

ATTENUATION-BASED LIGHT FIELD DISPLAYS

Bachelor Thesis

Adrian Wälchli

June 3, 2016

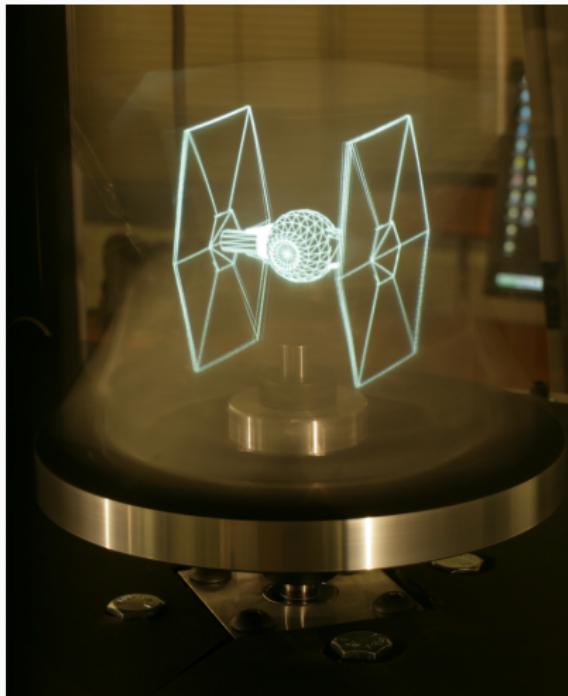
Institut für Informatik und angewandte Mathematik

OUTLINE

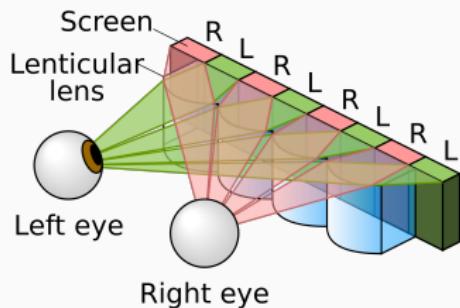
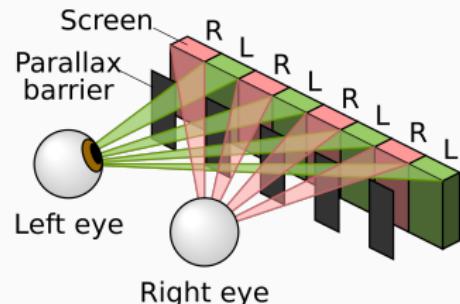
1. Introduction
2. Light Fields
3. Attenuation Display
4. Spectral Analysis

INTRODUCTION

EXISTING 3D DISPLAYS



Jones et al. [2007]



en.wikipedia.org/wiki/Autostereoscopy

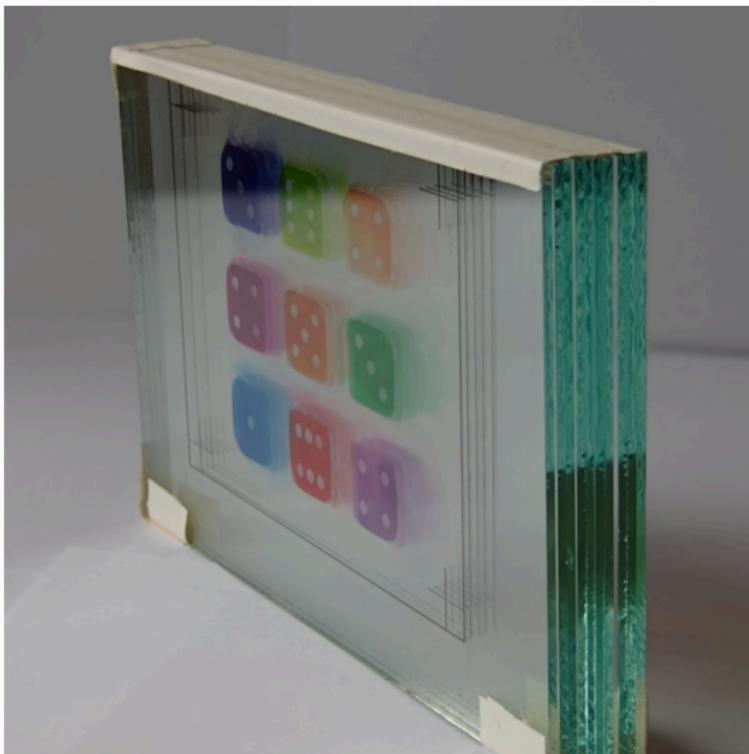
EXISTING 3D DISPLAYS



EXISTING 3D DISPLAYS



TODAY...



Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

Wetzstein et al. [2011]

Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

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Figure 1: Reconstructing a glass-free light field display using volumetric attenuation. (Left) A stack of optical light modulators (e.g., printed masks) reconstructs a target light field (here for a car) when illuminated by a lightfield. (Right) The target light field is shown in the upper left, together with the optimal five-layer decomposition, obtained with iterative tomographic reconstruction. (Middle) Optique projections for a viewer standing to the top left (magenta) and bottom right (cyan). Corresponding views of the target light field and five-layer prestige are shown on the left and right, respectively. Each attenuation-based 3D display allows accurate depth-resolution depiction of vector particles, occlusion, transmittance, and specularity, being exhibited in the front, the window, and the end of the road, respectively.

1 Introduction

We develop tomographic techniques for image synthesis on displays composed of compact volumes of light-absorbing material. Such attenuated attenuators reconstruct a 3D light field, according to the way it would have been observed by a lightfield. Since arbitrary oblique views may be inimicable with any single attenuator, iterative tomographic reconstruction minimizes the difference between the observed light field and the reconstructed light field, starting on attenuation. As multi-layer generalizations of conventional parallel barriers, such displays are shown, both by theory and experiment, to support depth, transmittance, and specularity architectures. For 3D display, spatial resolution, depth of field, and brightness are increased compared to parallel barriers. For a plane at 3 m, we show that our displays can support a resolution of 1000 × 1000 pixels, a depth of 10 cm, and a dynamic range of 1000:1 for high dynamic range displays, extending existing boundaries and providing the first extension to multiple, distinct layers. We consider two fabrication methods for these displays: direct inkjet-based light field displays using an inexpensive fabrication method; separating multiple printed incompatibles with acrylic sheets.

Keywords: computational displays, light fields, autostereoscopic 3D displays, high dynamic range displays, tomography

Links: DOI PDF WWW Vimeo

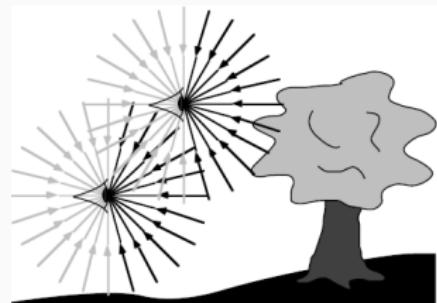
3D displays are designed to replicate as many perceptual depth cues as possible. As surveyed by Lipton [1982], these cues can be classified into three main categories: binocular disparity, motion parallax, and motion blur. Researchers have explored numerous cues, including perspective, shading, and occlusion, to obtain the illusion of depth with 2D images. Including motion parallax and accommodation, existing 2D displays are limited in their field of view and resolution. As a result, 3D displays are designed to provide the lacking binocular cues of disparity and convergence, along with these missing monocular cues. Current 3D displays preserve disparity, but require special eyewear to do so. In contrast, our displays are autostereoscopic, meaning that no monocular display replicates disparity and motion parallax without encumbering the viewer. As categorized by Frahera [2005], our displays fall under the category of volumetric displays. In addition, they are similar to volume rendering [Kao and Kao 1998] and integral imaging [Lippmann 1908], volumetric displays [Bhandal and Schatzke 1996], and holograms [Slinger et al. 1998]. However, our displays are different from these in that they are primarily restricted to static scenes viewed under controlled illumination [Klig et al. 2001]. Research is addressing these issues [Kao and Kao 1998; Kao et al. 2000; Kao et al. 2001]. Our displays remain practical alternatives utilizing well-established, low-cost fabrication. Furthermore, volumetric displays can replicate similar depth cues with faster free refresh rates [Frahera 2005].

This paper continues our work on autostereoscopic displays, complementing our work on light-field displays, which we dub “Layered 3D” displays. Differing from volumetric displays with light-emitting layers, overlaid attenuation patterns allow objects to appear in front of or behind other objects, supporting depth, transmittance, parallel, occlusion, and specularity. While our theoretical contributions apply equally well to dynamic displays, such as stacks of liquid crystal panels, we focus on static displays. This paper is organized to demonstrate the principles of tomographic image synthesis. Specifically, we produce multi-layer attenuators using 2D printed transparencies, separated by acrylic sheets (see Figures 1 and 2).

