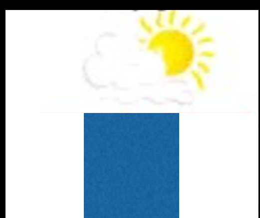

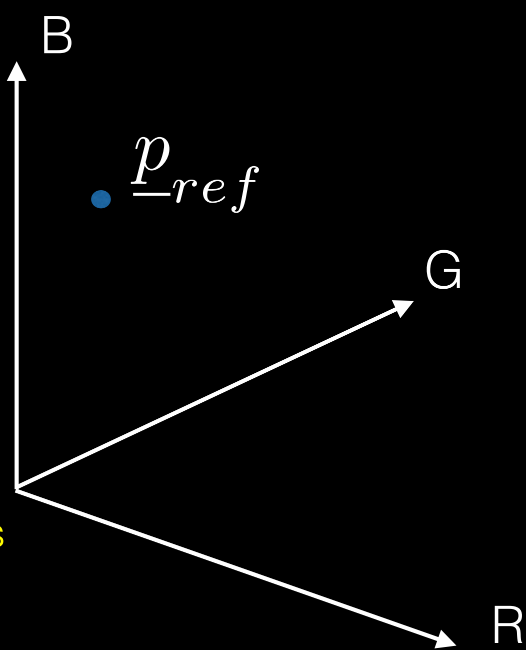

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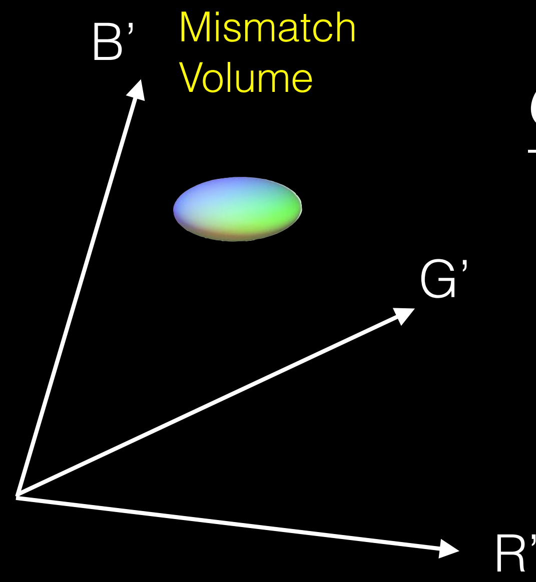
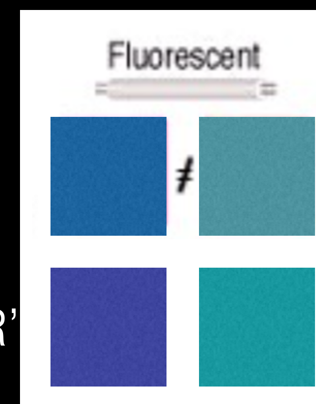


$\underline{Q}(\lambda)$



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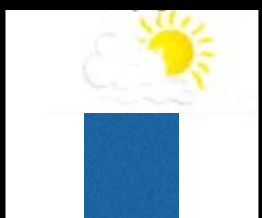
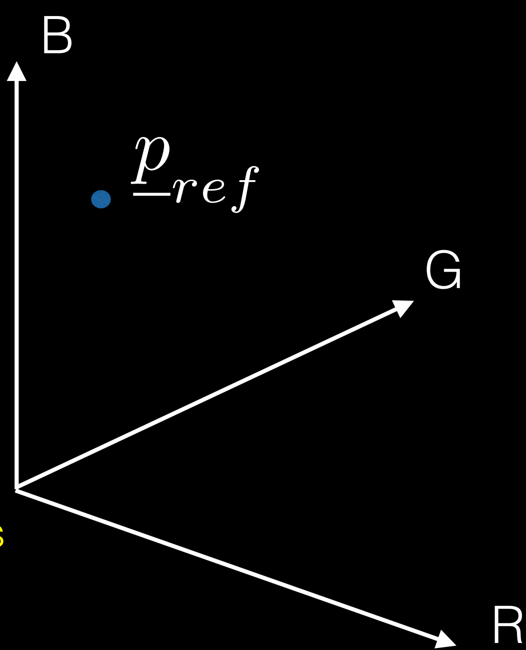
$\underline{R}(\lambda)$





Many reflectances
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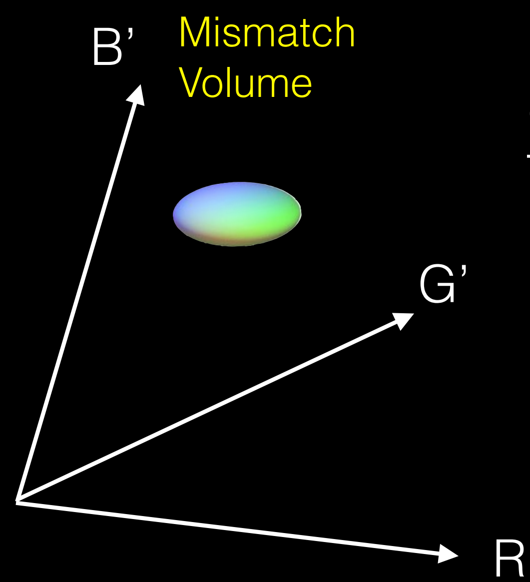
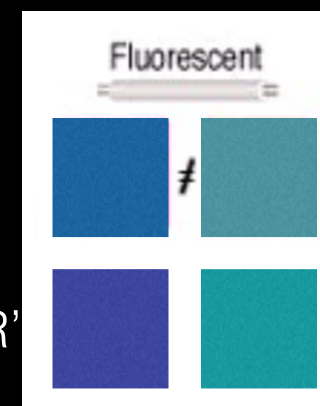


$\underline{Q}(\lambda)$



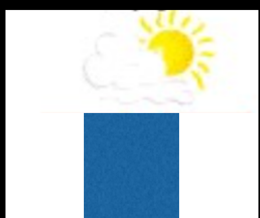
Solve for the 'Mismatch volume'
analogous to how we solved for
the OCS

$$\max_{S(\lambda)} ||\underline{n}.\underline{q}|| \;\; s.t. \;\; \left\{ \right.$$

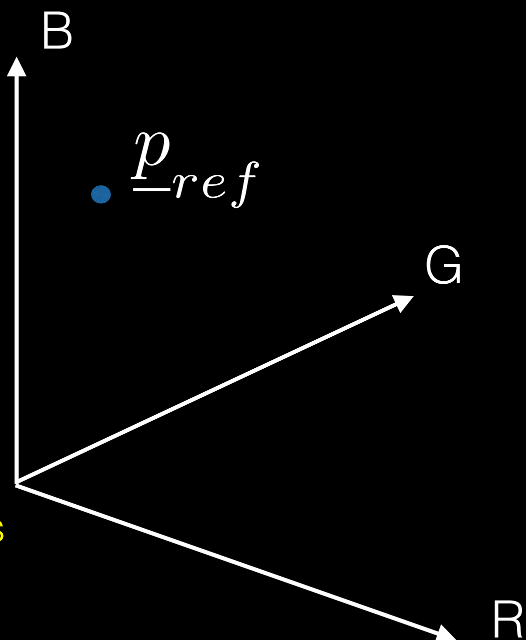
Metamer Mismatch Volume

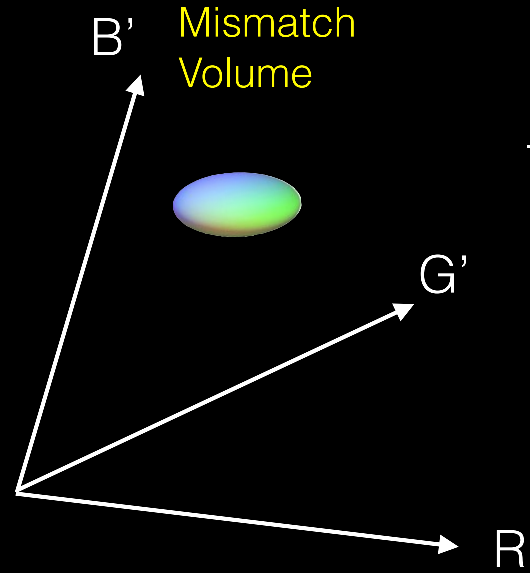
a measure of how well spectrum is recovered

$\underline{R}(\lambda)$

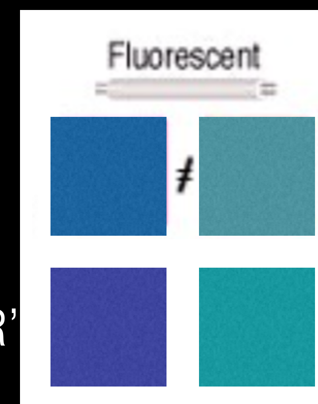


Many reflectances $S(\lambda)$ integrate to the same ref RGB





$\underline{Q}(\lambda)$



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Metamer Mismatch Volume

a measure of how well spectrum is recovered

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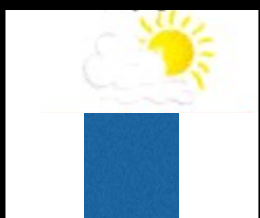

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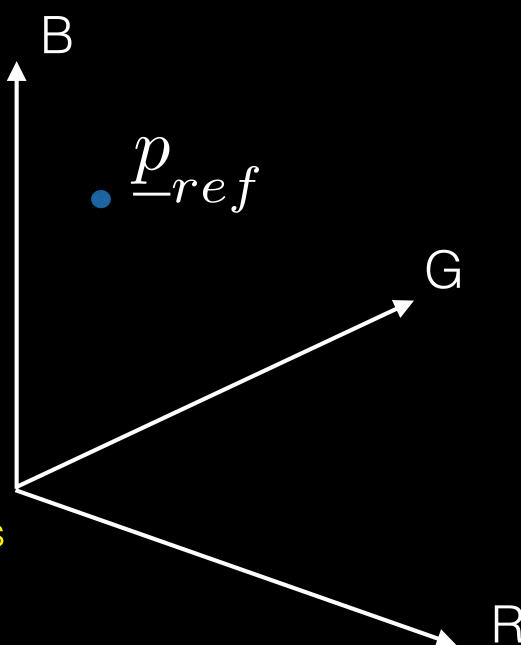
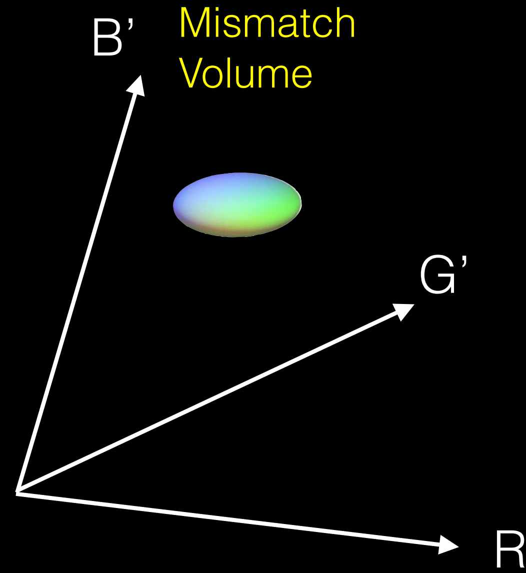
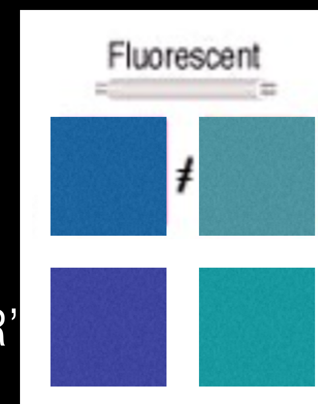




$\underline{Q}(\lambda)$



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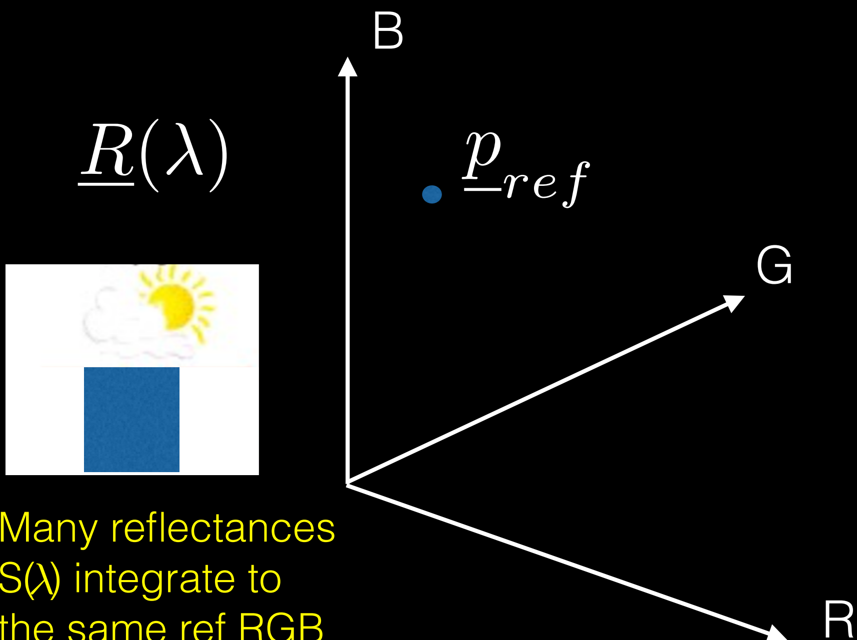
a measure of how well spectrum is recovered



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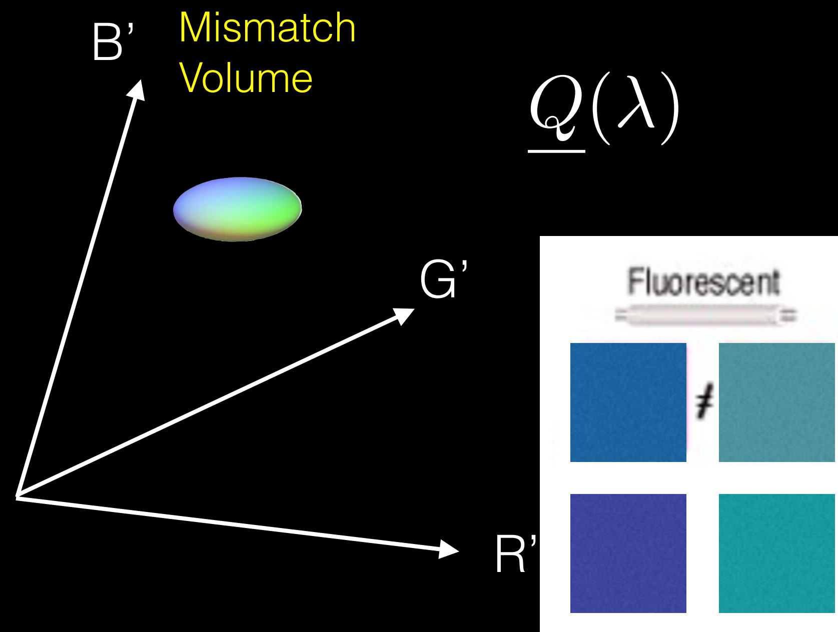

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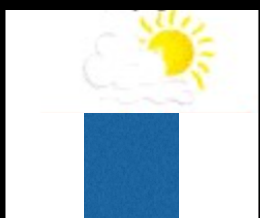
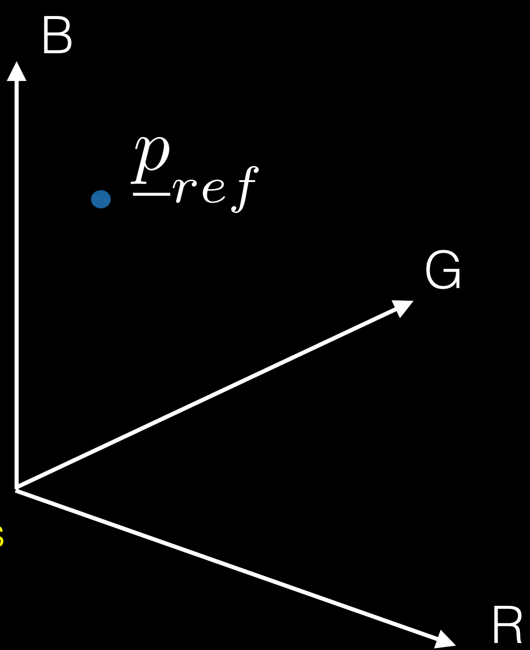
Metamer Mismatch Volume

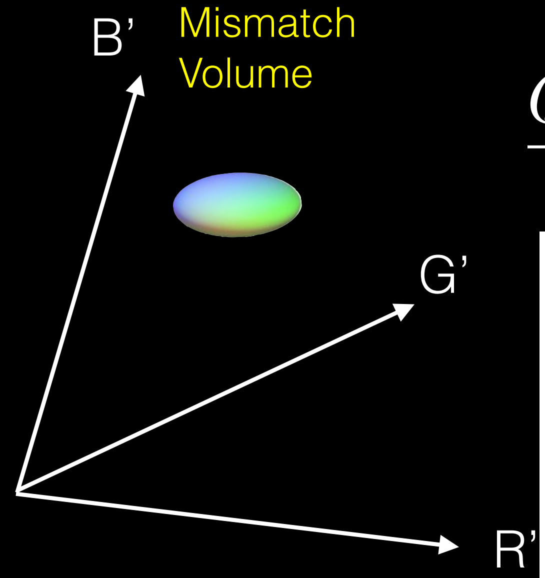
a measure of how well spectrum is recovered

