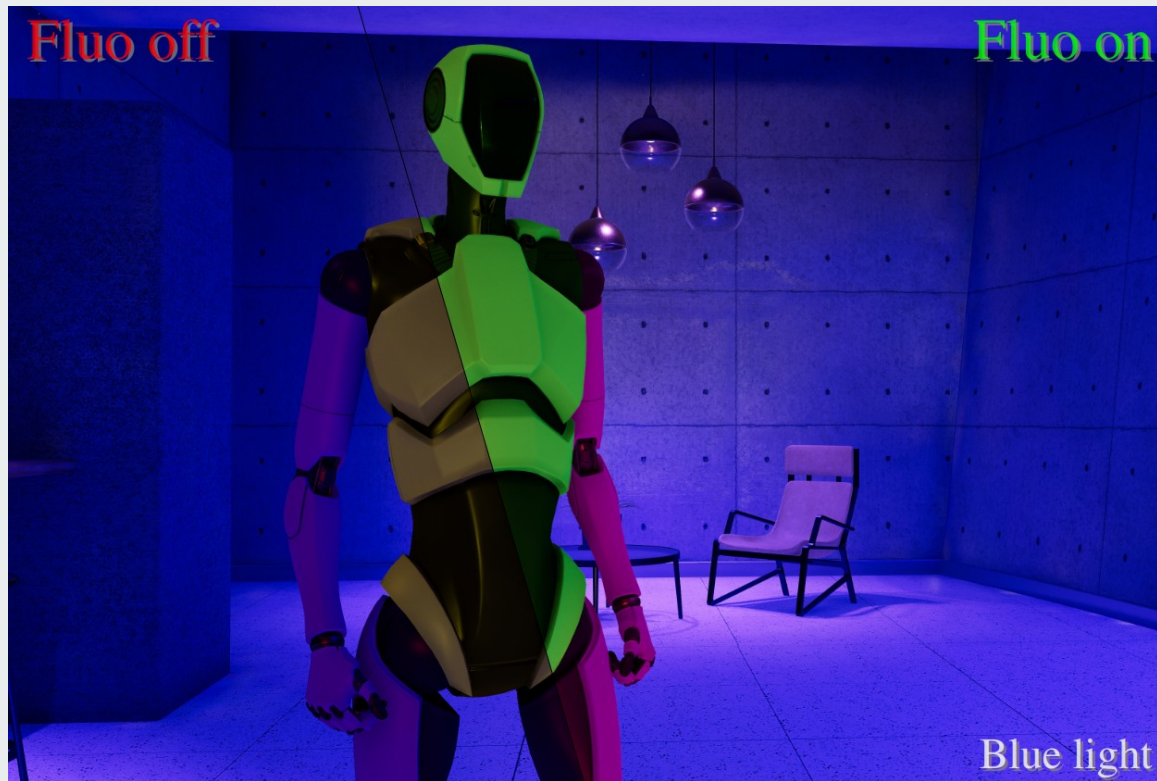


Non-Orthogonal Reduction for Rendering Fluorescent Materials in Non-Spectral Engines

A. Fichet, L. Belcour, P. Barla

GdL 10 Juillet 2024
Gaspard Thévenon

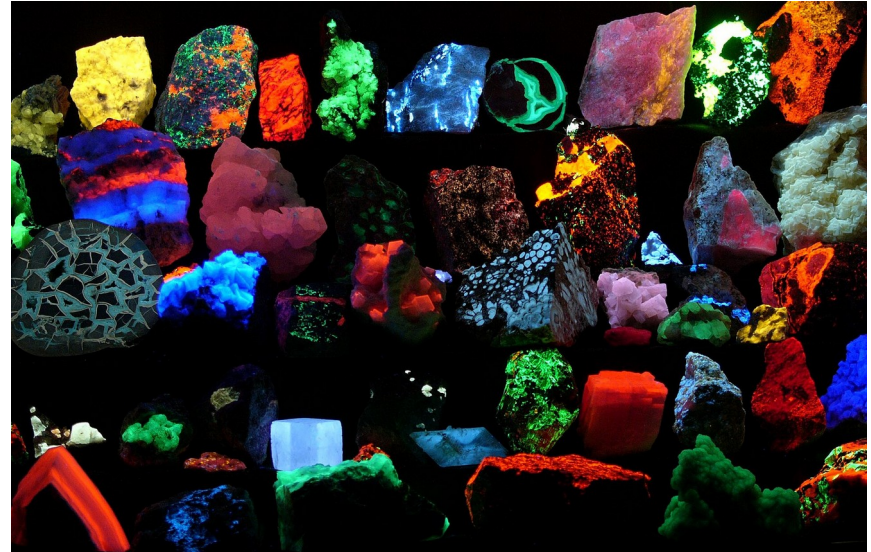


What is “fluorescence” ?

Standard materials, when lit at a wavelength λ , will only re-emit at this wavelength (with more or less intensity).