LIGHT FIELDS

THE PLENOPTIC FUNCTION

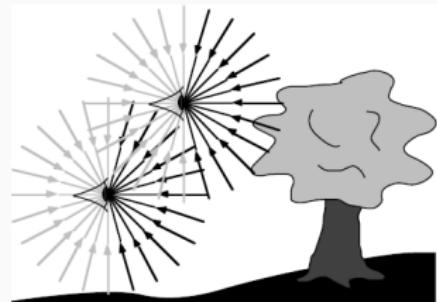
- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

THE PLENOPTIC FUNCTION

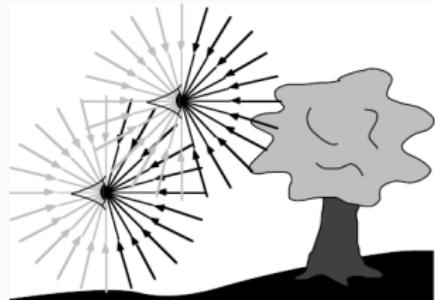
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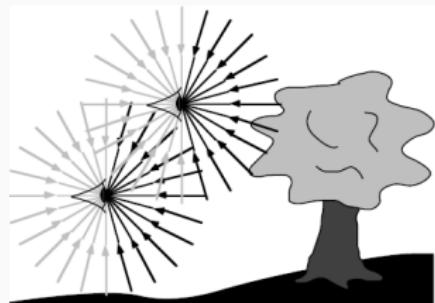
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THE PLENOPTIC FUNCTION

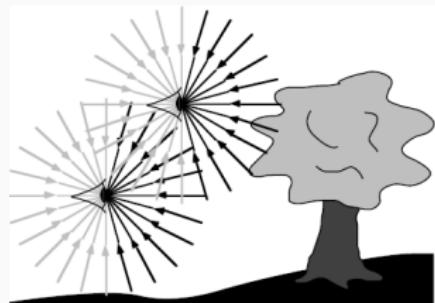
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Adelson and Bergen [1991]

THE PLENOPTIC FUNCTION

- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

THE 4D LIGHT FIELD

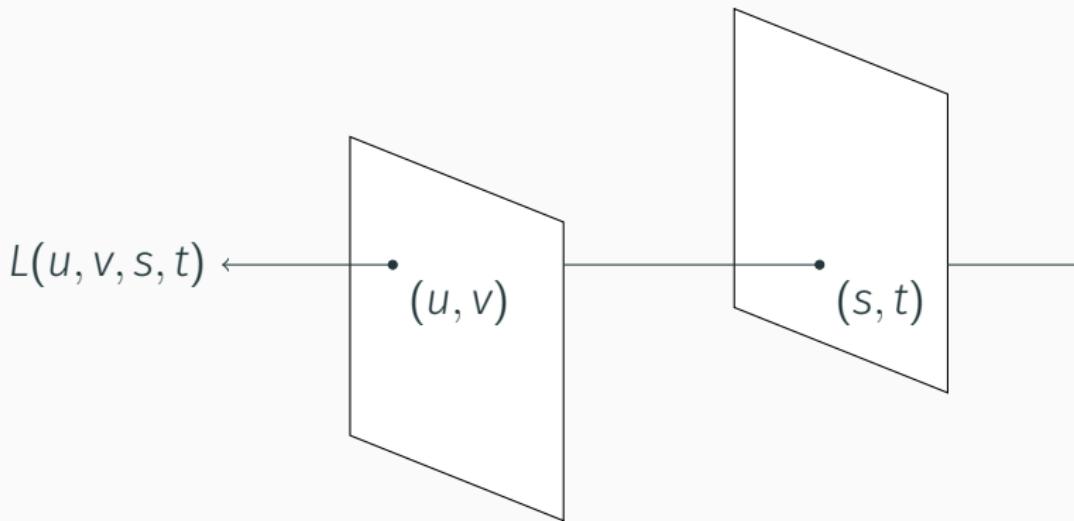
- Reduce dimensions of P
- $L(u, v, s, t)$
- Defined by two planes