$\underline{R}(\lambda)$

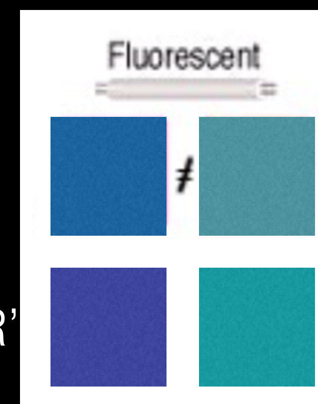




Many reflectances S(λ) integrate to the same ref RGB



$\underline{Q}(\lambda)$



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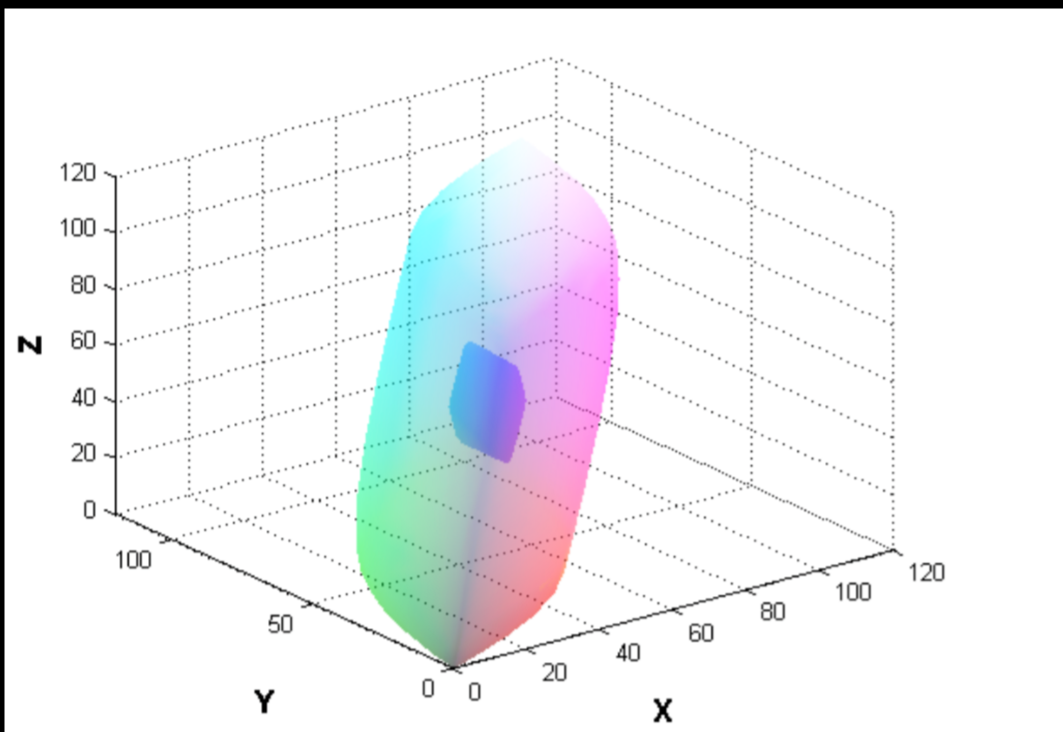
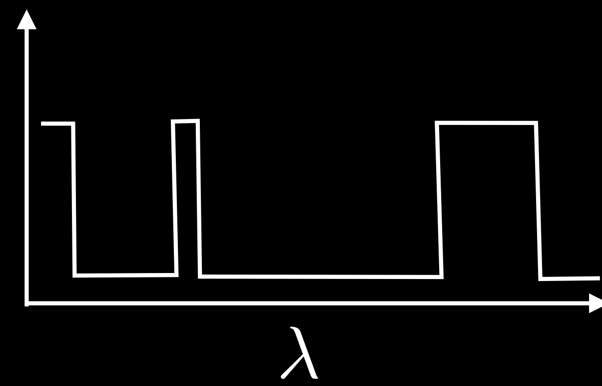
Metamer Mismatch Volume



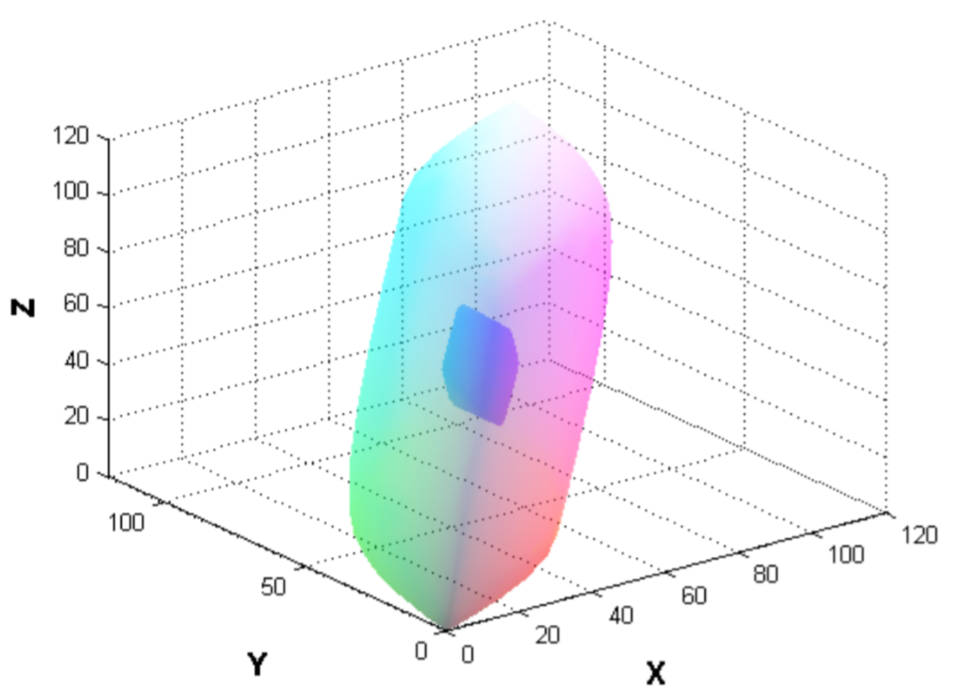
Metamer Mismatch Volumes of Flat Grey

Brian Funt, Hamidreza Mirzaei* and Alexander D. Logvinenko; *Simon Fraser University; Vancouver, Canada; **Glasgow Caledonian University; Glasgow, UK*



A lot of theory 'assumes' the reflectances on the boundary of the metamer mismatch volume is '0-1' and has 5 transitions

Metamer Mismatch Volume



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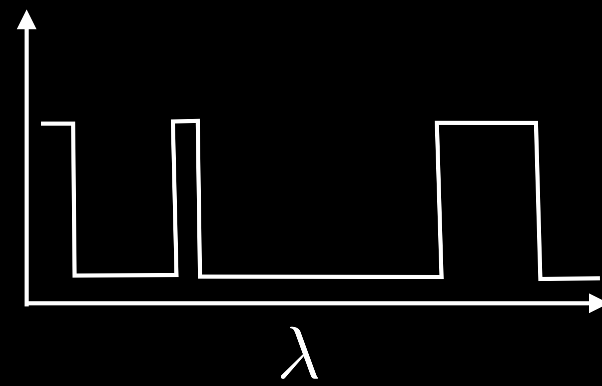


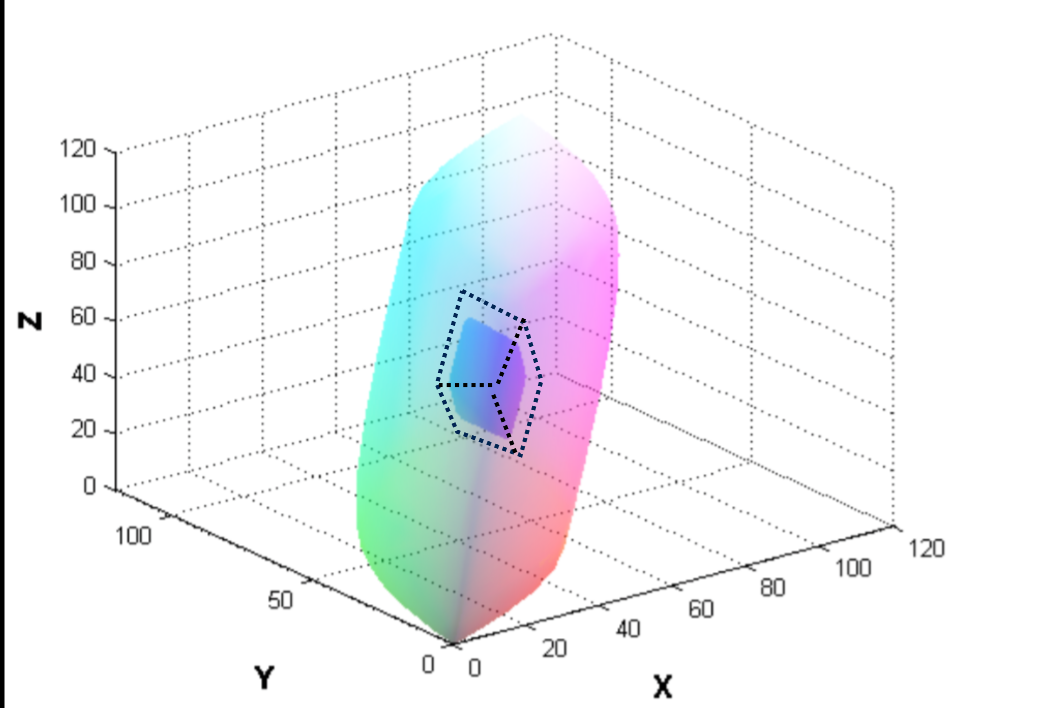
A lot of theory 'assumes' the reflectances on the boundary of the metamer mismatch volume is '0-1' and has 5 transitions

This assumption is wrong. Using the optimisation method for computing metamer sets produces 50% larger volumes.

Metamer mismatch volumes using spherical sampling

Michal Mackiewicz[1], Hans J. Rivertz,[2], Graham D. Finlayson[1]; [1] School of Computing Sciences, University of East Anglia, Norwich, UK; [2] Norwegian University of Science and Technology, Trondheim, Norway

Metamer Mismatch Volume



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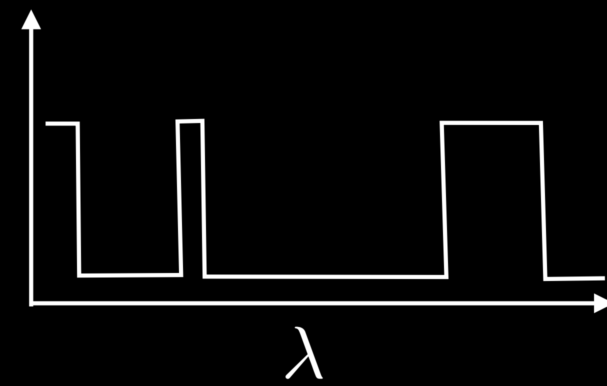

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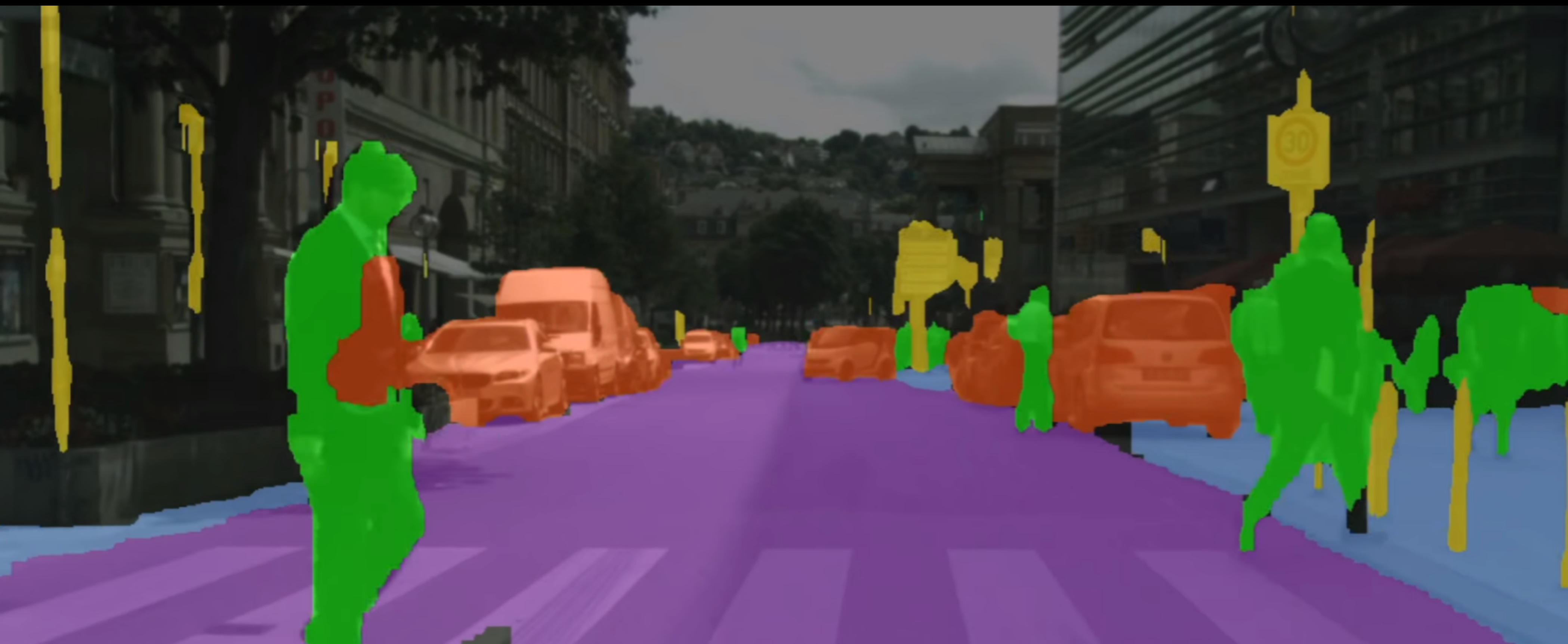
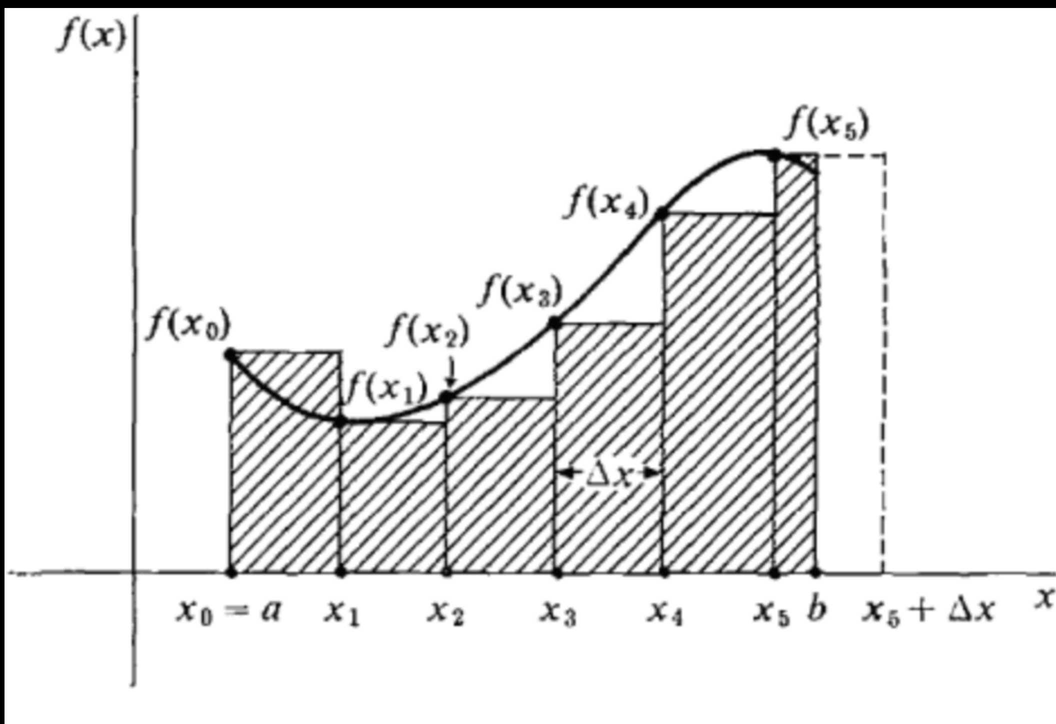
Metamer Sets:

Can we recover 'material' from images?



And does this help solve vision tasks?