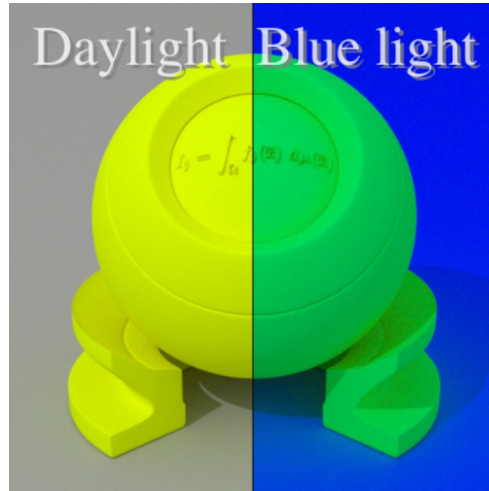


Fluorescent materials, when lit at a wavelength λ , can re-emit this energy at different wavelengths.

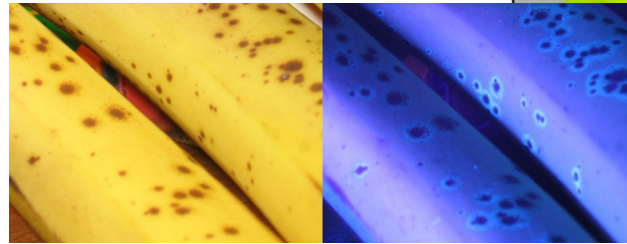


Visible effects of fluorescence

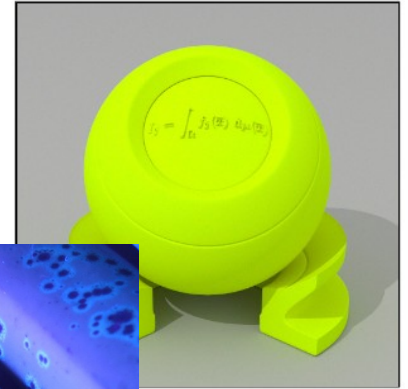
Two major visual effects of fluorescence:



Hue shift



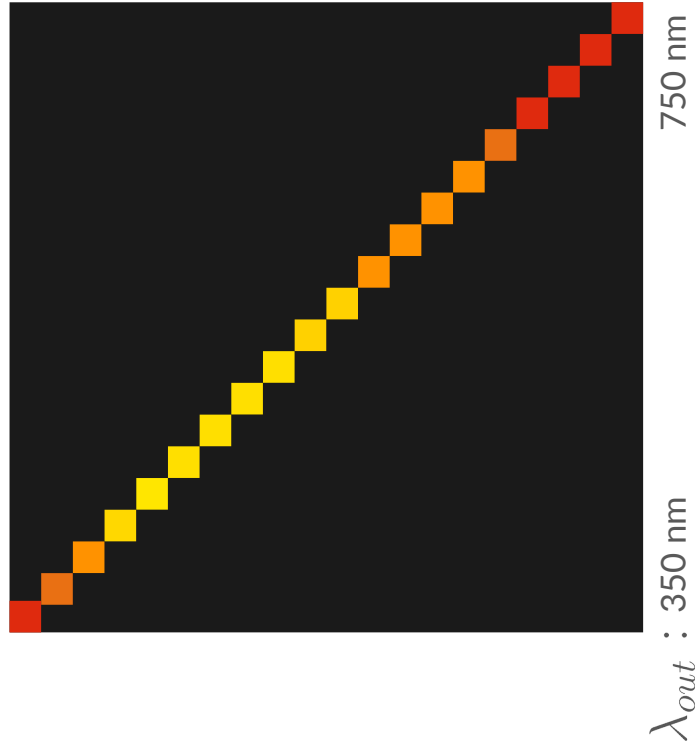
“Increased” brightness



Donaldson matrices

$\lambda_{in} : 350 \text{ nm}$

750 nm



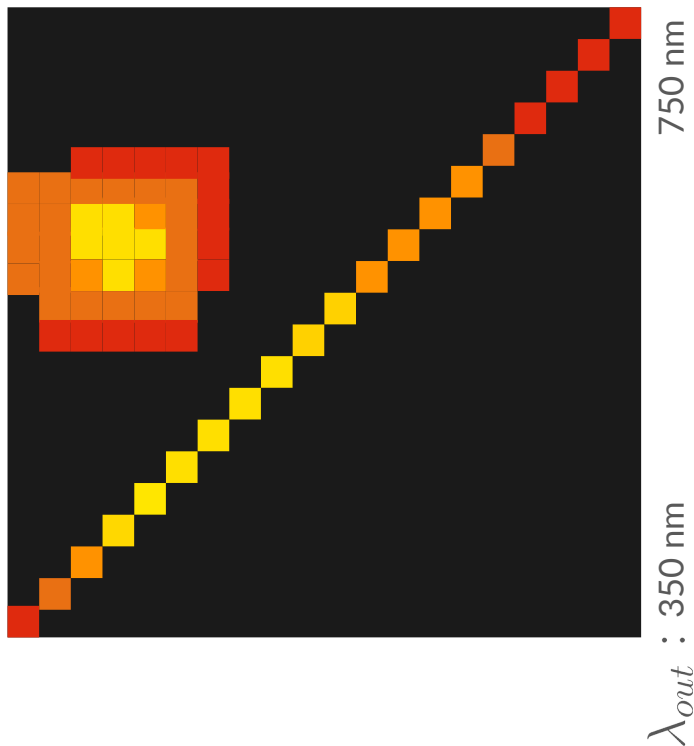
Represents a diffuse model

Non-fluorescent material:
only re-emits with input
wavelength

Donaldson matrices

$\lambda_{in} : 350 \text{ nm}$

750 nm

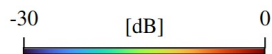
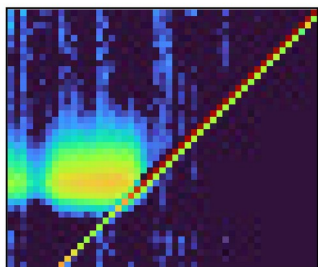
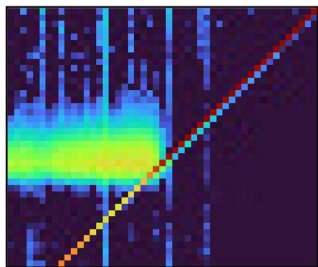


Fluorescent material:
for each input wavelength,
there's a spectral
distribution for the output

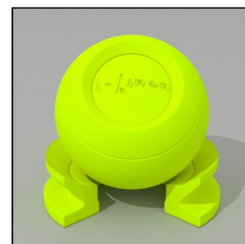
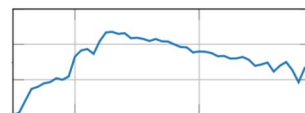
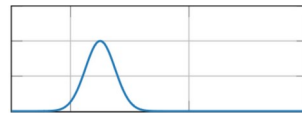
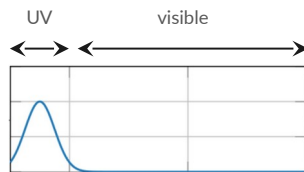
Real-life Donaldson matrices

IXCRLALE

TEXTYELL



Lighting:



Spectral rendering engines



Spectral engines compute a rendering with a discretization of the wavelength spectrum, not with RGB channels -> allows them to render wavelength-dependent phenomena, such as fluorescence.

Resolves the spectral rendering eq :

$$L_o(\omega_o, \lambda_o) = \iint \rho(\omega_i, \omega_o, \lambda_i, \lambda_o) L_i(\omega_i, \lambda_i) \langle \omega_i, \omega_n \rangle d\omega_i d\lambda_i$$

In the case of diffuse reflectance, we can use the Donaldson matrix for the BRDF:

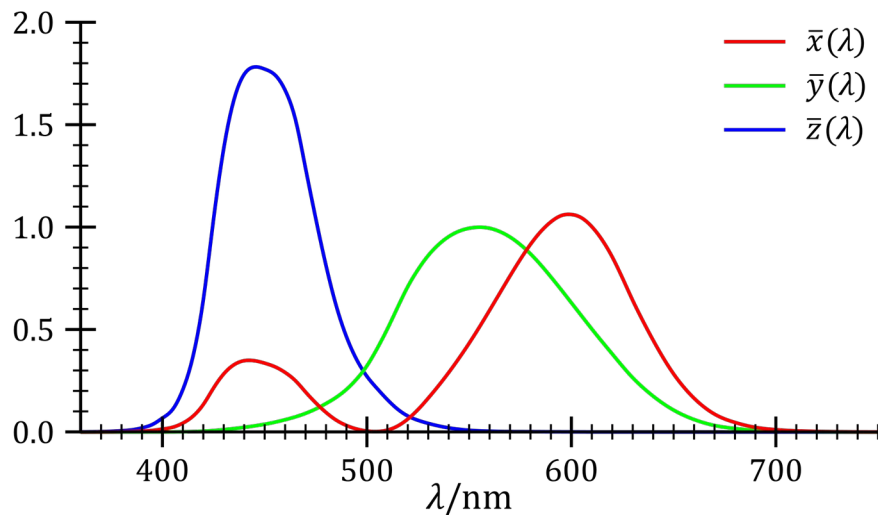
$$L_o(\omega_o, \lambda_o) = \int \frac{\mathcal{P}(\lambda_i, \lambda_o)}{\pi} \int L_i(\omega_i, \lambda_i) \langle \omega_i, \omega_n \rangle d\omega_i d\lambda_i$$

Spectral rendering engines



To transform the spectral distribution back into XYZ channels, standard **Color Matching Functions (CMFs)** are used: the product of the spectrum with each of the CMFs is integrated.