THE 4D LIGHT FIELD

- Reduce dimensions of P
- $L(u, v, s, t)$
- Defined by two planes

THE 4D LIGHT FIELD

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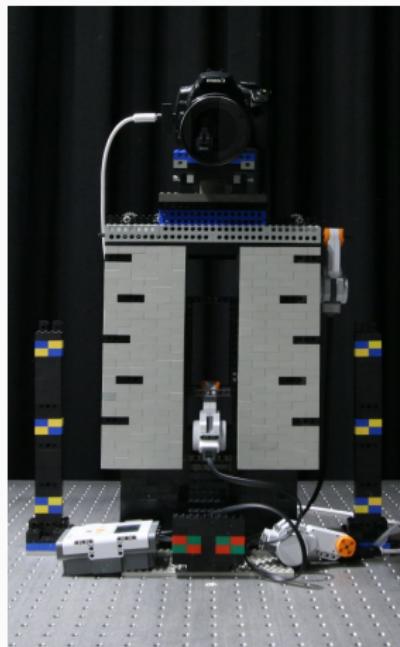


LIGHT FIELD ACQUISITION



Stanford camera array. Source: lightfield.stanford.edu

LIGHT FIELD ACQUISITION



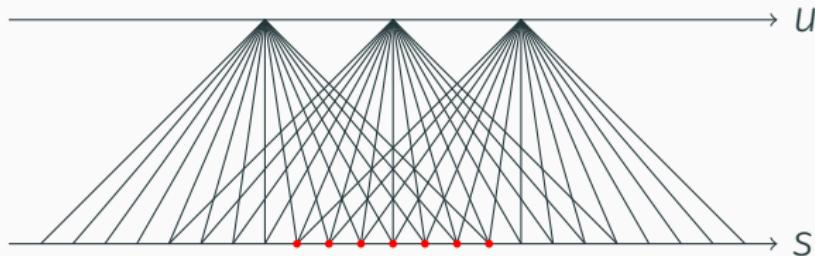
Lego gantry. Source: lightfield.stanford.edu

LIGHT FIELD ACQUISITION

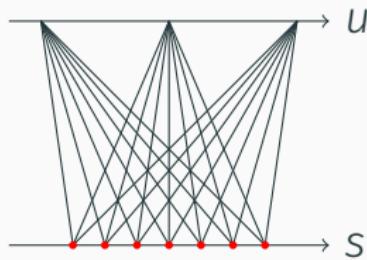
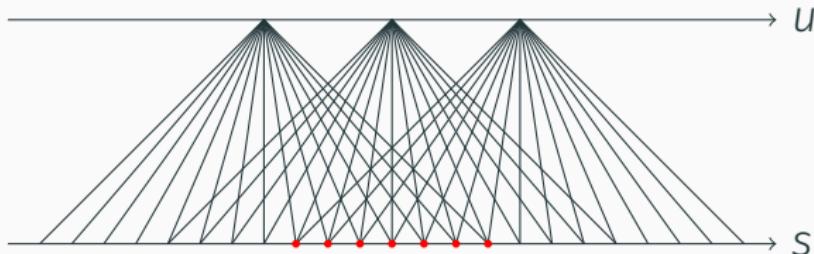