Discretely …



$$\int_{\omega} \underline{R}(\lambda) S(\lambda) d\lambda$$

$$\underline{\rho} = \mathcal{R}^t \underline{S}$$

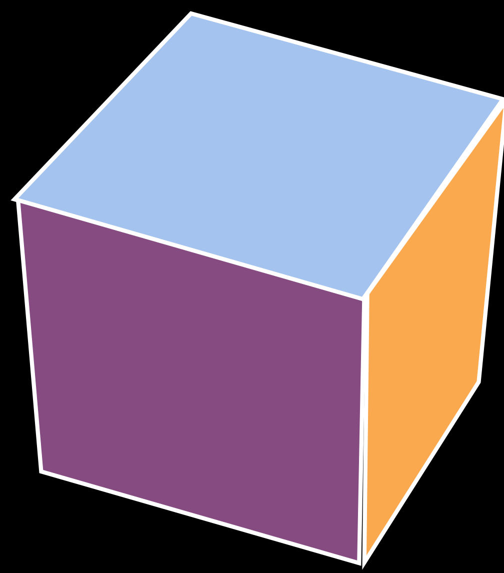
3x1 RGB

Nx3 matrix of
'effective' sensitivities

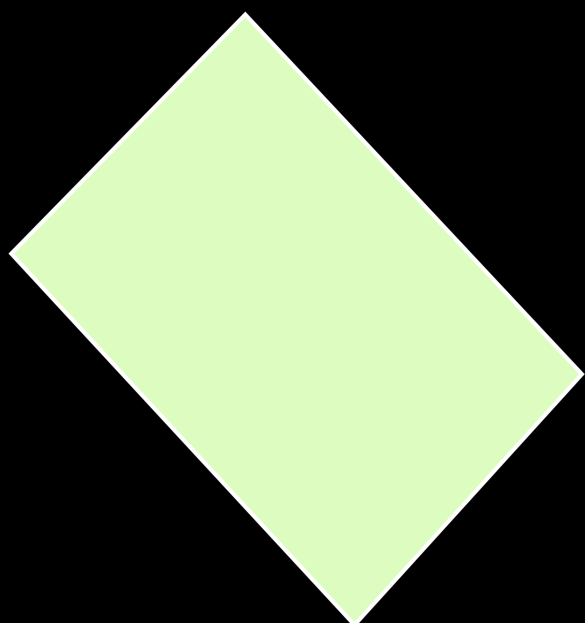
Nx1 reflectance
vector

The Set of all Reflectances

Hyper-cube
constraint
(if 31 sample
wavelengths then
31 dimensional hypercube)

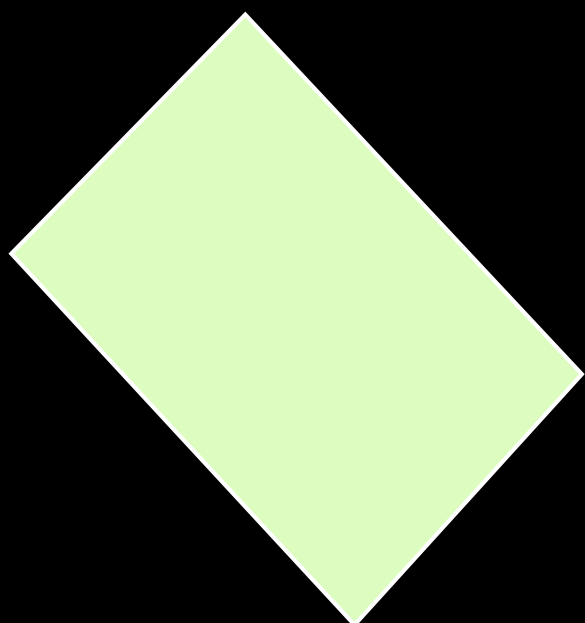


Reflectances that ‘project’ to $\underline{p}$



Reflectance hyper-plane
constraint: All vectors $\underline{S}$
that ‘project’ to the same
RGB lie on a plane
(if 31 sample
wavelengths then
28 dimensional affine hyperplane or ‘flat’)

Reflectances that ‘project’ to p



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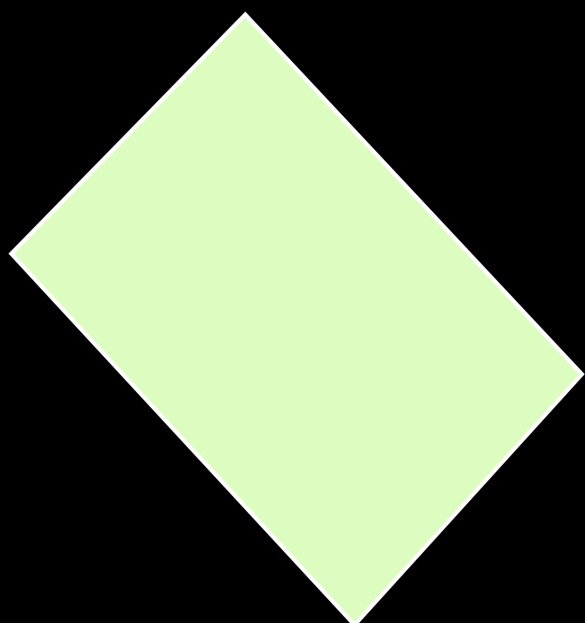
$$\mathcal{R}^t \underline{S} = \underline{p} \equiv$$
$$\mathcal{R}^t[\mathcal{R}\underline{\alpha} + \mathcal{R}^{\perp}\underline{\beta}] = \underline{p}$$

Reflectances that ‘project’ to $\underline{p}$



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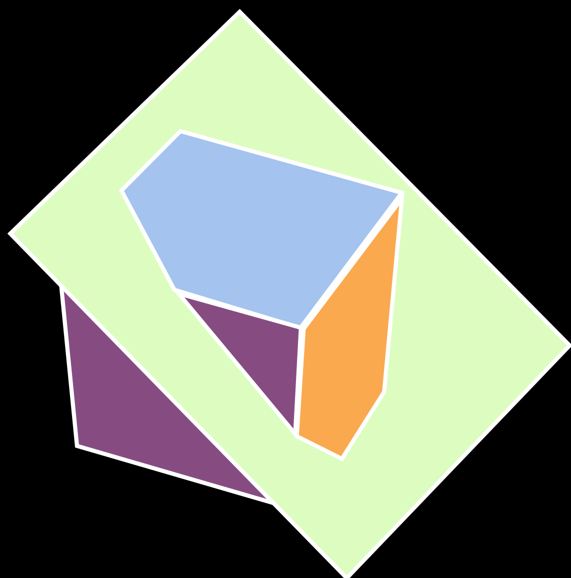
$$\mathcal{R}^t [\mathcal{R}\underline{\alpha} + \mathcal{R}^\perp \underline{\beta}] = \underline{p}$$

$$\underline{S}_{ref} + \sum_{i=1}^{28} Black_i(\lambda)\beta_i$$

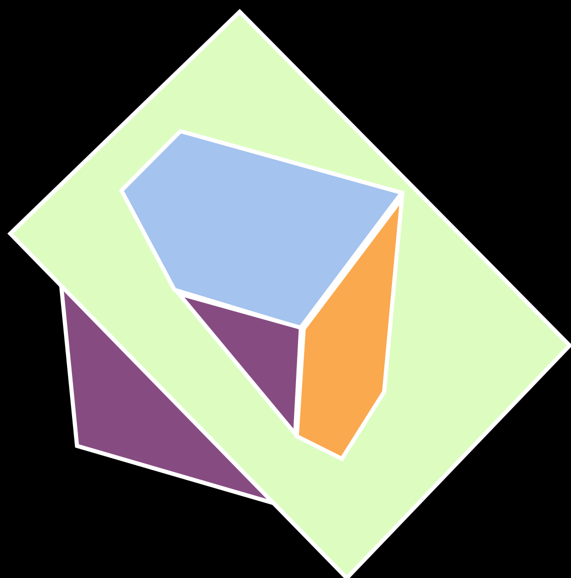
Metamer Sets



The Metamer Set is the intersection
of a hyper-cube with a hyper-plane
(can have complex geometry [thousands
of points, computationally hard]

$$O(n^{d/2})$$

Metamer Sets



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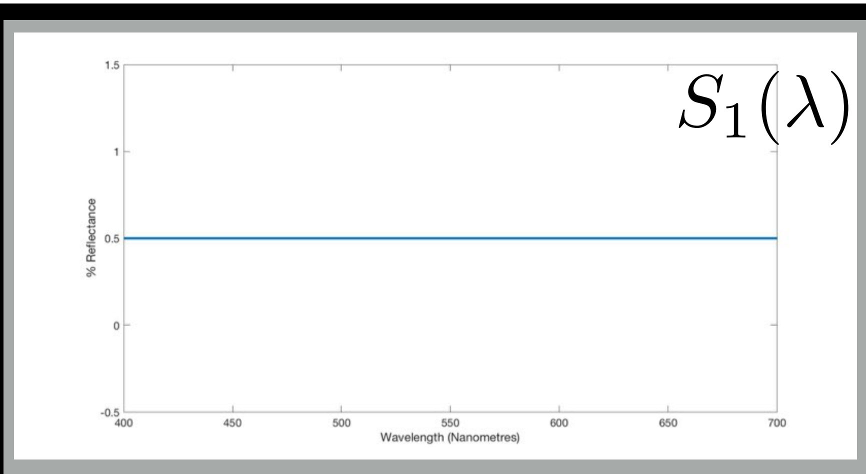
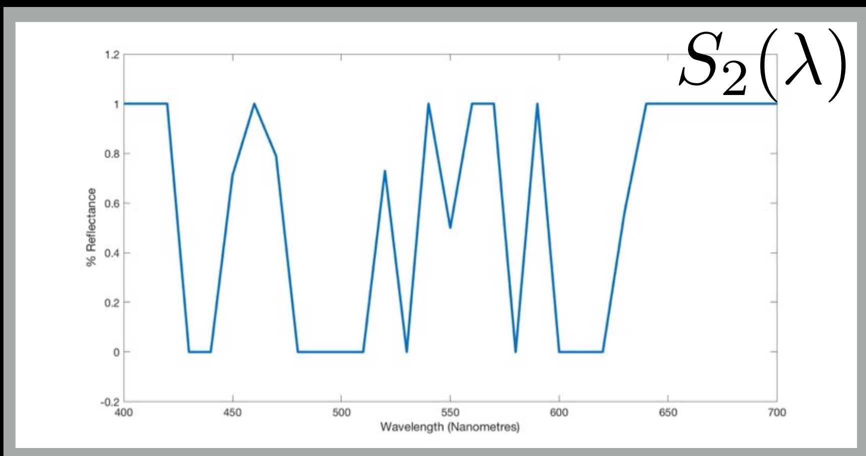
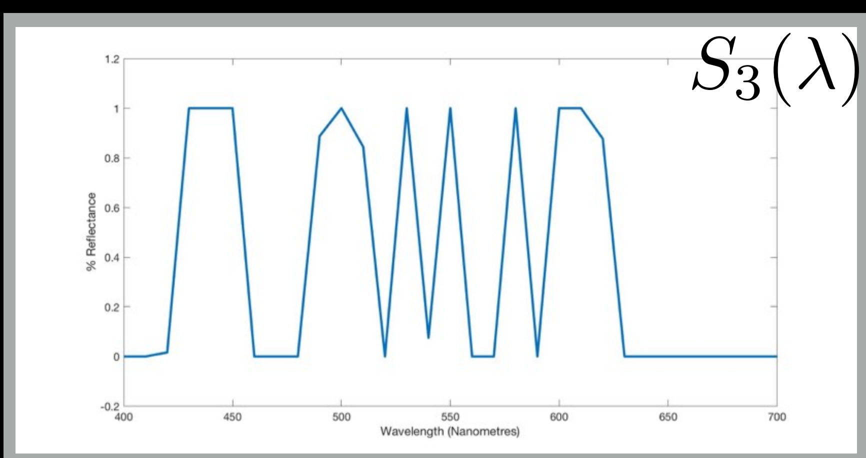
$$O(n^{d/2})$$

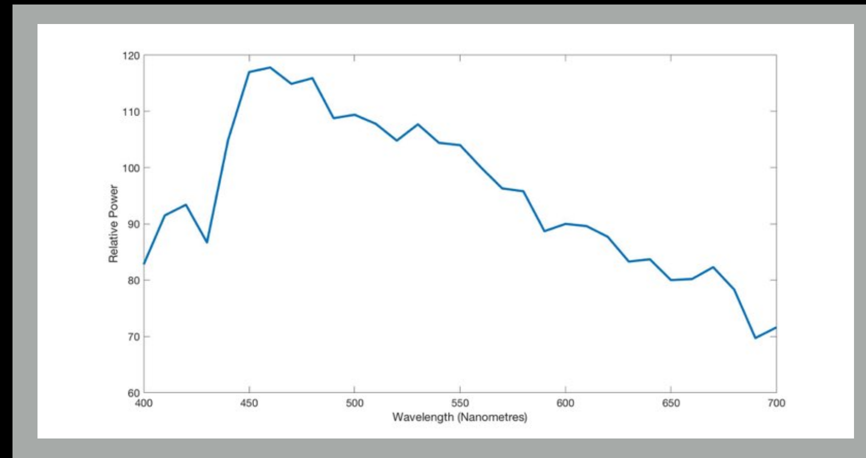
A hypercube is the intersection of half spaces
delimited by the cube's faces (hyperplanes)

Intersection of half spaces in N-D is
found using ND convex hull algorithm

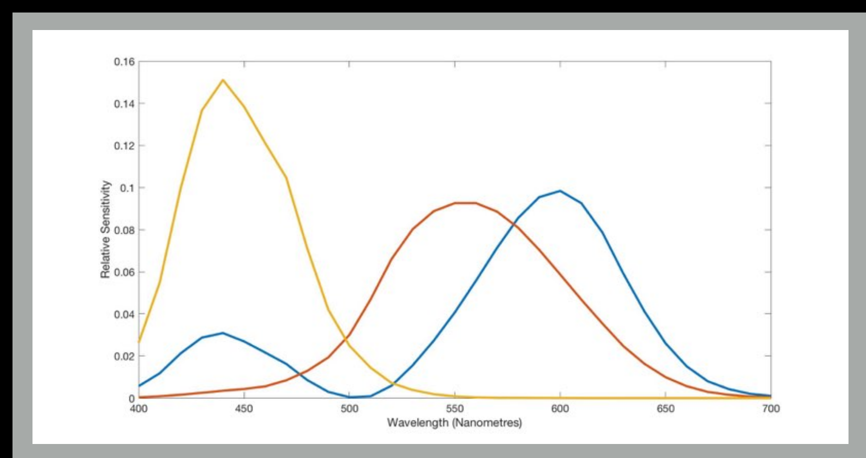




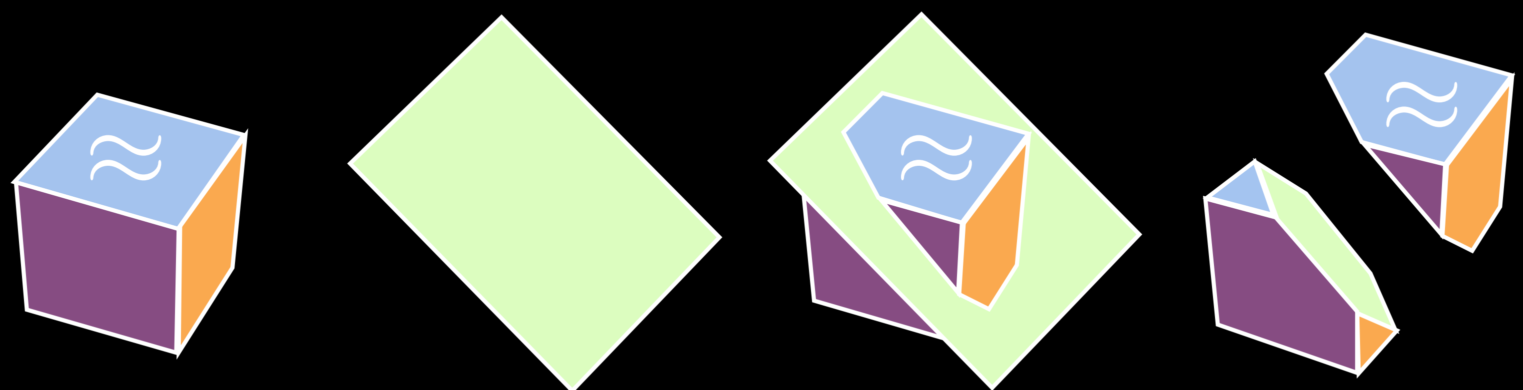




$$\int_\omega \underline{Q}(\lambda)E(\lambda)S(\lambda)d\lambda \quad =[47\ 49\ 53]$$



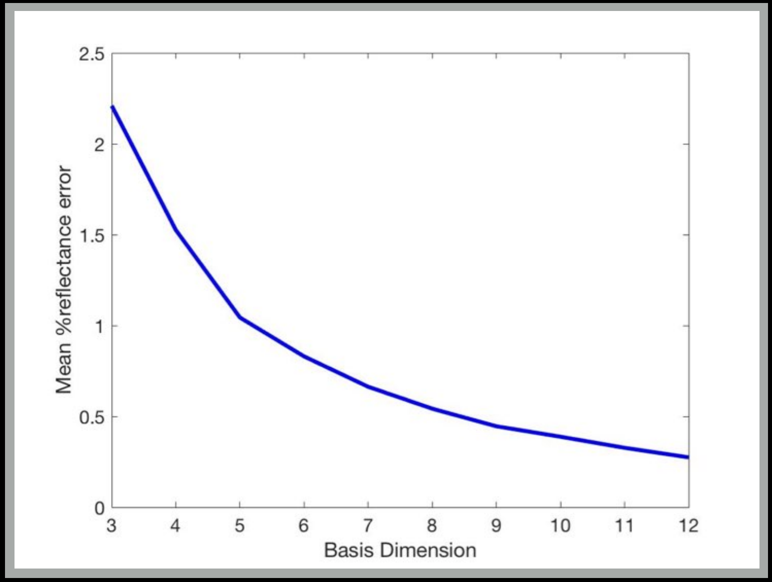
Basic Metamer Sets

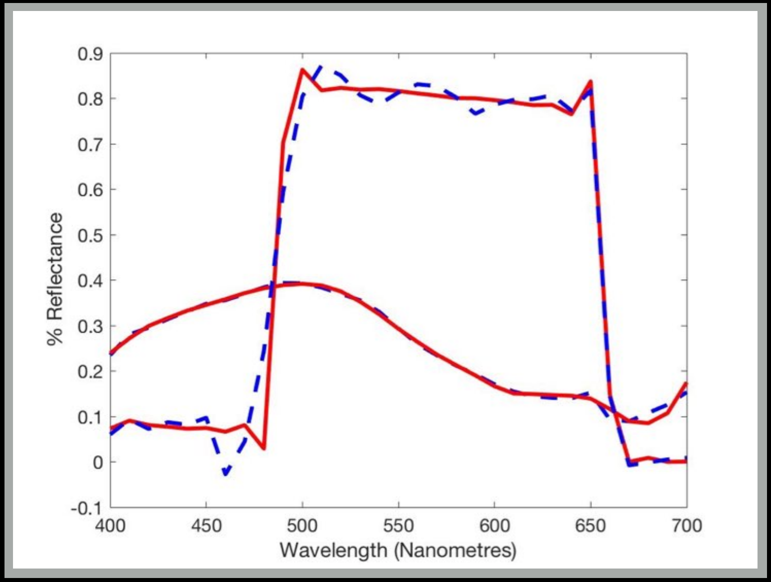


≈ denotes N-dimensional reflectances that ‘live’ inside the 31-d hypercube (N<<31)