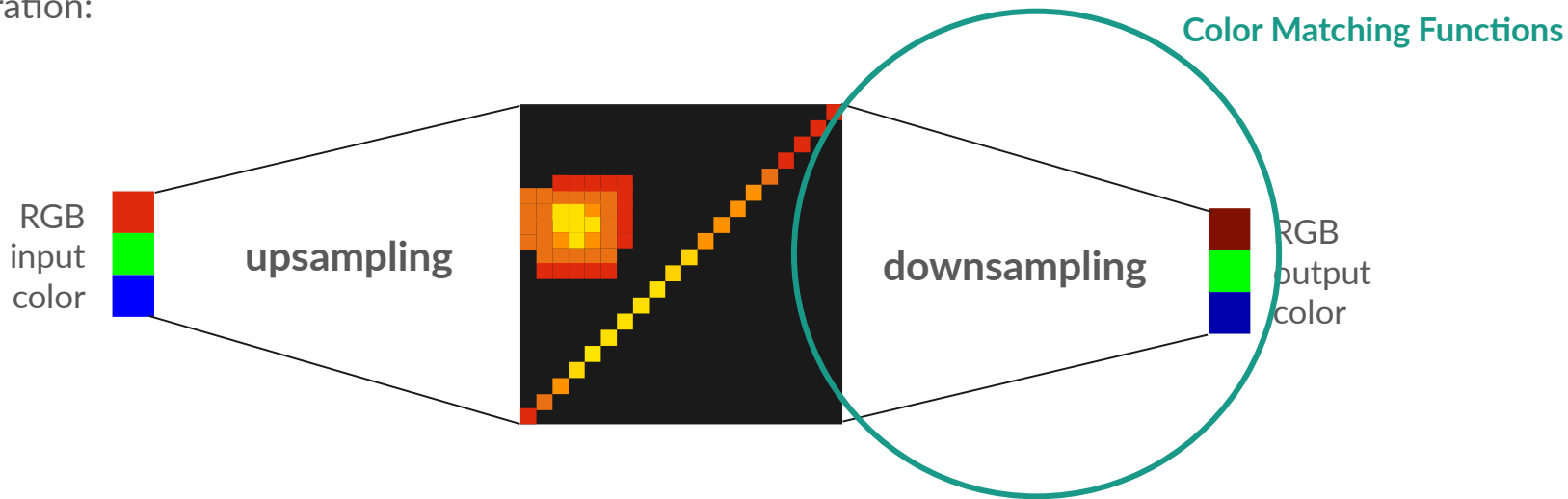
$$\mathbf{c}_o(\omega_o) = \int L_o(\omega_o, \lambda_o) \mathbf{s}(\lambda_o) d\lambda_o$$



Looks like everything works, so what's wrong ?

Most renderers are non-spectral. The objective of the article is to render fluorescent materials, but only using RGB channels.

It means that we need to encode an upsampling and downsampling step into a simple RGB operation:



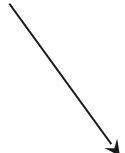
Idea of the general approach

The idea is to have a 3x3 kernel: $c_{out} = P_{rgb} \times c_{in}$

computed from the Donaldson NxN matrix of the material, composited with Nx3 and 3xN matrices independent of the material:

$$\mathbf{c}_o = \mathbf{down} \left[\int \frac{\mathcal{P}(\lambda_i, \lambda_o)}{\pi} \int \mathbf{up}[\mathbf{c}_i](\lambda_i) \langle \omega_i, \omega_n \rangle d\omega_i d\lambda_i \right]$$

$$P_{rgb} = A \times P \times B$$


$$\mathbf{down}[f]_k = \int f(\lambda_o) s_k(\lambda_o) d\lambda_o$$

$$\mathbf{down}[\mathbf{f}] = S^T \times \mathbf{f}$$

Previous work

Acquisition and Analysis of Bispectral Bidirectional Reflectance and Radiation Distribution Functions

Mathias B. Hullin¹ Johannes Hanika² Boris Ajdin² Hans-Peter Seidel¹ Jan Kautz² Hendrik P. A. Lensch²
¹MPI Informatik ²Ulm University ³University College London

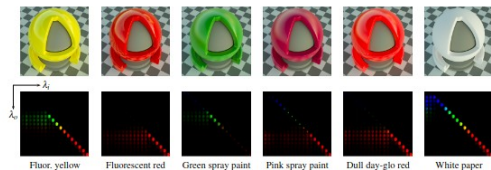


Figure 1: Fluorescent materials absorb part of the incoming light at wavelength λ_i and reradiate it at the longer wavelength λ_r . We have measured bispectral BRDFs to capture such materials and render them in the spectral environment map of a winter sunset. The bottom row depicts slices of the bispectral BRDF, showing one rendered sphere for each pair of incident and reflected or reradiated wavelengths $(\lambda_i, \lambda_r) \in [400\text{nm}; 720\text{nm}] \times [380\text{nm}; 720\text{nm}]$. Fluorescence is represented by the off-diagonal entries.