Lytro plenoptic camera. Source: de.wikipedia.org/wiki/Lytro

RE-PARAMETERIZATION TO GLOBAL COORDINATES



RE-PARAMETERIZATION TO GLOBAL COORDINATES



RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw



Rectified



RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw

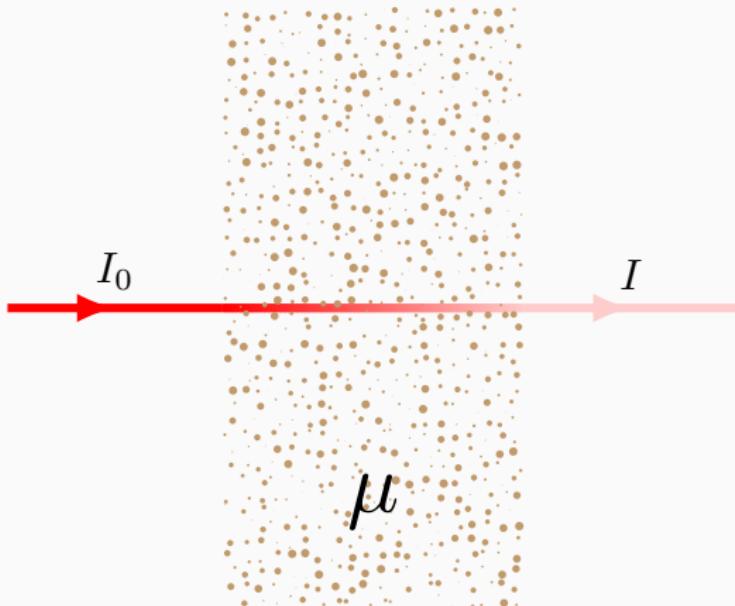


Rectified



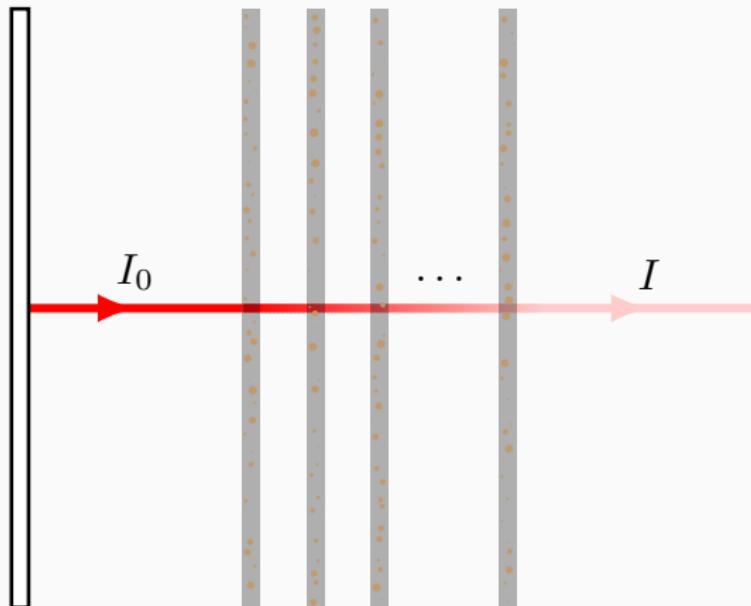
ATTENUATION DISPLAY

THE BEER-LAMBERT LAW



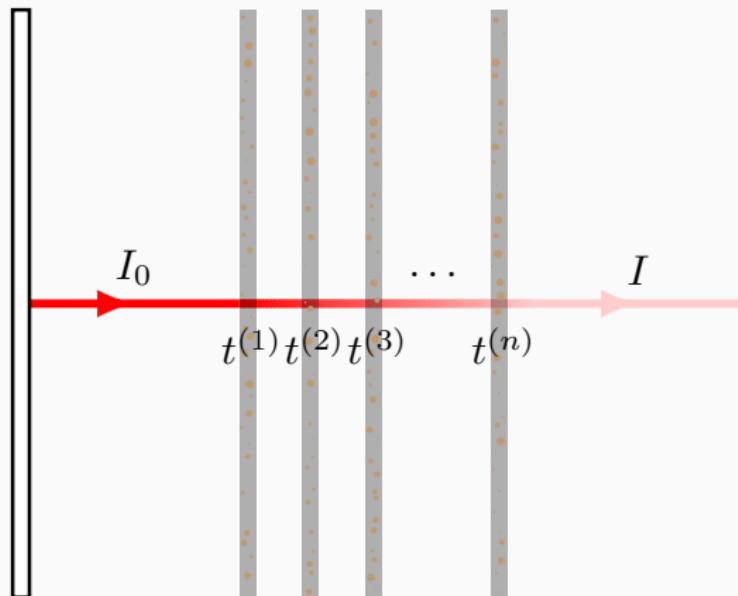
$$\frac{I}{I_0} = \exp \left(- \int_{\mathcal{R}} \mu(r) dr \right)$$