Basis Approximations

$$S(\lambda) \approx \sum_{i=1}^{N} \sigma_i S_i(\lambda)$$





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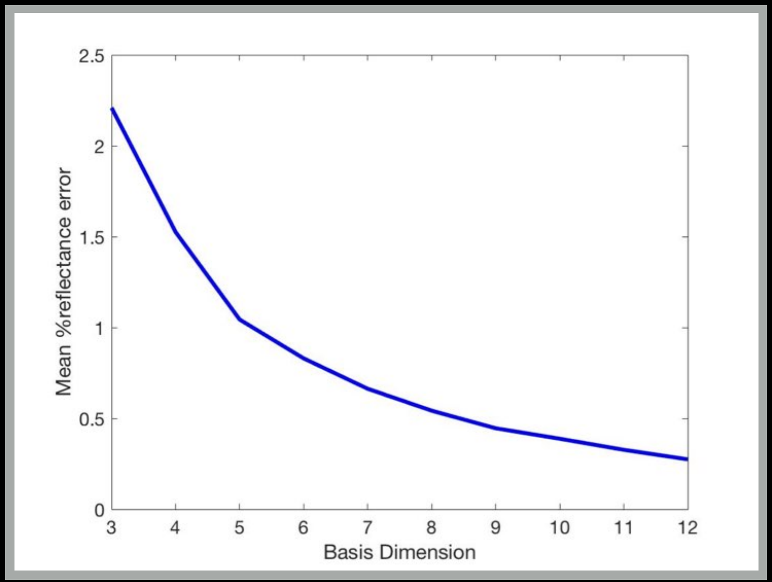
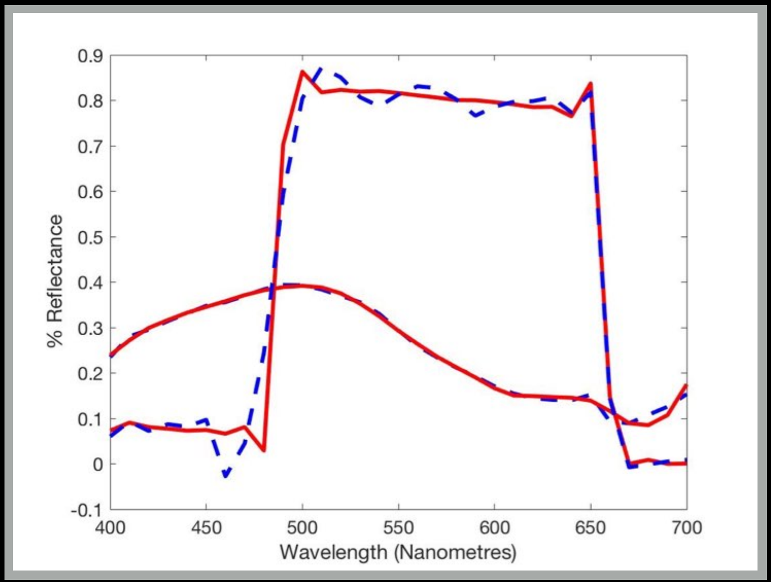
How many basis functions are needed?

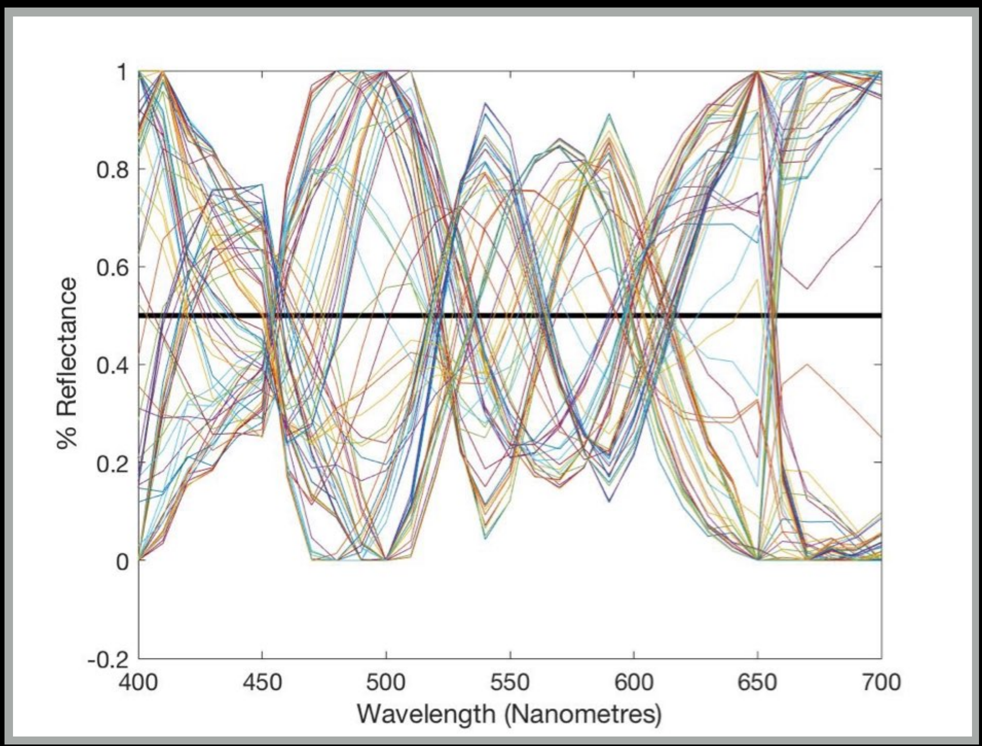


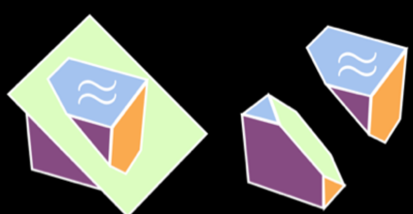


Shown: ‘extremal’ metamers for grey reflectance assuming 7 dimensional CVA basis set

These are solved for *exactly* because

i) hypercube constraints in 7D are defined by 14 hyperplanes





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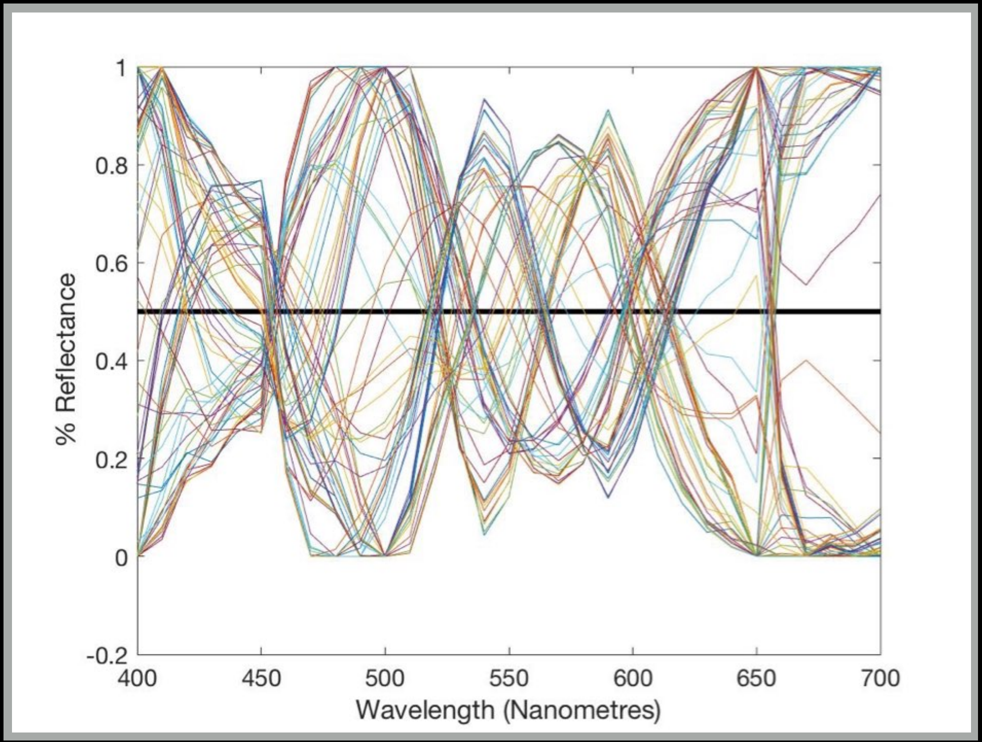

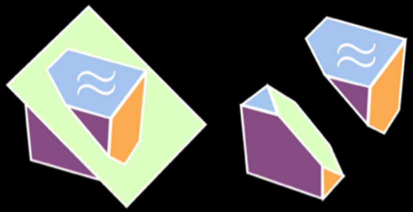

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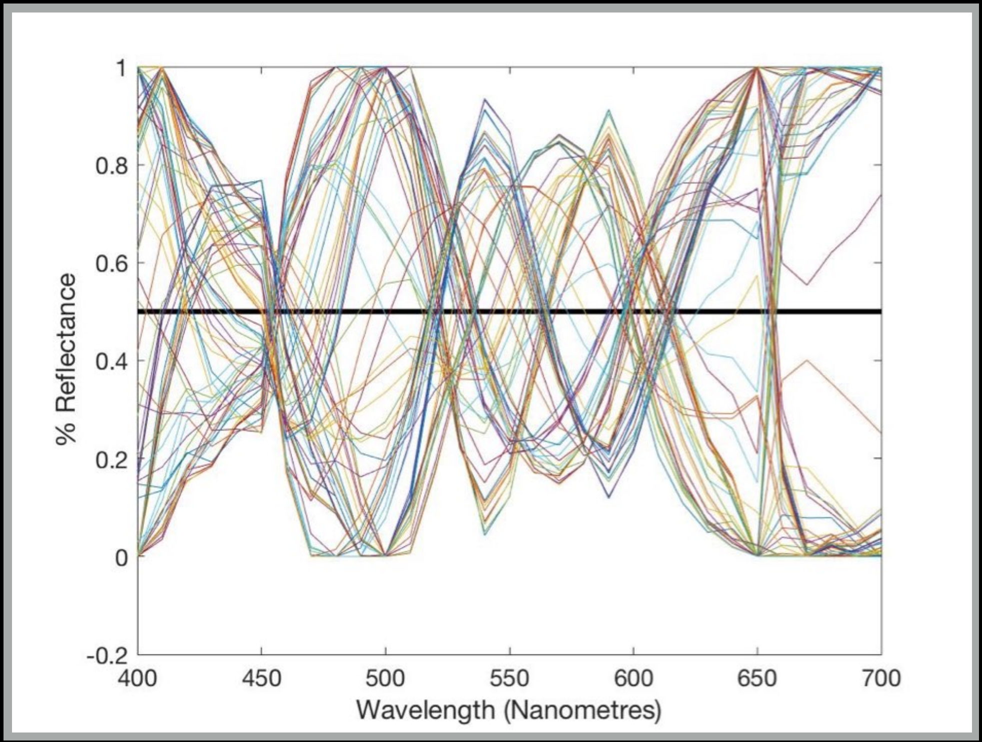

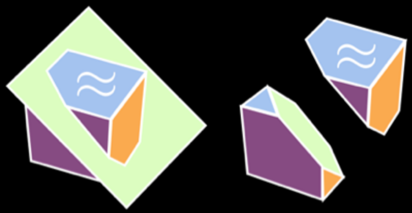

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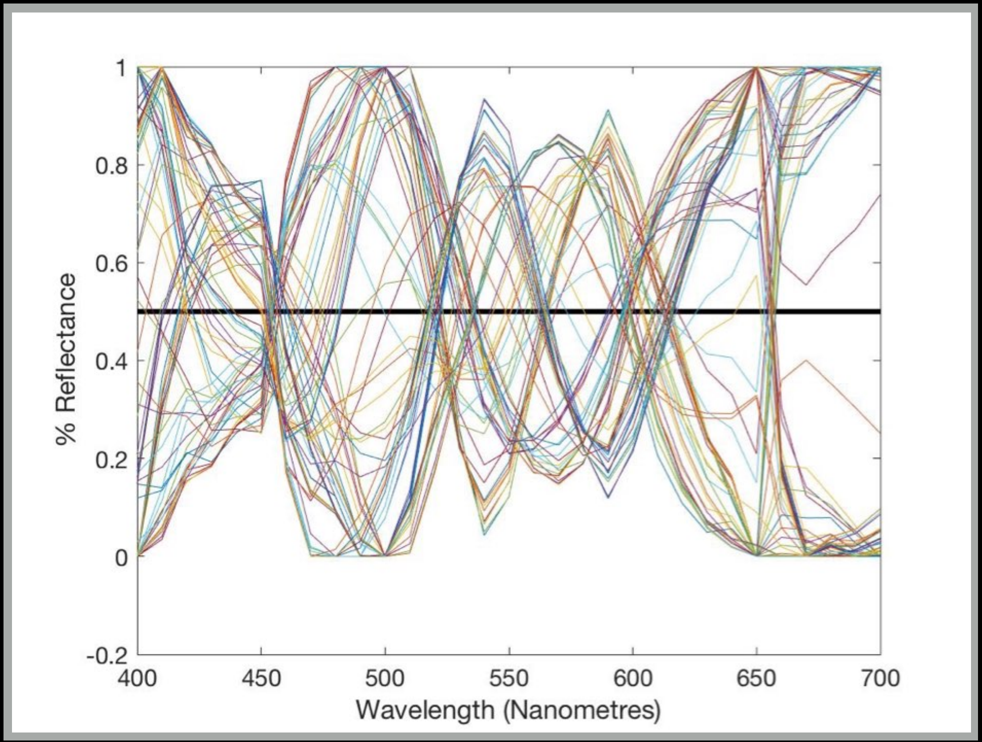

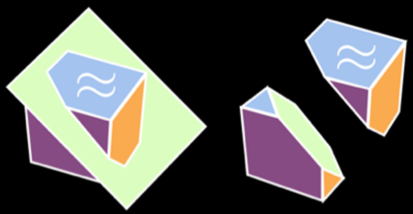

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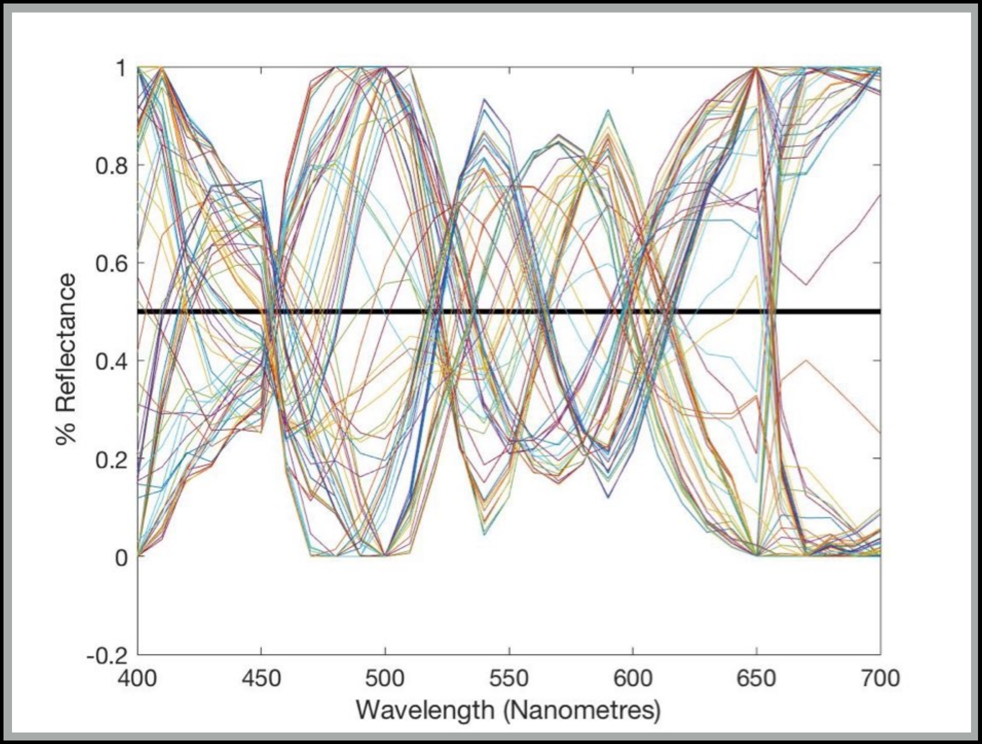

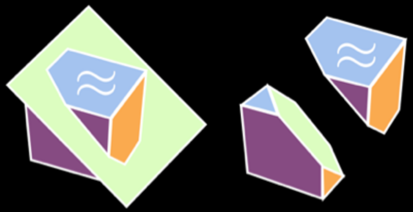

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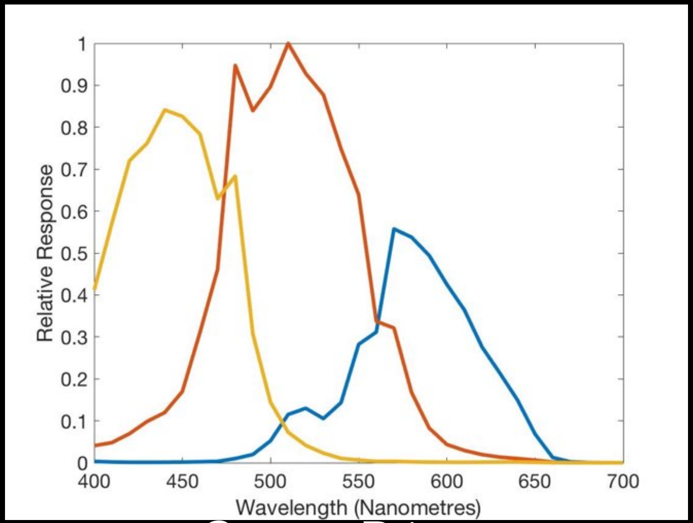
v) Can calculate basic metamer sets for 12,13,14 dimensional basis (more degrees of freedom than typically used