Abstract

In fluorescent materials, light from a certain band of incident wavelengths is reradiated at longer wavelengths, i.e., with a reduced per-photon energy. While fluorescent materials are common in everyday life, they have received little attention in computer graphics. Especially, no bidirectional irradiance measurements of fluorescent materials have been available so far. In this paper, we extend the well-known concept of the bidirectional reflectance distribution function (BRDF) to account for energy transfer between wavelengths, resulting in a *Bispectral Bidirectional Reflectance and Radiation Distribution Function (Bispectral BRDRF)*. Using a bidirectional and bispectral measurement setup, we acquire reflectance and radiation data of a variety of fluorescent materials, including vehicle paints, paper and fabric, and compare their renderings with RGB, RGB+RGB, and spectral BRDFs. Our acquisition is guided by a principal component analysis on complete bispectral data taken under a sparse set of angles. We show that in order to faithfully reproduce the full bispectral information for all other angles, only a very small number of wavelength pairs needs to be measured at a high angular resolution.

CR Categories: I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture—Reflectance;

I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture;

Keywords: fluorescence, spectral BRDF, bispectral BRDRF, bispectral rendering

1 Introduction

Fluorescent materials change the wavelength of light upon reflection. This applies to many everyday materials, for instance human

teeth, utility vehicle paints, detergents (fabric whiteners), or even ordinary photocopying paper. This shift of wavelength causes compelling visual effects if it occurs within the visible spectrum or turns UV radiation into visible light. In particular, many fluorescent surfaces appear brighter than perfectly white surfaces (Figure 2).

The underlying physical mechanism is well understood. A fluorescent medium consists of atoms or molecules that absorb incident photons at a given wavelength, and re-emit them after a short time (in the order of 10^{-8} s). During this time interval, the electrons of the fluorescent molecule remain in an excited state above the ground energy level. The re-emission of a photon occurs as the fluorophore relaxes to its ground state. Due to mechanical interaction with the surrounding molecules, some of the excitation energy is lost during this process, leading to a change of wavelength, or Stokes shift. As required for conservation of energy, except in the case of multi-photon interactions, this shift always occurs towards longer wavelengths, corresponding to a loss in per-photon energy.

The wavelength-shifting behavior of a fluorescent material can be intuitively described *hypercolor* using a so-called *reradiation matrix* (Donaldson 1954), specifying for each combination of incoming and outgoing wavelengths the amount of reradiated light. At

“Acquisition and Analysis of Bispectral Bidirectional Reflectance and Reradiation Distribution Functions”, Hullin et al, 2010

Suggests to use: $P_{rgb} = \bar{S}^T P \bar{S}$

with $\bar{S} = [\bar{s}_r, \bar{s}_g, \bar{s}_b]$



normalized CMFs

Previous work

Acquisition and Analysis of Bispectral Bidirectional Reflectance and Radiation Distribution Functions

Mathias B. Hullin¹ Johannes Hanika² Boris Ajdin² Hans-Peter Seidel¹ Jan Kautz² Hendrik P. A. Lensch³
¹MPI Informatik ²Ulm University ³University College London

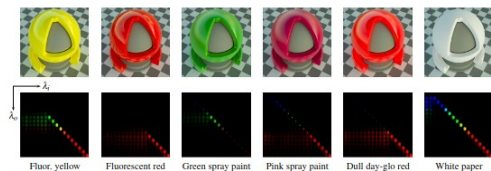


Figure 1: Fluorescent materials absorb part of the incoming light at wavelength λ_i and reradiate it at the longer wavelength λ_o . We have measured bispectral BRDFs to capture such materials and render them in the spectral environment map of a winter sunset. The bottom row depicts slices of the bispectral BRDF, showing one rendered sphere for each pair of incident and reflected or reradiated wavelengths $(\lambda_o, \lambda_i) \in [400\text{nm}; 720\text{nm}] \times [380\text{nm}; 720\text{nm}]$. Fluorescence is represented by the off-diagonal entries.

Abstract

In fluorescent materials, light from a certain band of incident wavelengths is reradiated at longer wavelengths, i.e., with a reduced per-photon energy. While fluorescent materials are common in everyday life, they have received little attention in computer graphics. Especially, no bidirectional irradiance measurements of fluorescent materials have been available so far. In this paper, we extend the well-known concept of the bidirectional reflectance distribution function (BRDF) to account for energy transfer between wavelengths, resulting in a *Bispectral Bidirectional Reflectance and Radiation Distribution Function* (Bispectral BRDF). Using a bidirectional and bispectral measurement setup, we acquire reflectance and radiation data of a variety of fluorescent materials, including vehicle paints, paper and fabric, and compare their renderings with RGB, RGB+K, and spectral BRDFs. Our acquisition is guided by a principal component analysis on complete bispectral data taken under a sparse set of angles. We show that in order to faithfully reproduce the full bispectral information for all other angles, only a very small number of wavelength pairs needs to be measured at a high angular resolution.