THE BEER-LAMBERT LAW



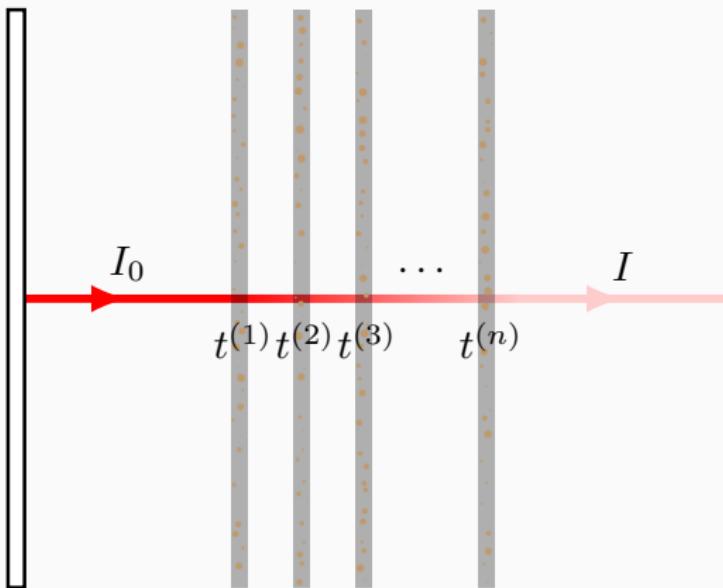
$$\frac{I}{I_0} = \exp \left(- \int_{\mathcal{R}} \mu(r) dr \right)$$

THE BEER-LAMBERT LAW



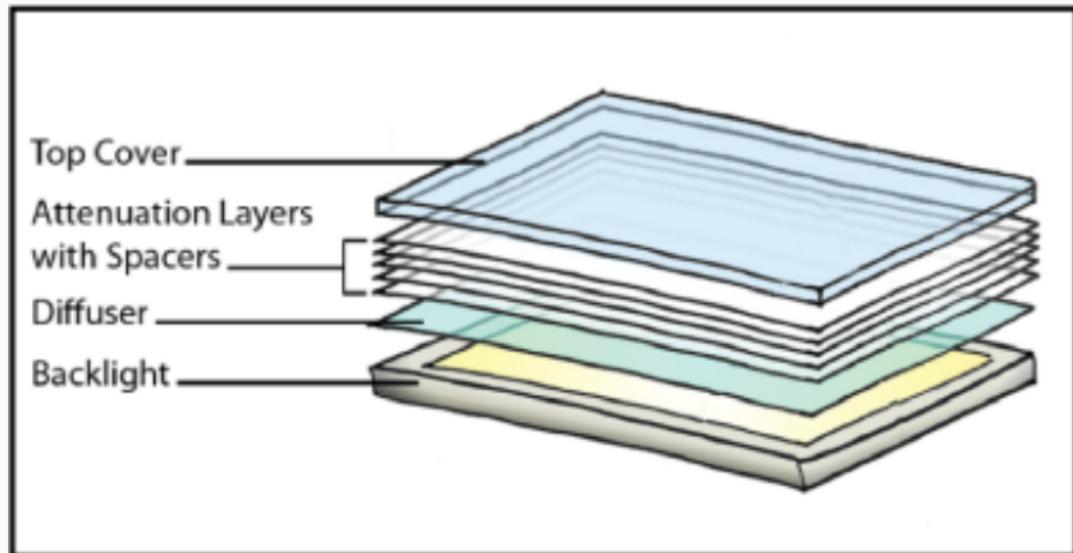
$$\frac{I}{I_0} = \exp \left(- \int_{\mathcal{R}} \mu(r) dr \right) = \prod_i t^{(i)}$$

THE BEER-LAMBERT LAW



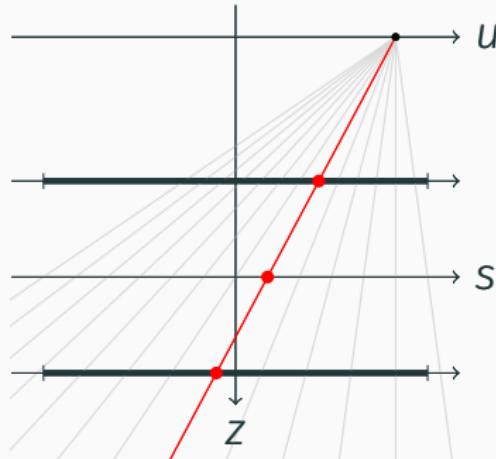
$$\frac{I}{I_0} = \exp \left(- \int_{\mathcal{R}} \mu(r) dr \right) = \prod_i t^{(i)} = \exp \left(- \sum_i a^{(i)} \right)$$

DISPLAY ARCHITECTURE



Wetzstein et al. [2011]