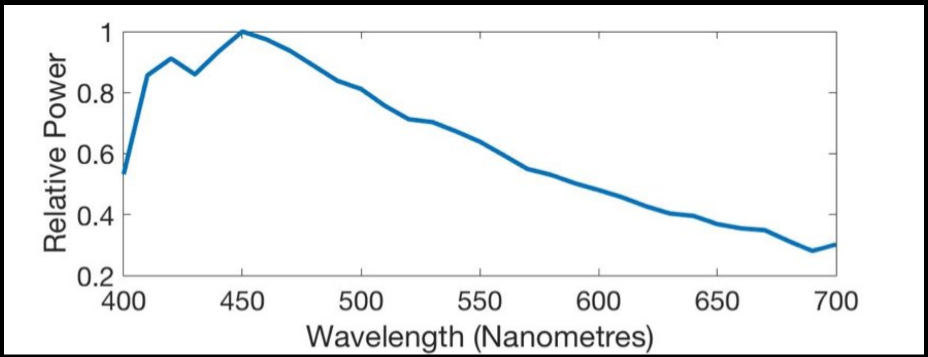
Worked Example

$\underline{Q}(\lambda)$

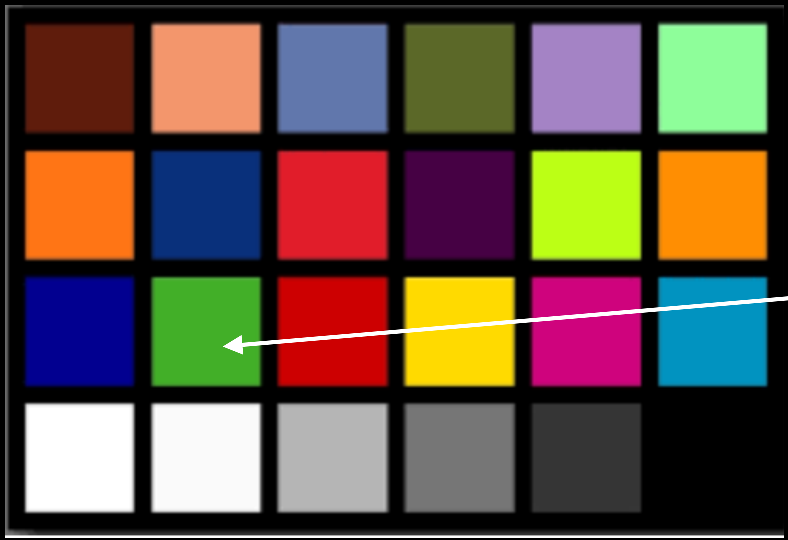


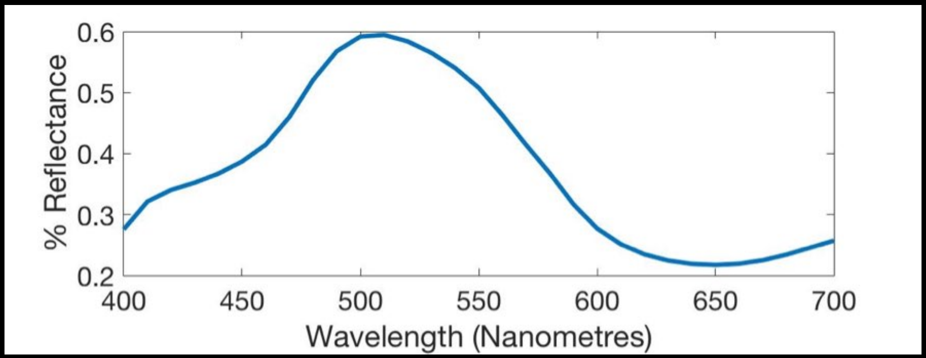
Canon D1
Spectral Sensitivities

$E(\lambda)$

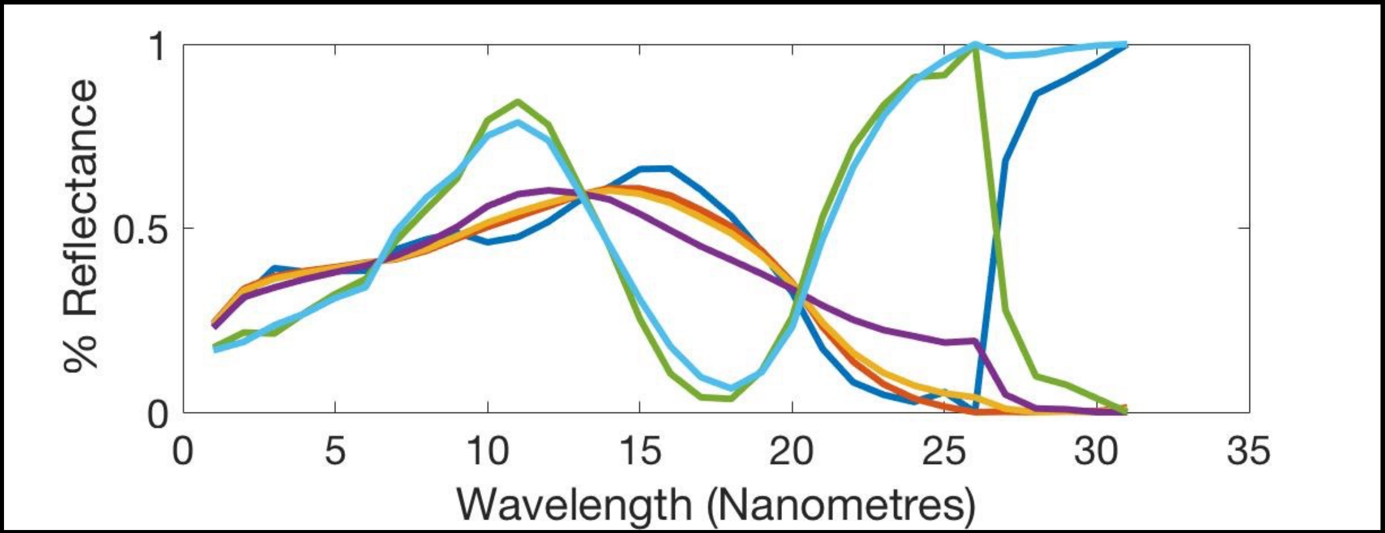


$S(\lambda)$





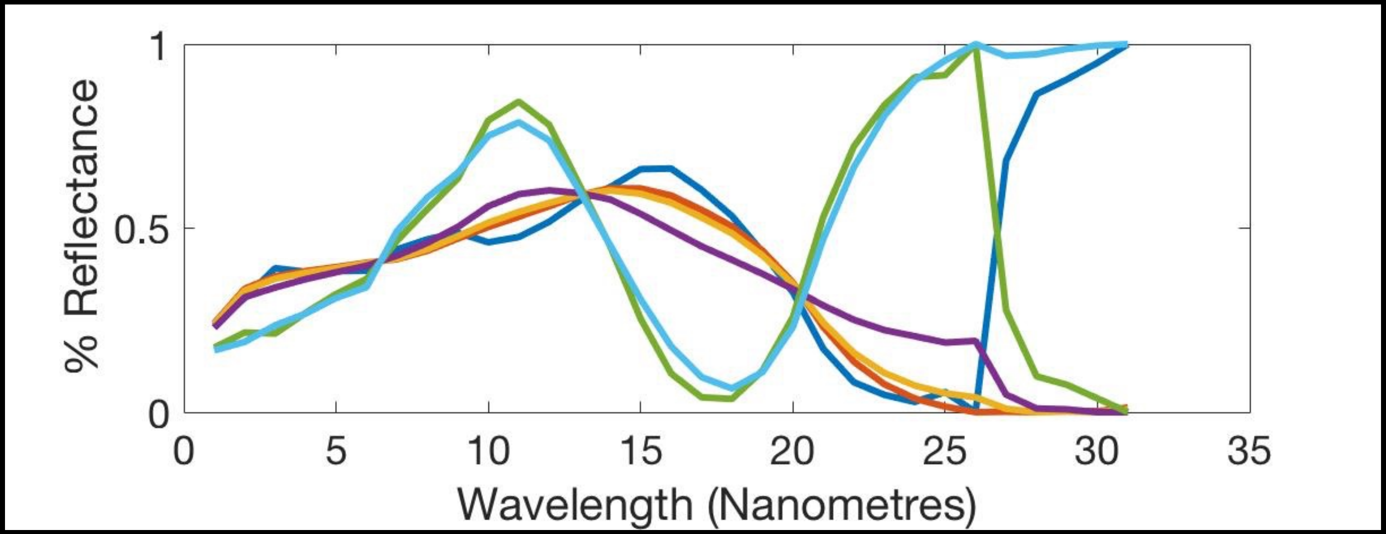
$$\int \underline{Q}(\lambda))E(\lambda)S(\lambda)d\lambda \ = [1.19 \ \ 4.24 \ \ 2.56]$$



The spectra shown lie on the convex hull of the 'Metamer Set'

All spectra integrate to [1.19 4.24 2.45]

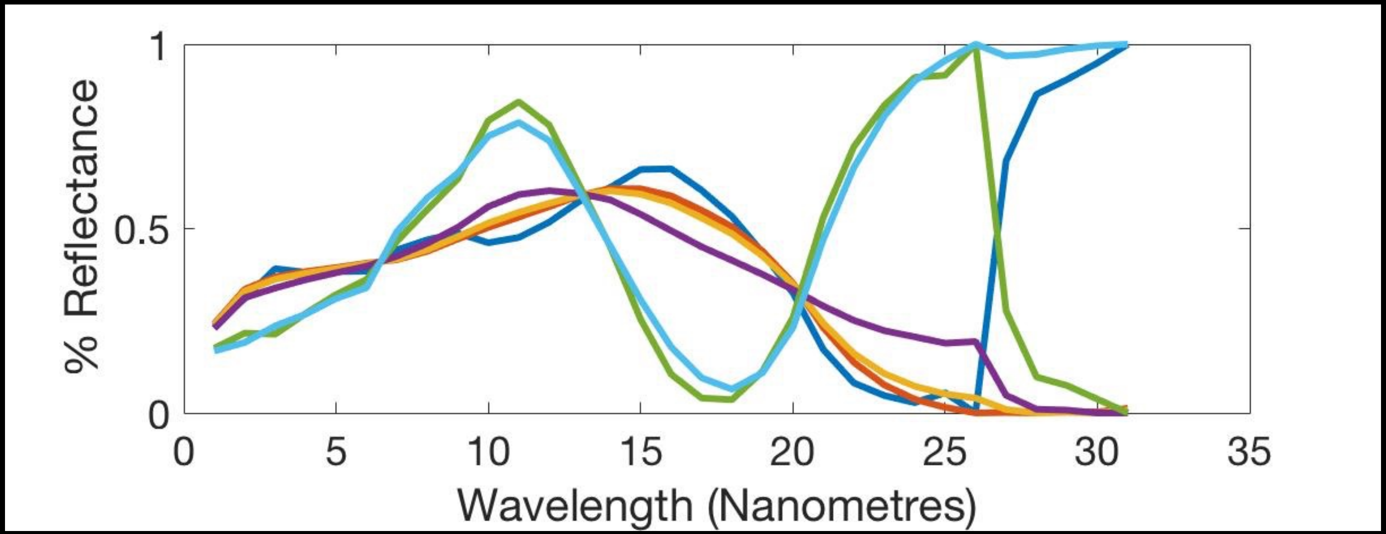
All convex combinations integrate to [1.19 4.24 2.45]



We are trying to characterise all reflectances which integrate to a single RGB.

$$\mathcal{R}^t \underline{S} = \underline{p} \equiv$$
$$\mathcal{R}^t [\mathcal{R}\underline{\alpha} + \mathcal{R}^{\perp}\underline{\beta}] = \underline{p}$$

$$\underline{S}_{ref} + \sum_{i=1}^{2} Black_i(\lambda)\beta_i$$



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The set comprises a ref spectrum that projects to the desired RGB and a combination of spectra that is orthogonal to the sensor space

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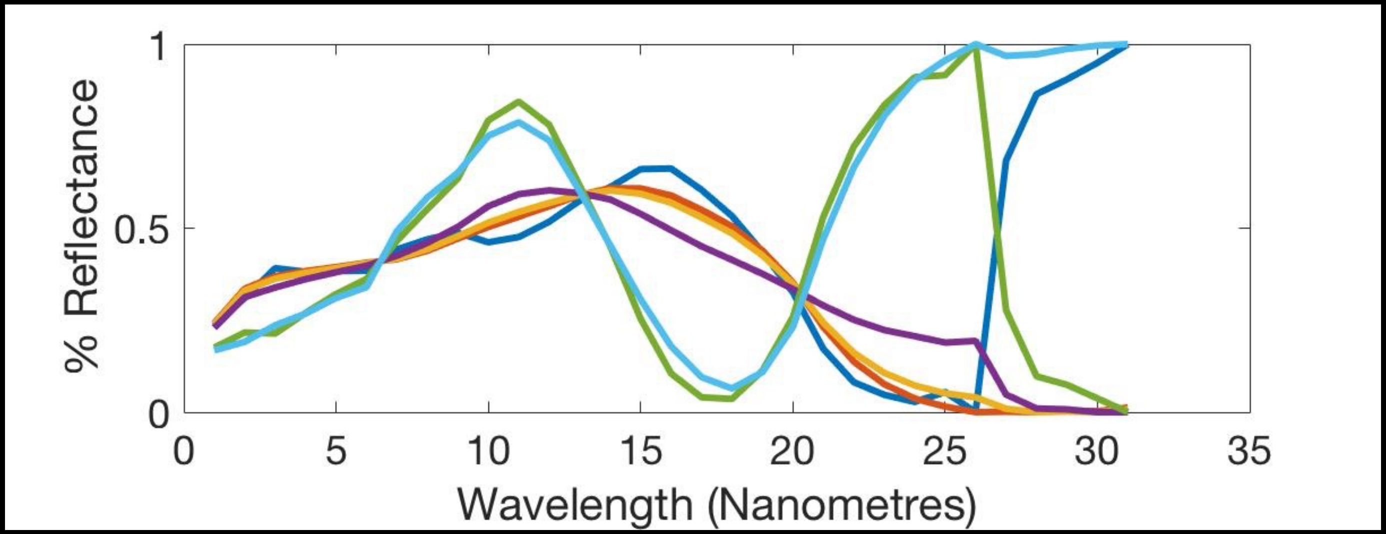

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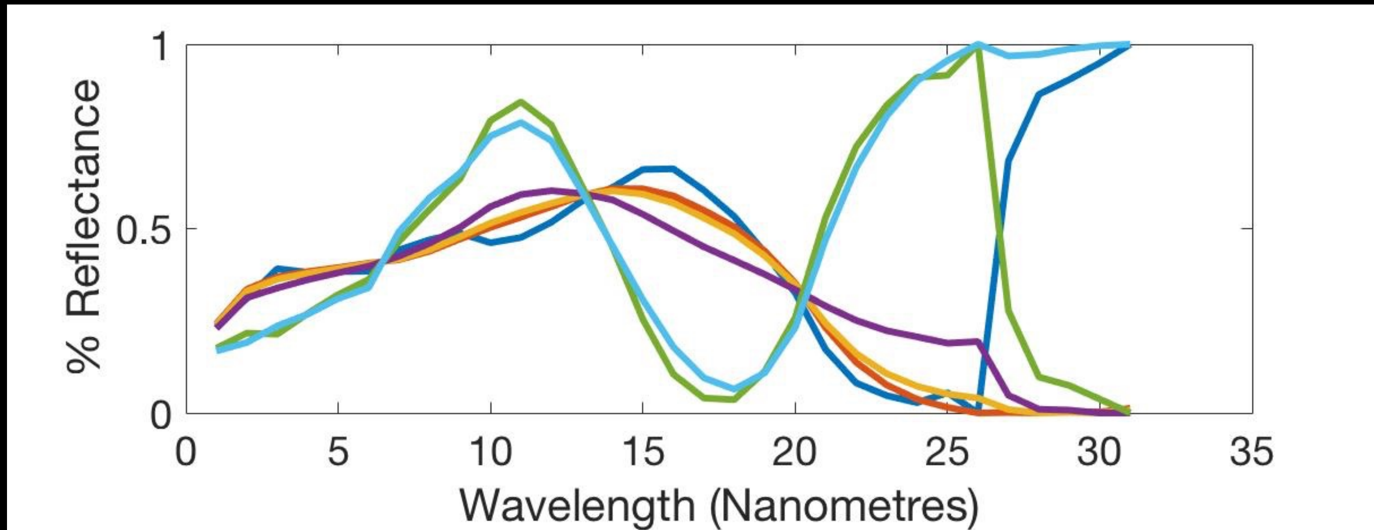
If the reflectance basis is 5D. There is a single ref reflectance and a 2-dimensional set of metameric blacks

$$\underline{S}_{ref} + \sum_{i=1}^{2} Black_i(\lambda)\beta_i$$



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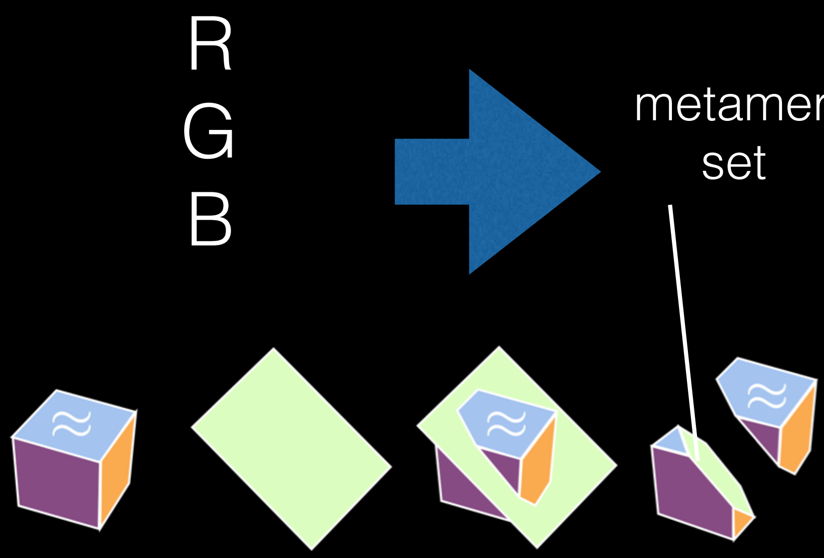
If the reflectance basis is 5D. There is a single ref reflectance and a 2-dimensional set of metameric blacks