CR Categories: I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture—Reflectance;

I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture;

Keywords: fluorescence, spectral BRDF, bispectral BRDF, bispectral rendering

1 Introduction

Fluorescent materials change the wavelength of light upon reflection. This applies to many everyday materials, for instance human

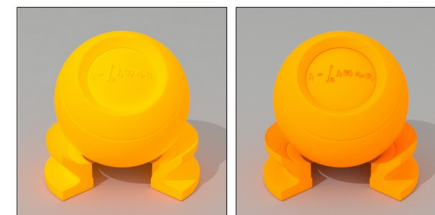
teeth, utility vehicle paints, detergents (fabric whiteners), or even ordinary photocopying paper. This shift of wavelength causes competing visual effects if it occurs within the visible spectrum or turns UV radiation into visible light. In particular, many fluorescent surfaces appear brighter than perfectly white surfaces (Figure 2).

The underlying physical mechanism is well understood. A fluorescent medium consists of atoms or molecules that absorb incident photons at a given wavelength, and re-emit them after a short time (in the order of 10^{-8} s). During this time interval, the electrons of the fluorescent molecule remain in an excited state above the ground energy level. The re-emission of a photon occurs as the fluorophore relaxes to its ground state. Due to mechanical interaction with the surrounding molecules, some of the excitation energy is lost during this process, leading to a change of wavelength, or Stokes shift. As required for conservation of energy, except in the case of multi-photon interactions, this shift always occurs towards longer wavelengths, corresponding to a loss in per-photon energy.

The wavelength-shifting behavior of a fluorescent material can be intuitively described *hypercolor* using a so-called *reradiation matrix* (Donaldson 1954), specifying for each combination of incoming and outgoing wavelengths the amount of reradiated light. At

“Acquisition and Analysis of Bispectral Bidirectional Reflectance and Reradiation Distribution Functions”, Hullin et al, 2010

Issue : it doesn't work



(a) Naive Reduction

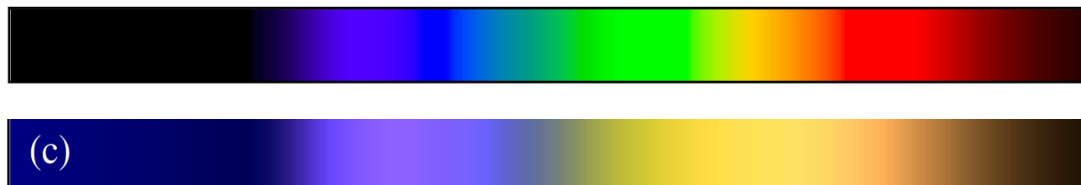
(b) Spectral Reference

Conclusion of the article: we need spectral rendering for fluorescent materials.

Issue with this naive approach

There is creation of unwanted energy. This is visible even for an identity Donaldson matrix:

$$\bar{S}^T \bar{S} \neq I_3$$



The CMFs matrix is not orthogonal. Applying it like this doesn't preserve the light spectrum.

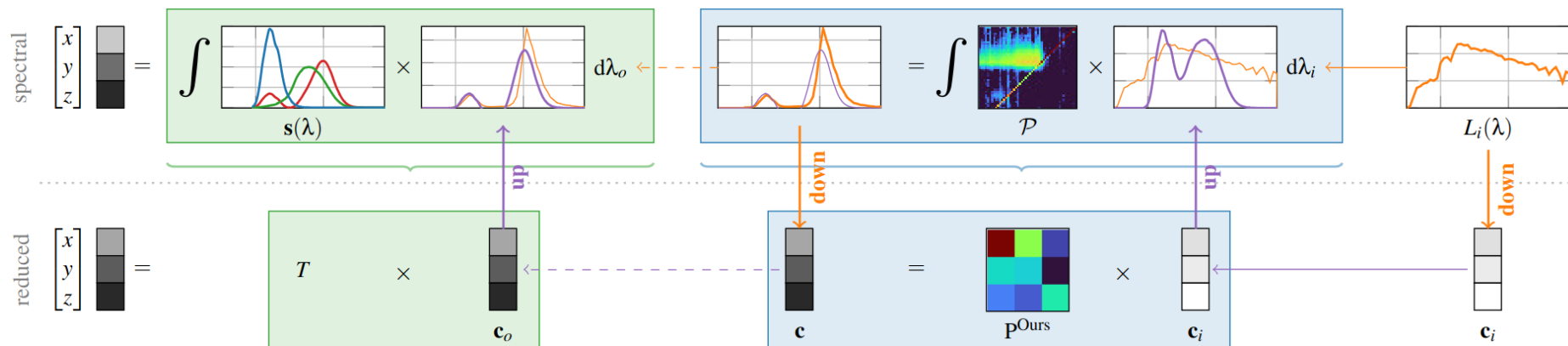
Solution for non-orthogonal CMFs

This motivates to take the upsampling matrix

as the matrix of the dual set of the CMFs: $\tilde{S} = (SS^T)^{-1}S$

yielding $S^T \tilde{S} = I_3$

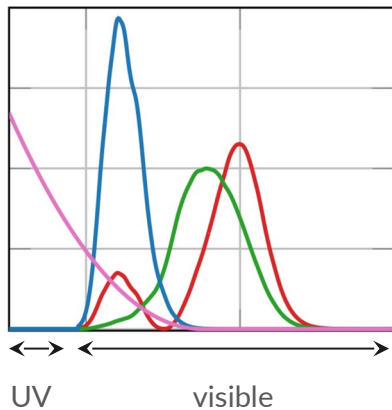
Pipeline for the study



orange: exact spectral distribution
purple: distribution estimated with their process

T is a matrix to transform the color basis into XYZ/RGB (for now, 3x3 identity)

Incorporating UV



They add a 4th curve to the CMFs, to take UVs into account.