LIGHT TRANSMISSION



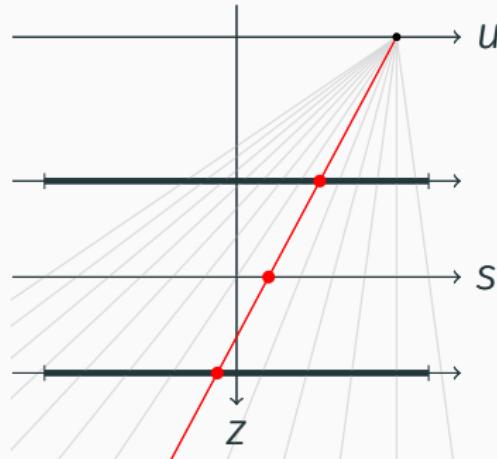
$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

L_m Color of ray m

t Transmission

h Intersection

LIGHT TRANSMISSION



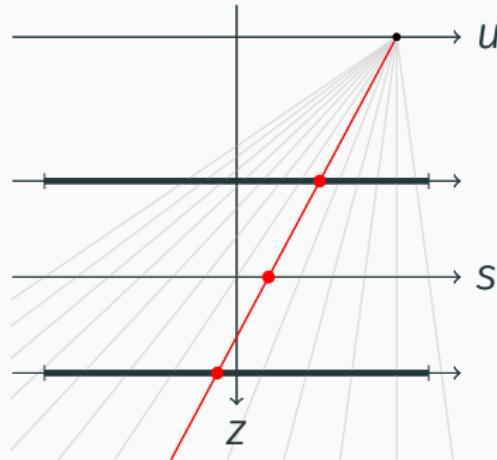
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LIGHT TRANSMISSION



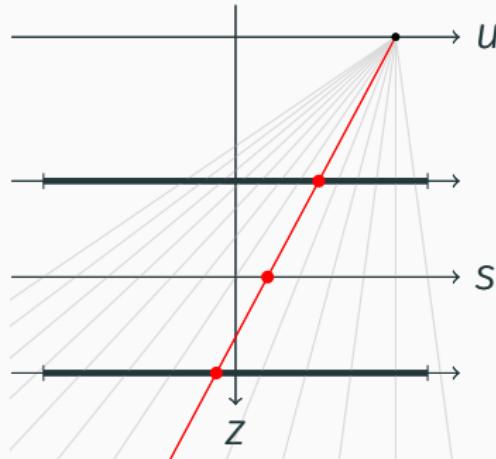
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LIGHT TRANSMISSION



$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

L_m Color of ray m

t Transmission

h Intersection

From now on: $L_0 = 1$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
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- This is hard

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

 $t = e^{-a}$

$$\log(L_m) = - \sum_{n=1}^N a^{(n)}(h(m, n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain
- **Solve for absorbance**

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

 $t = e^{-a}$

$$\log(L_m) = - \sum_{n=1}^N a^{(n)}(h(m, n))$$

RAY CASTING

- One linear constraint per ray
- Create a big matrix P
- Matrix encodes intersections

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$$\log(L_m) = - \sum_{n=1}^N a^{(n)}(h(m, n))$$

RAY CASTING

$$P = \begin{pmatrix} & \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 & \alpha_9 & \alpha_{10} \\ \bar{L}_1 & & & 1 & & & & 1 & & & \\ \bar{L}_2 & & & & 1 & & & & 1 & & \\ \bar{L}_3 & 1 & & & & & & & & 1 & \\ \bar{L}_4 & & 1 & & & & & & & & 1 \\ \hline \bar{L}_5 & & & & 1 & & & & & 1 & \\ \bar{L}_6 & & & 1 & & & & 1 & & & \\ \bar{L}_7 & 1 & & & & & & & & 1 & \\ \hline \bar{L}_8 & & & & 1 & & & 1 & & & \\ \hline \bar{L}_9 & & 1 & & & & & & 1 & & \\ \bar{L}_{10} & & & 1 & & & & & & 1 & \\ \hline \bar{L}_{11} & & & 1 & & & & & & 1 & \\ \bar{L}_{12} & & & 1 & & & & & & & 1 \end{pmatrix}$$

THE EQUATION

$$\log(L) = -P\alpha$$

- $\log(L)$ Vectorized log light field
- α Vector holding unkowns

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OPTIMIZATION PROBLEM

$$\operatorname{argmin}_{\alpha} \|P\alpha + \log(L)\|^2$$

subject to $\alpha \geq 0.$

- Proposed by Wetzstein et al. [2011]
- System is overdetermined
- Need iterative solver