The metamer set is a 2-dimensional hyperplane in 5D (which in turn is embedded in 31-D)

Reprojecting



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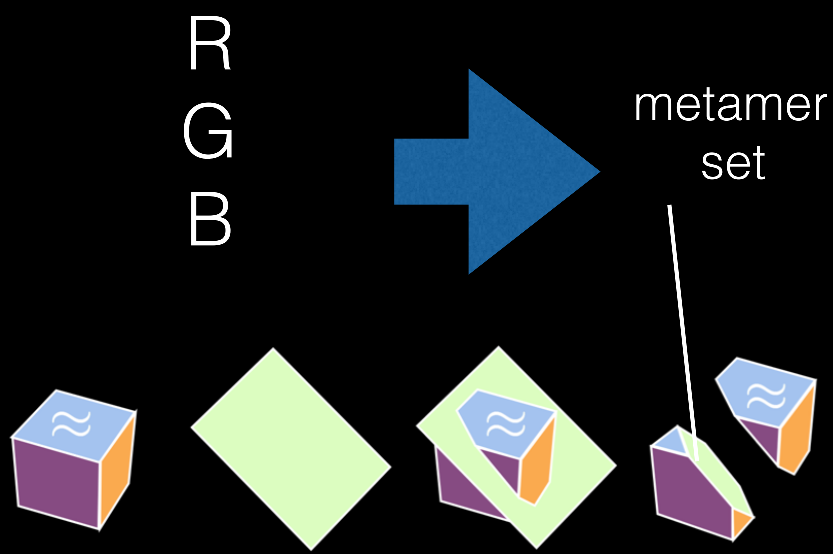
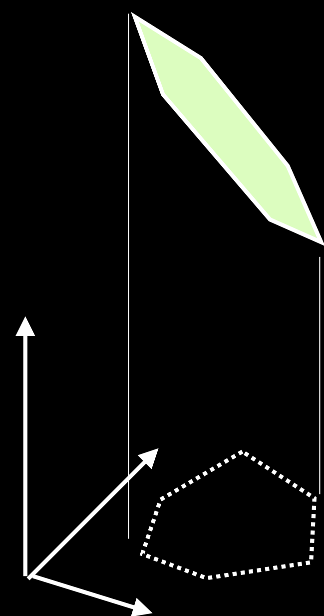
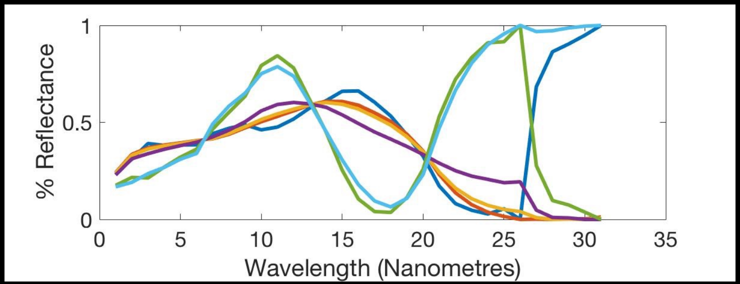




integrating
(projecting)
the metamer
set to a second
viewing condition
typically
generates
multiple ‘colors’

Re-projecting to XYZ



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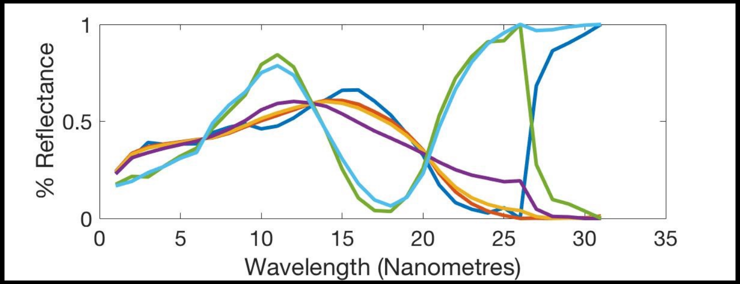
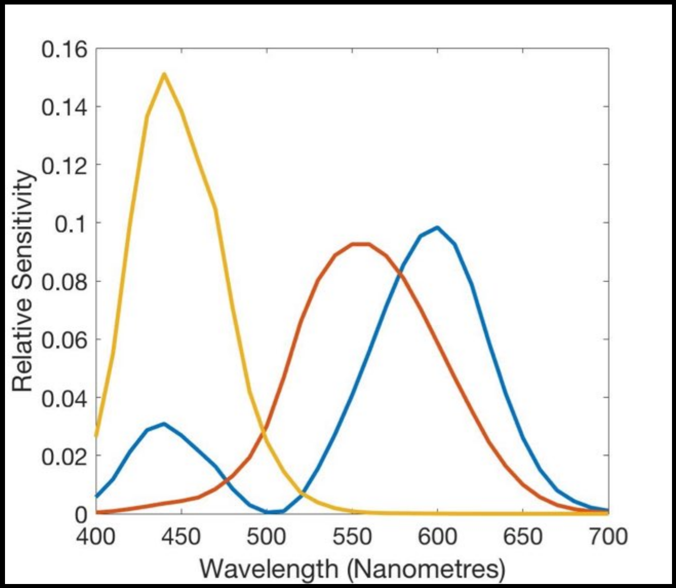


$$\int$$



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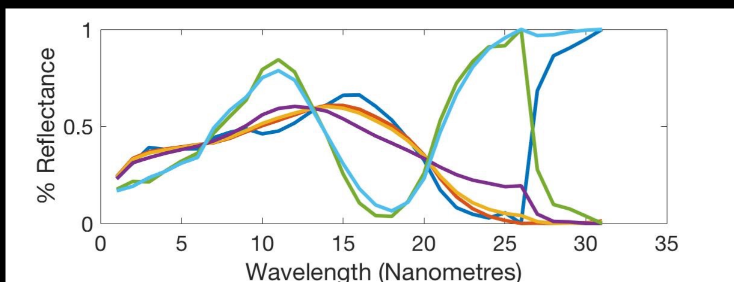

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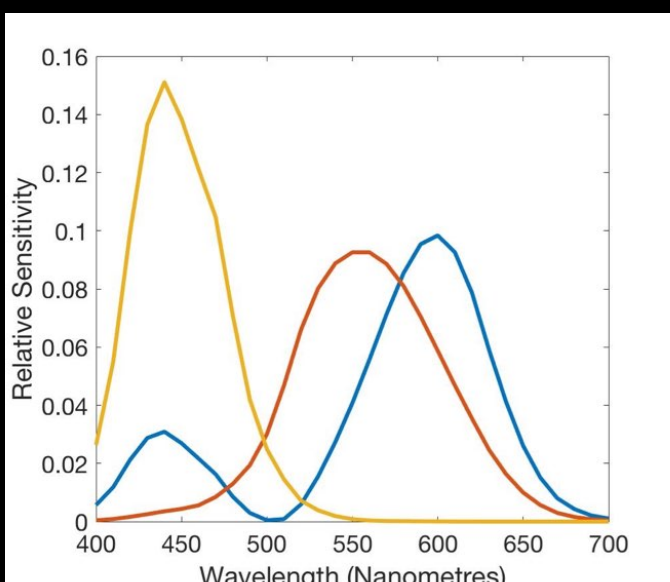
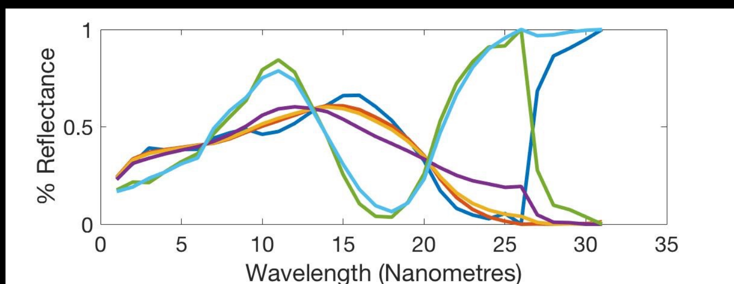


$$= \begin{matrix} 0.25 & 0.37 & 0.38 \\ 0.24 & 0.36 & 0.38 \\ 0.25 & 0.36 & 0.38 \\ 0.25 & 0.35 & 0.38 \\ 0.30 & 0.30 & 0.38 \\ 0.31 & 0.32 & 0.38 \end{matrix}$$

Re-projecting to XYZ



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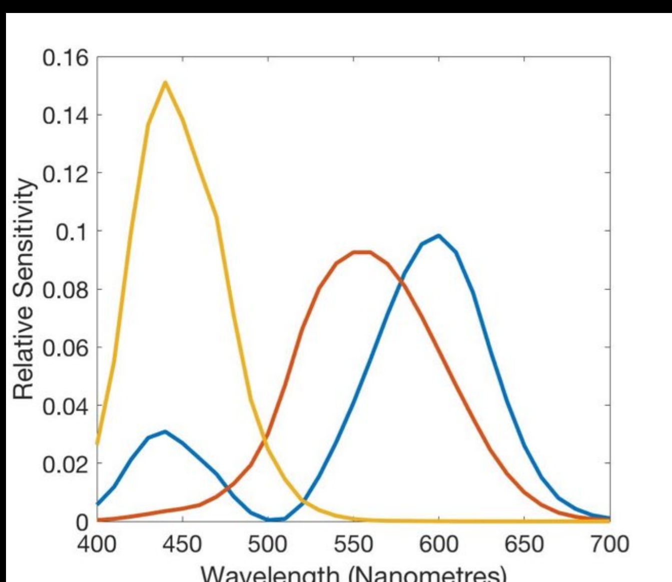

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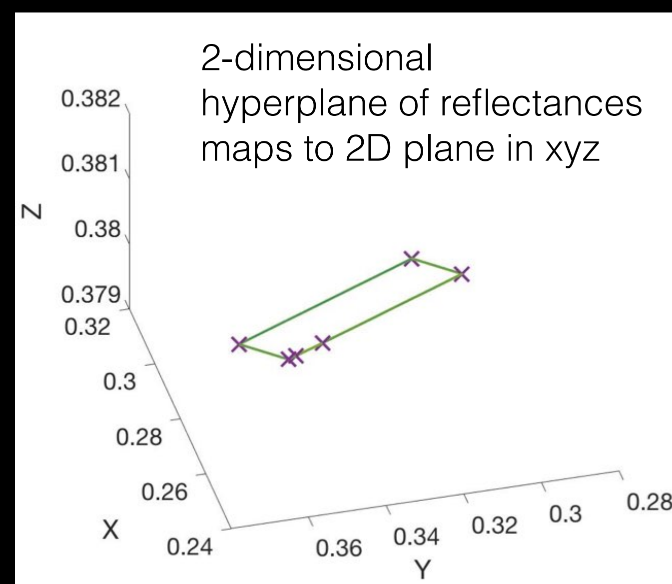
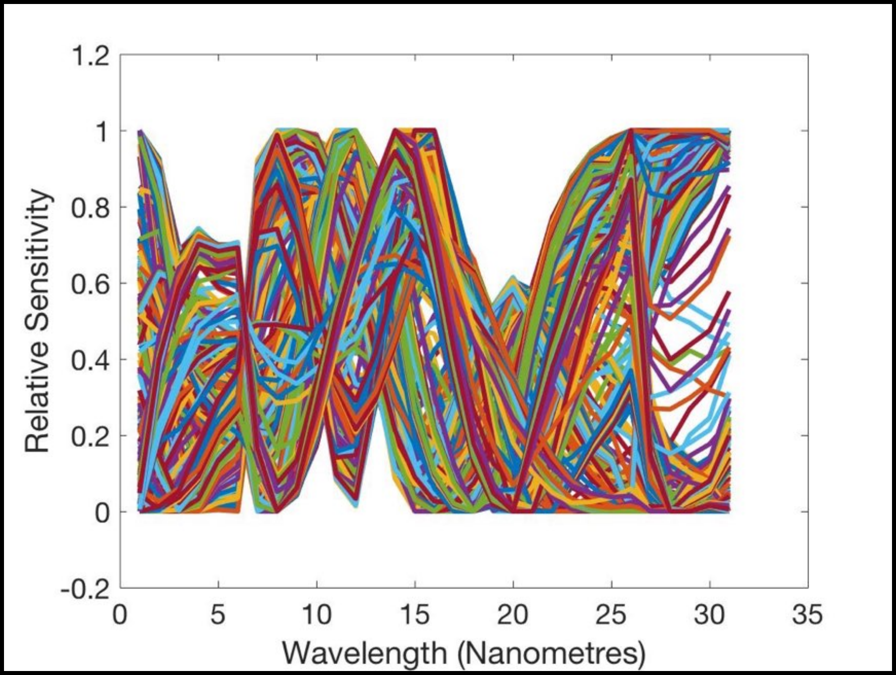
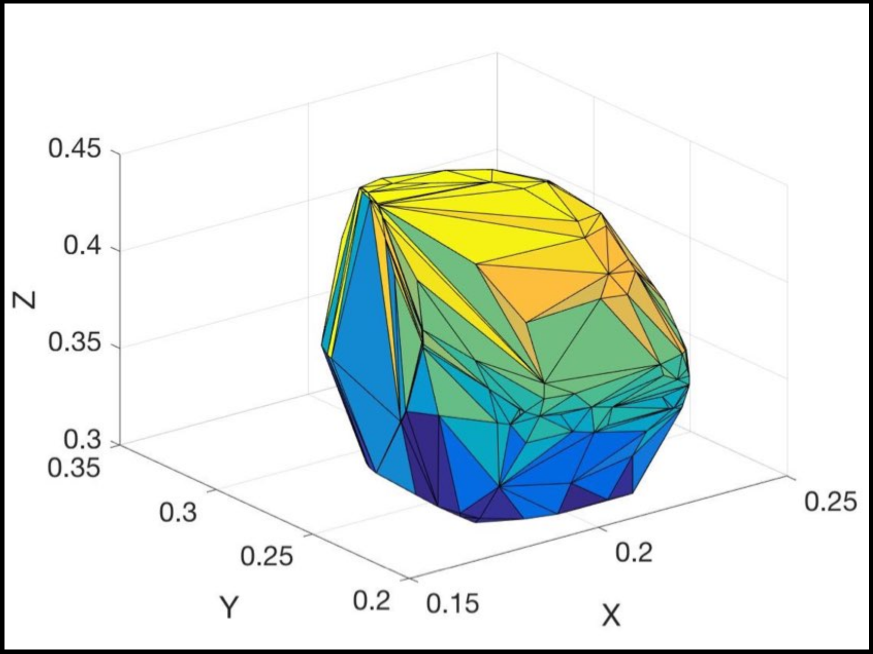


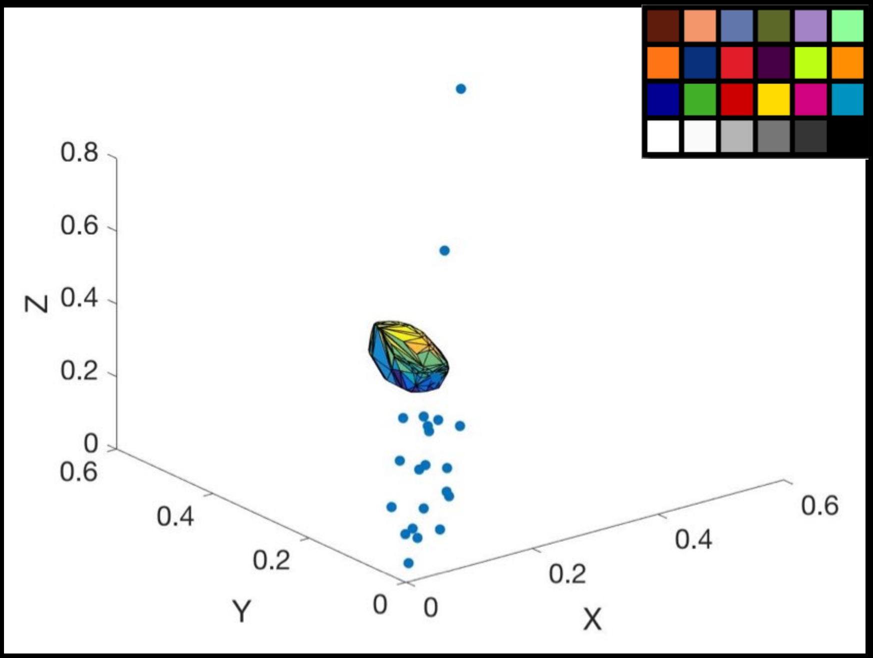


8 dimensional reflectance basis

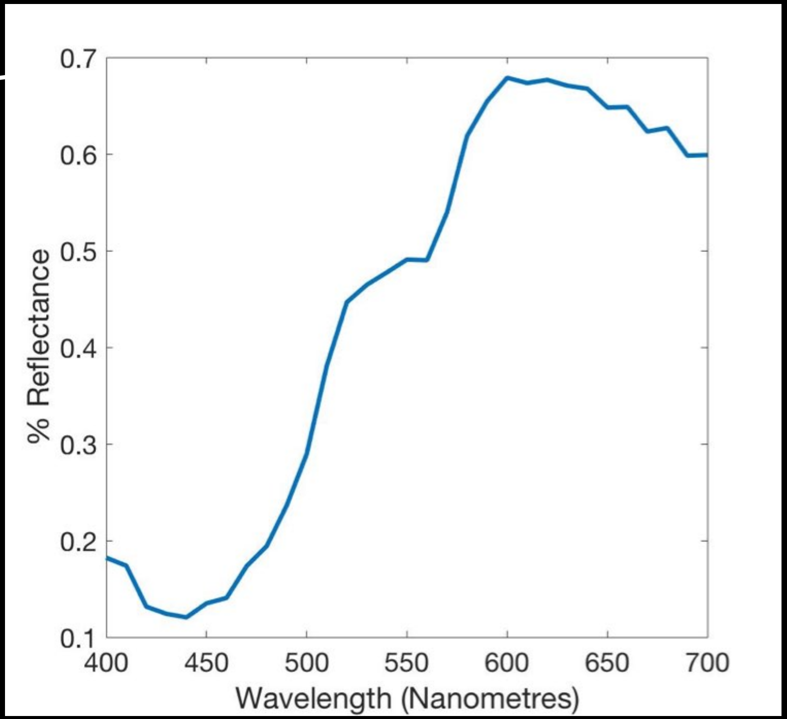
yields 5 dimensional bounded convex region (in 8-d space) of metamers.