Then, 4 components are used (XYZU).

For the final rendering, the last component is dropped.



(a) XYZ basis

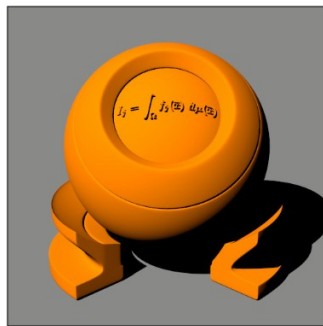


(b) XYZU basis

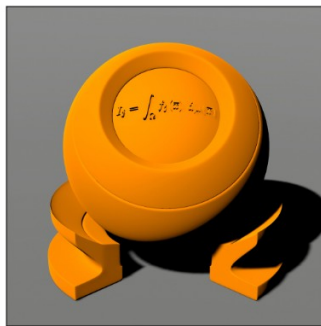


(c) Spectral Reference

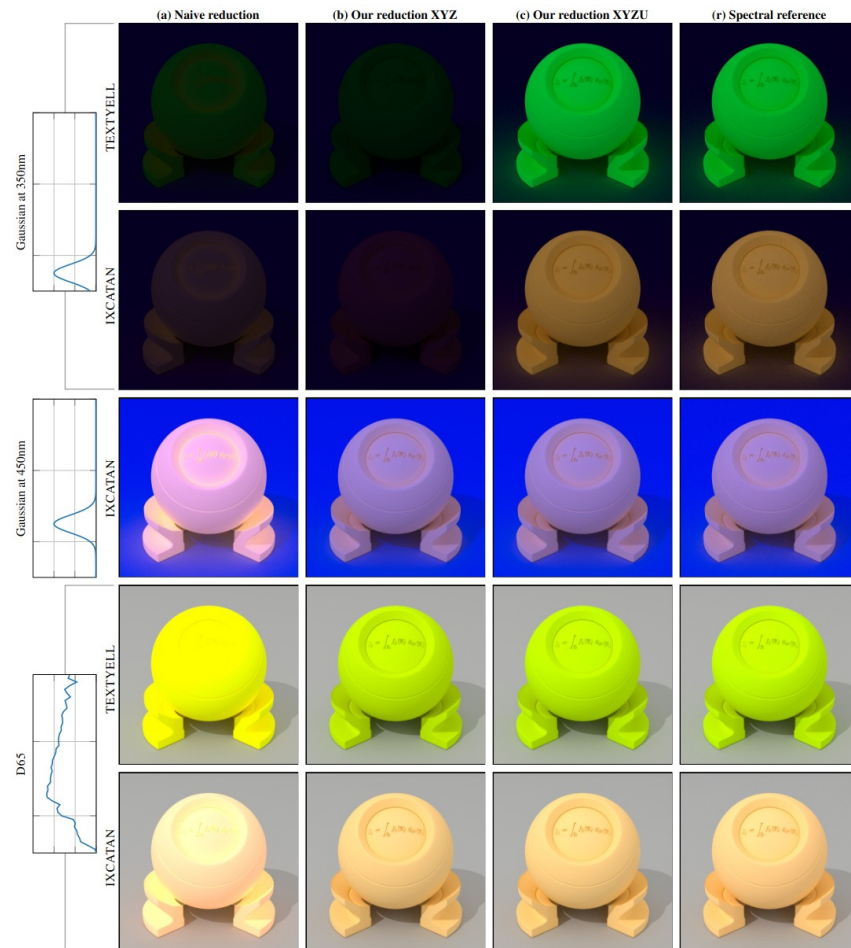
Comparison to a spectral reference



(a) Path traced



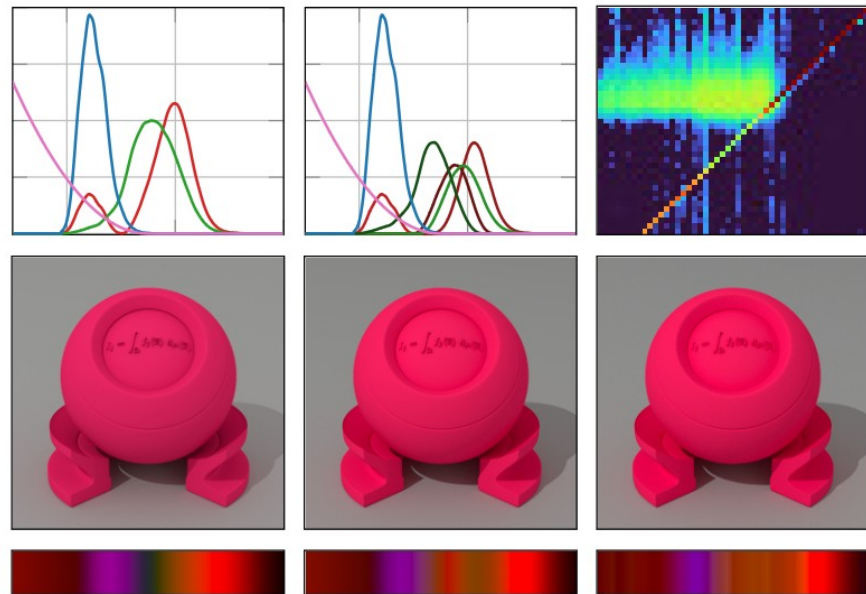
(b) Unity rendering



Limitations and future work

This method introduces approximation for light transports that are not generated by these basis functions.

In some cases, to be more faithful, one has to use alternative bases/more basis functions.



(a) Ours (4 bands)

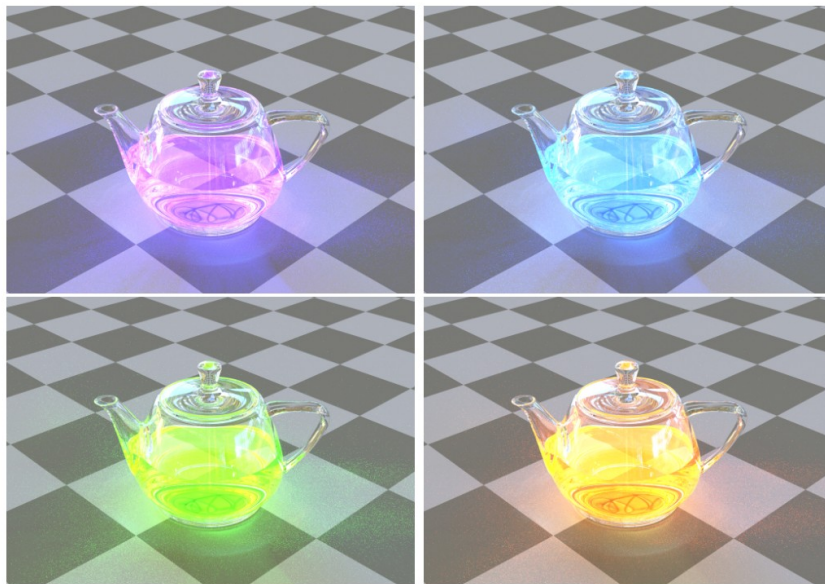
(b) Ours (7 bands)

(c) Spectral Reference

Limitations and future work

This method can't be applied for glossy fluorescent materials, where fluorescence is dependent on the incident angle,

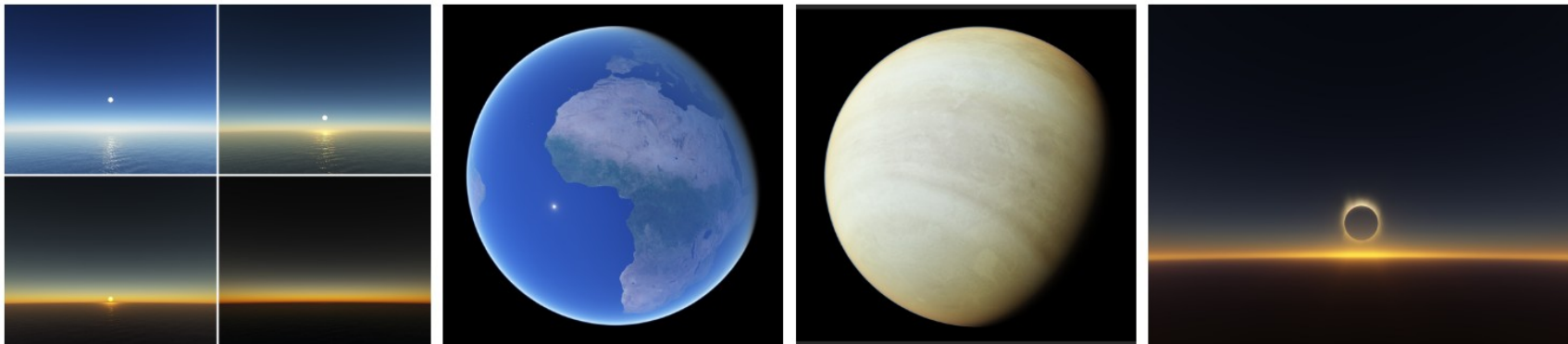
like the fluorescence BDSF models using the micro-facet theory.



Limitations and future work

Maybe, could also be applied to render other spectral-dependent phenomena (when directional/spectral dimensions are independent), such as rendering of atmosphere/water.

Could also be applied to fluorescence measurements, given we only ask for the 3x3 kernel.





Questions ?