All of which integrate to [1.19 4.24 2.56]

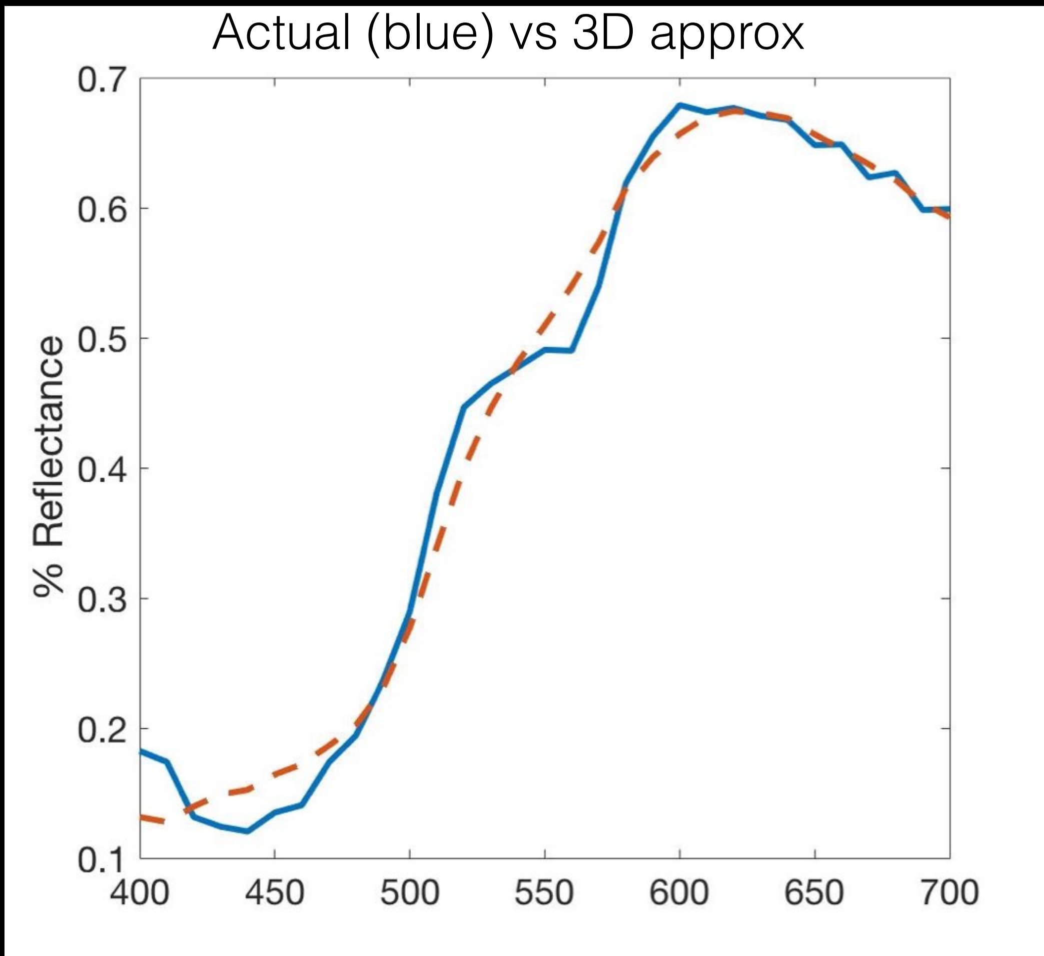




RGB to Spectra



How Many Dimensions?



ground-truth

closest in X-D metamer set

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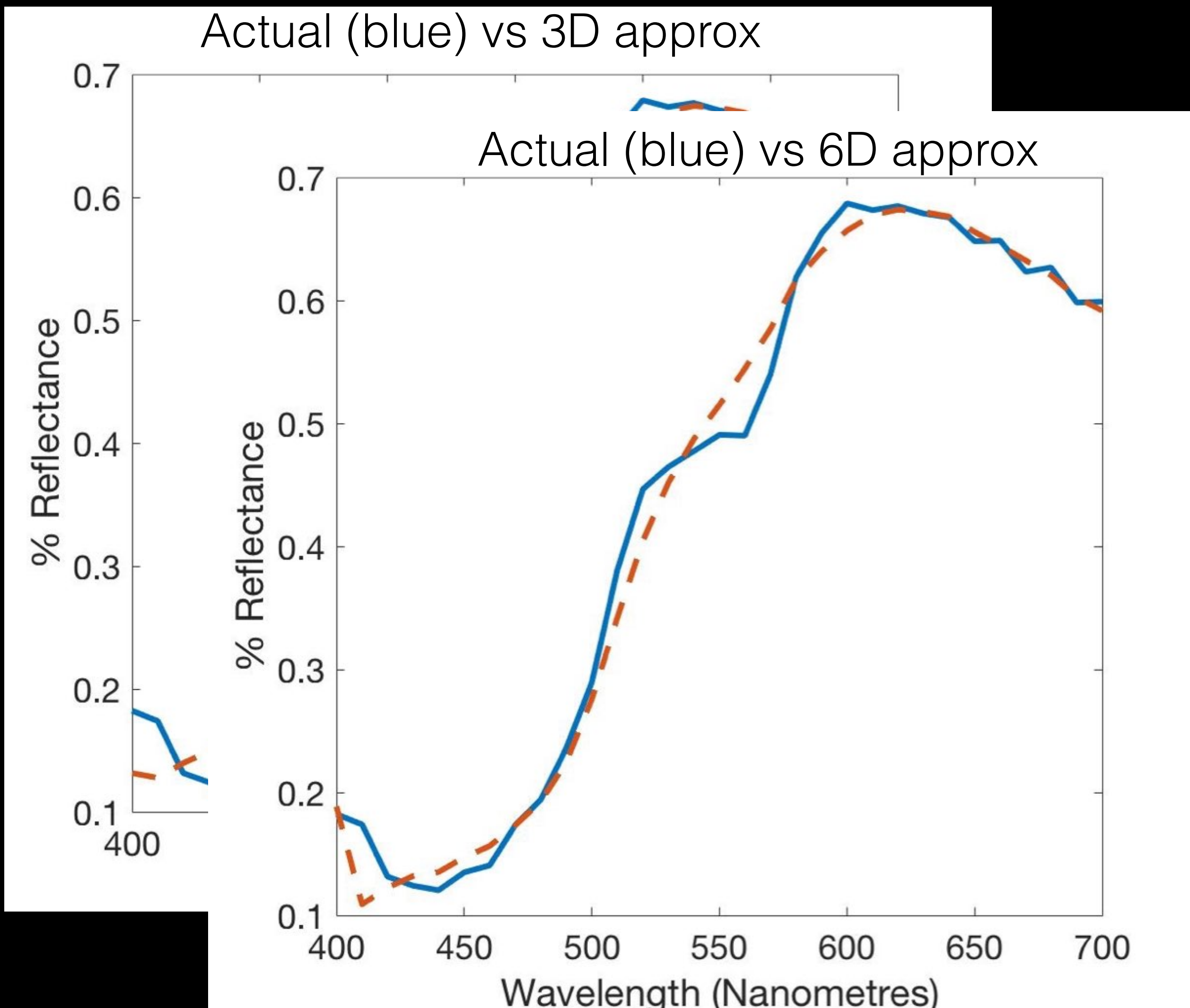

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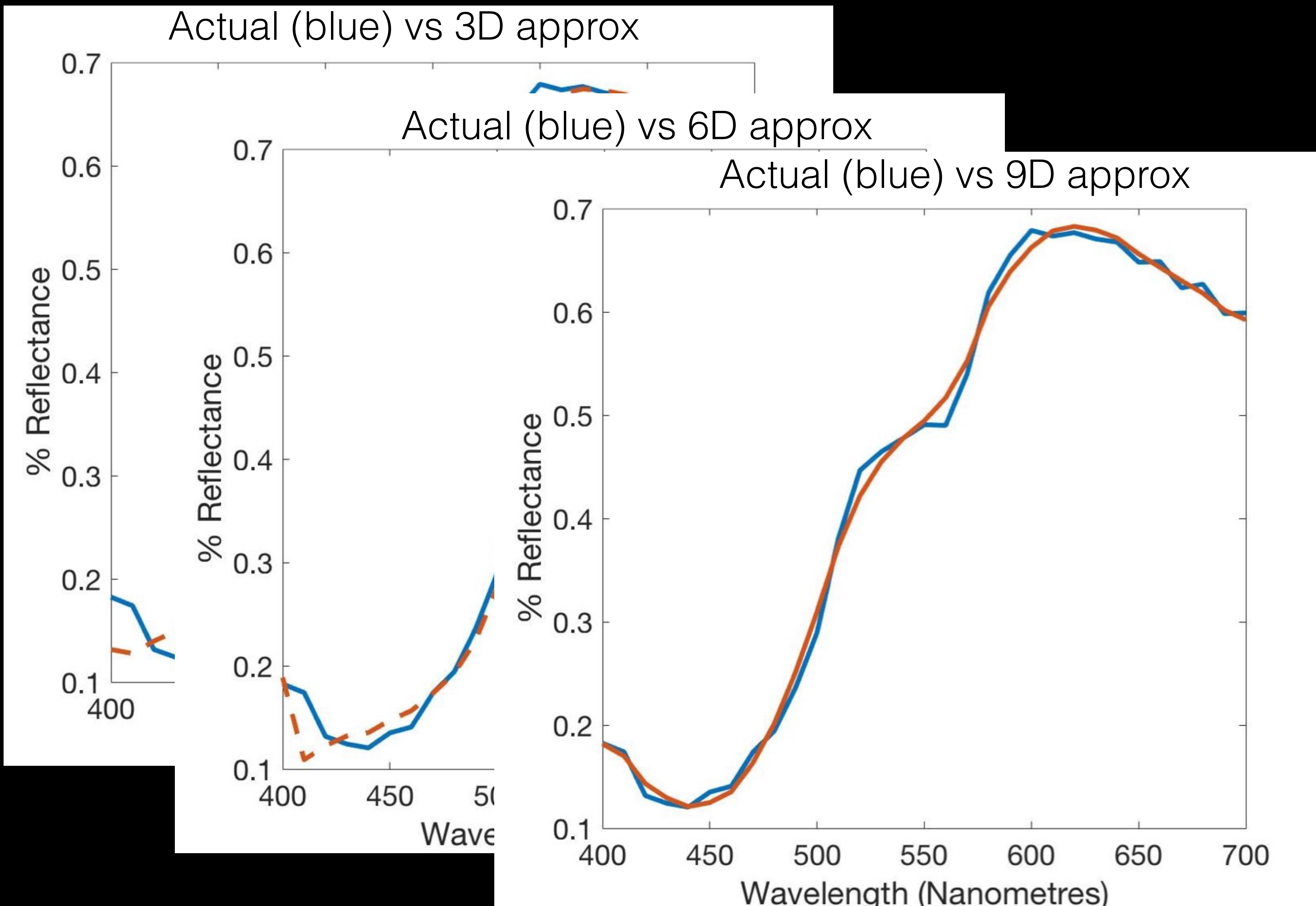

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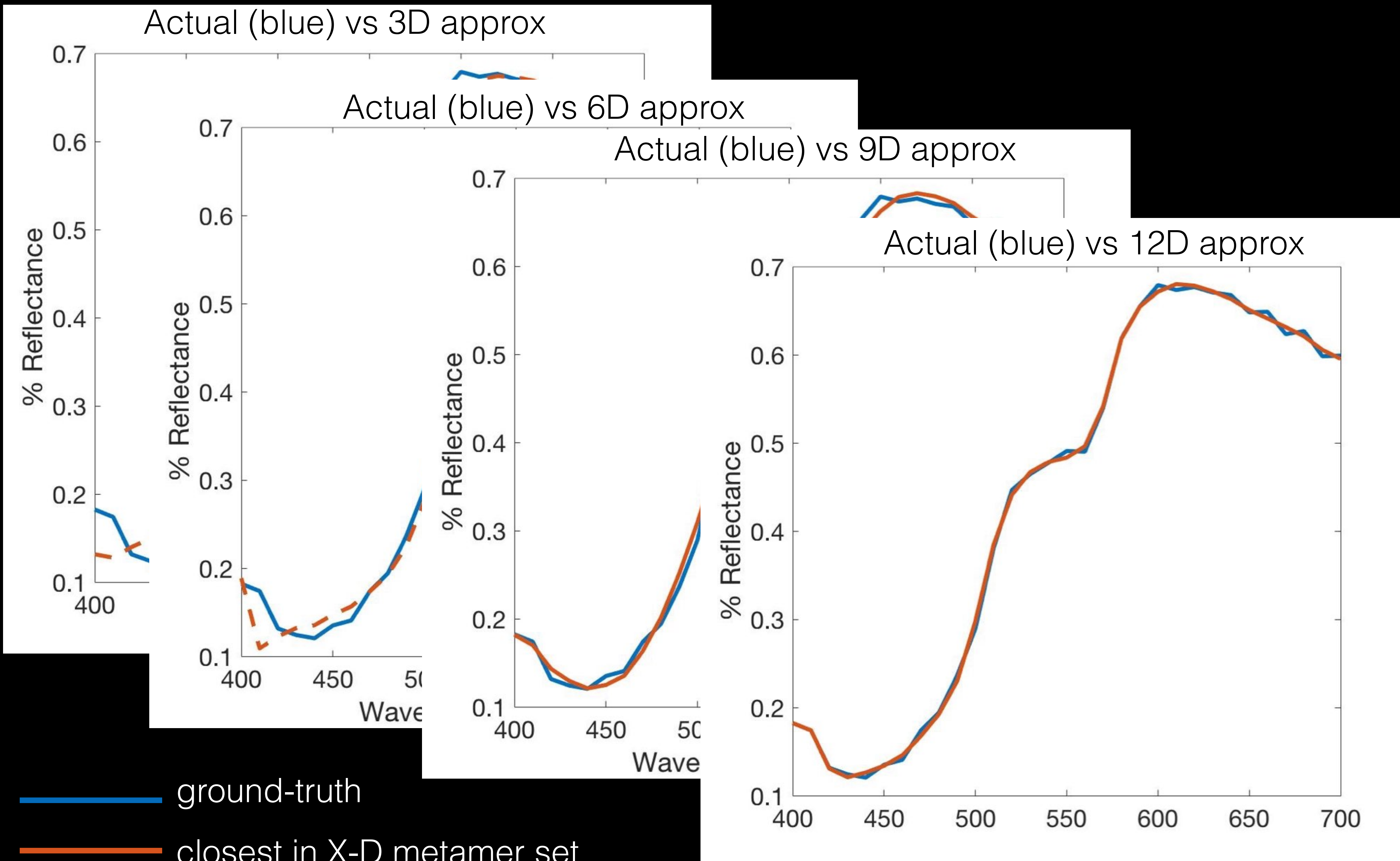
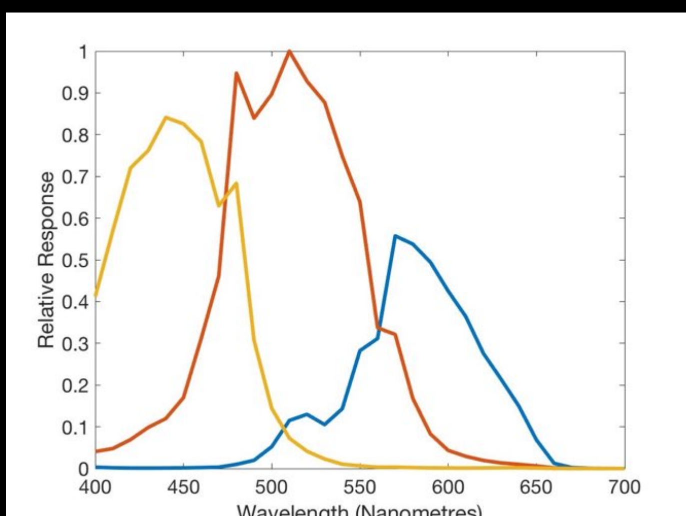


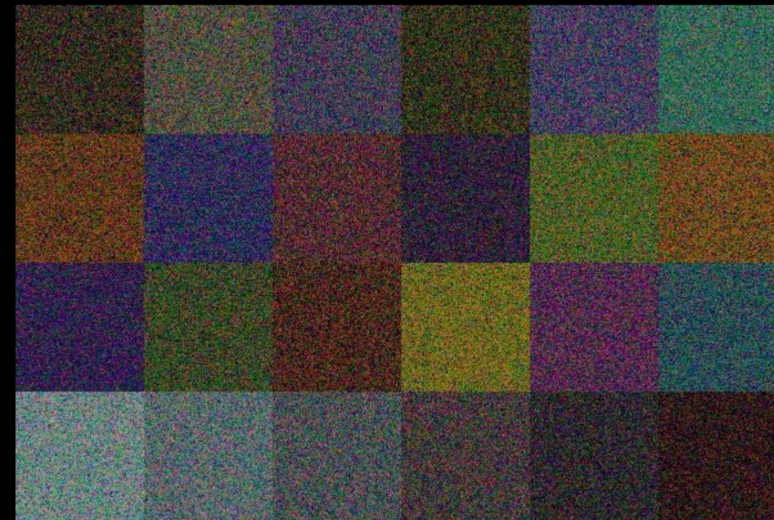
Variants on a theme

Noise: Example

1. Well capacity 50000 electrons
2. Between .1 and 200 photons/10Nm wavelength band
3. 10 bit quantization
4. Sensors scaled so one sensor at one wavelength captures 100% of the photons
5. Shot-noise (assumed normally distributed.



Canon D1
Spectral Sensitivities



What effect does noise have on the metamer set?

Intuitively, it becomes larger

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normal metamer set

$$\mathcal{R}_k \underline{S} = p_k \ , \ k \in \{R, G, B\}$$
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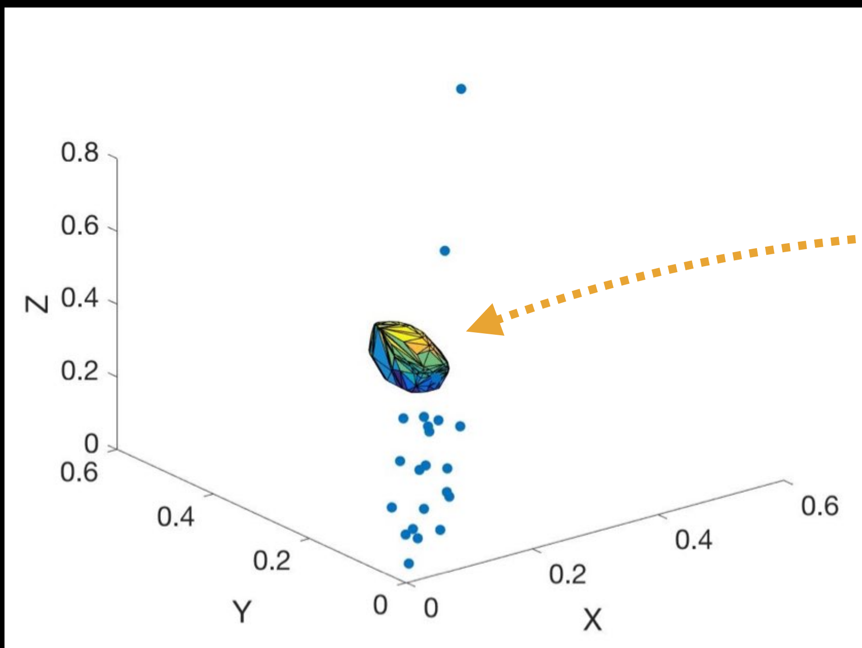
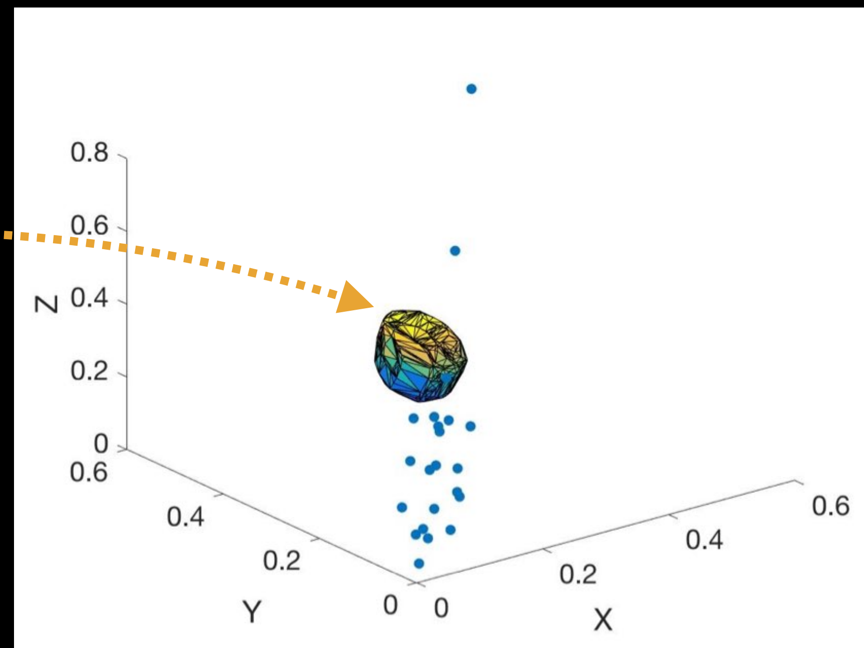
with ϵ noise

$$p_k - \epsilon \leq \mathcal{R}_k \underline{S} \leq p_k + \epsilon \ , \ k \in \{R, G, B\}$$
$$\underline{0} \leq \underline{S} \leq \underline{1}$$

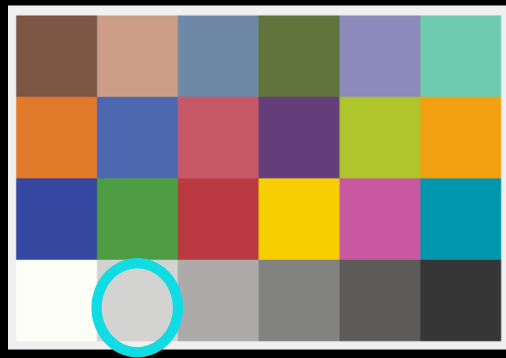
Noise



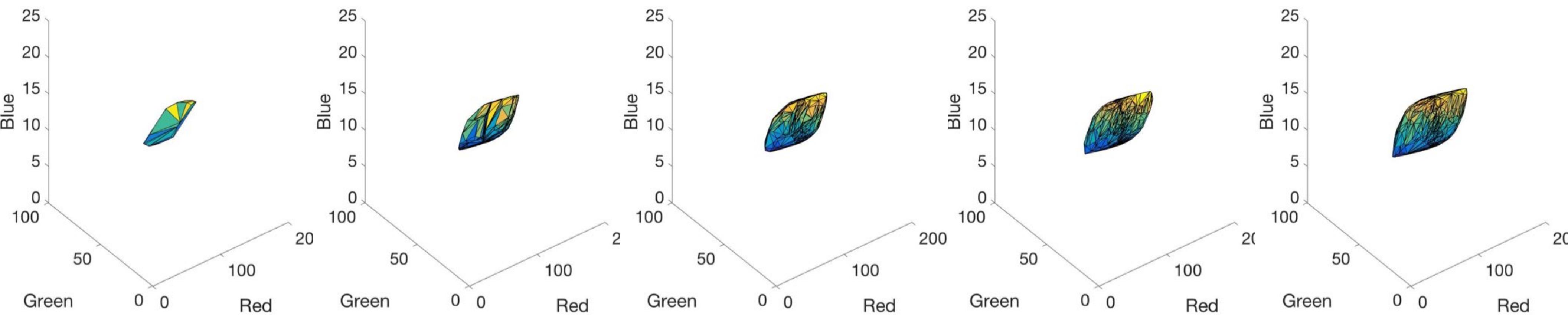


The ‘paramer’ set (computed with ~2% noise)
is 3* the volume of the noise free Metamer set

Noise vs Dimensionality

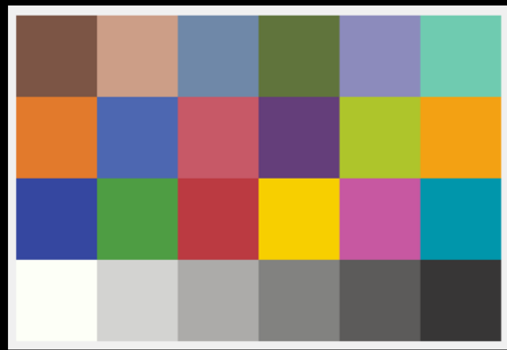


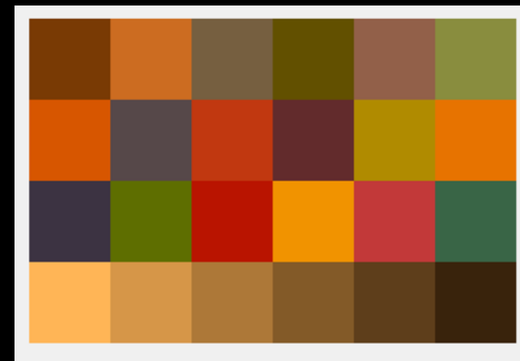
60% grey that maps to a single RGB could be the ‘projection of many metamers.
Under a second light the metamer set spans a set of possible RGBs

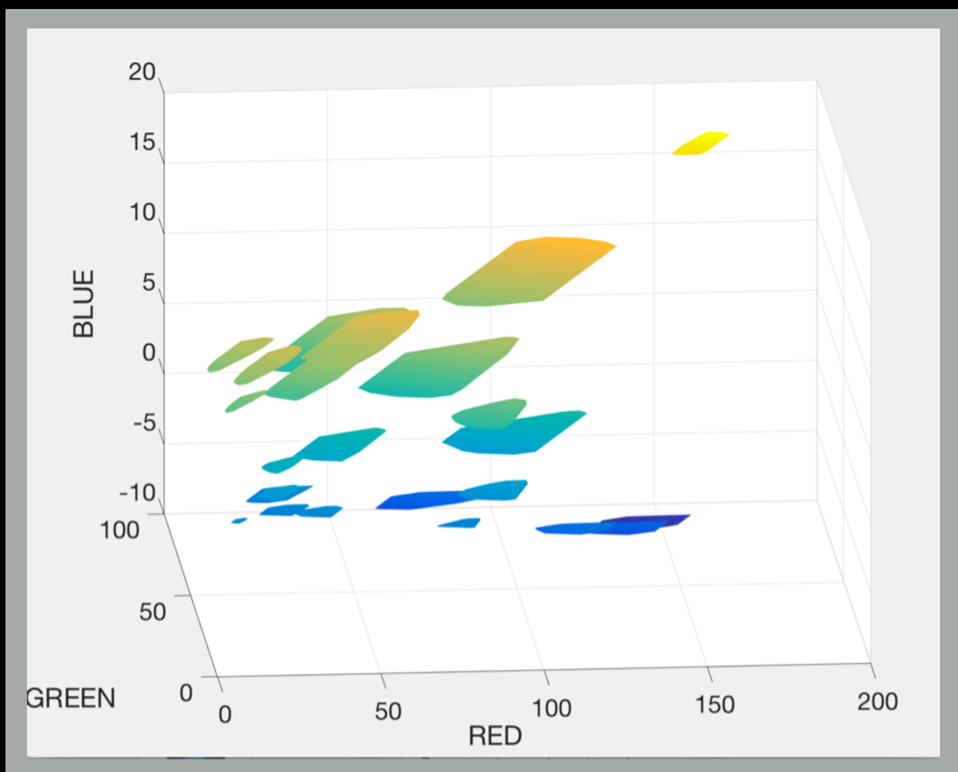


6 dimensional basis | 10 dimensional basis | 10 dimensional basis+noise | `all possible’ spectra | `all possible’ spectra+noise

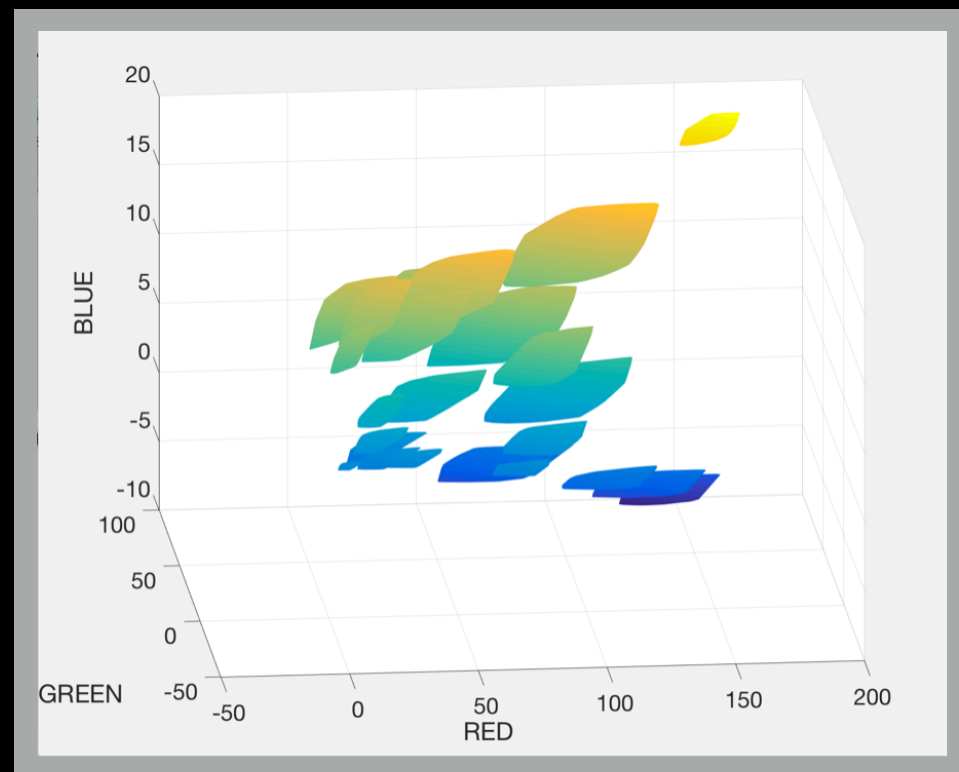
Invariant Metamer Sets





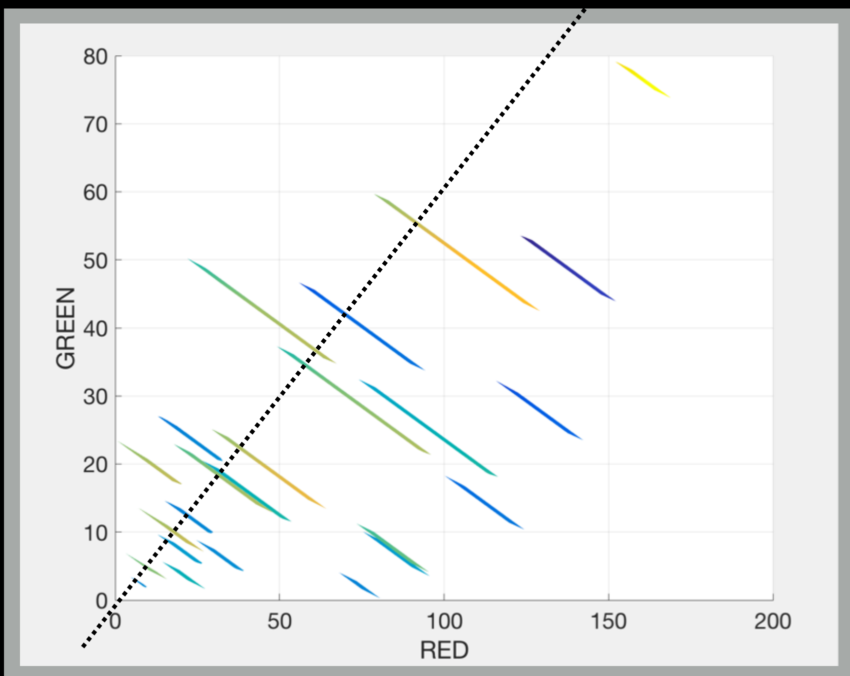


Metamer Set: 6 dimensional basis



Metamer Set: 10 dimensional basis

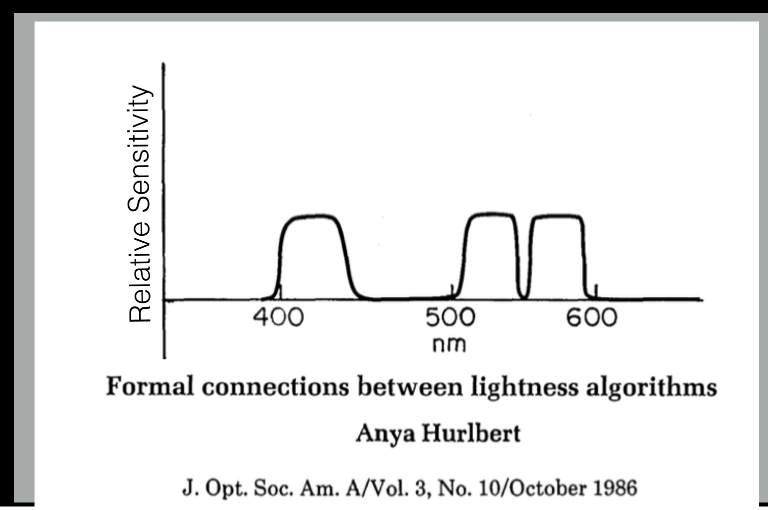
What are good sensors?



i) The projection in the 'luminance' direction has small metamer sets

ii) Possibly, given N>3 sensors, there are linear combinations which give RGB (sRGB?) with small metamer sets (use >3 sensors to get provably stable 3 sensor measurements)

iii) It can't just be about metamers. Below is an sensor set that has many of the same metamers for all lights



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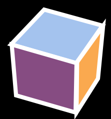

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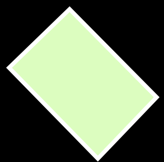

2) Reliably: what the 3 numbers ‘mean’ and how certain or uncertain they are (are you sure its not a road sign?)

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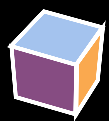

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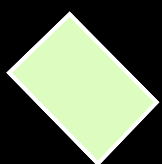

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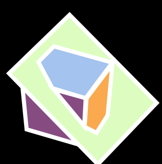

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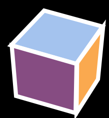

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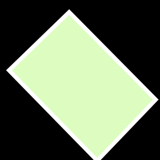

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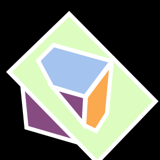

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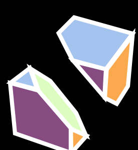

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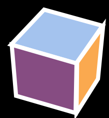

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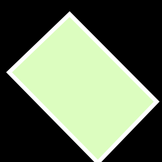

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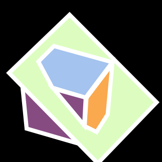

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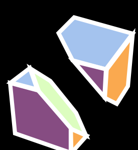

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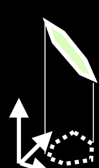

5) Next Steps? Metamer sets and other tools exist for answering a variety of questions. Example: “Metamer Constrained Colour Correction”