THE CONSTRAINT $\alpha \geq 0$

- Negative absorption ($\alpha < 0$) is physically not possible
- The theoretical model supports negative absorption
- Constraint reduces the space of possible solutions

EXAMPLE: LEGO TRUCK



$6 \times 6 \times 480 \times 640$
 ~ 2 minutes

EXAMPLE: LEGO TRUCK

Goal: Simulate viewing experience before assembly

$$I = e^{-P\alpha}$$

Original

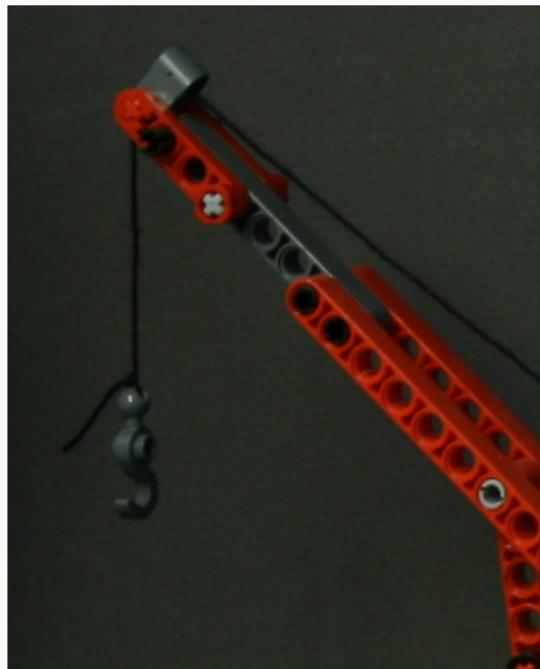


Simulation

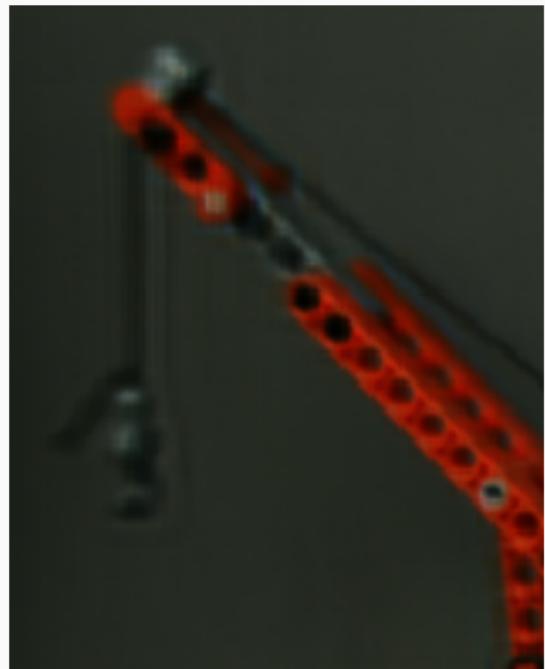


3 LAYERS

Original

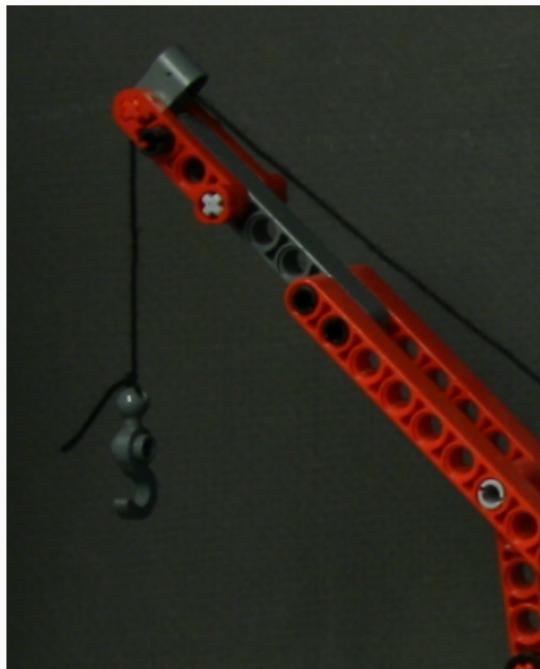


Simulation

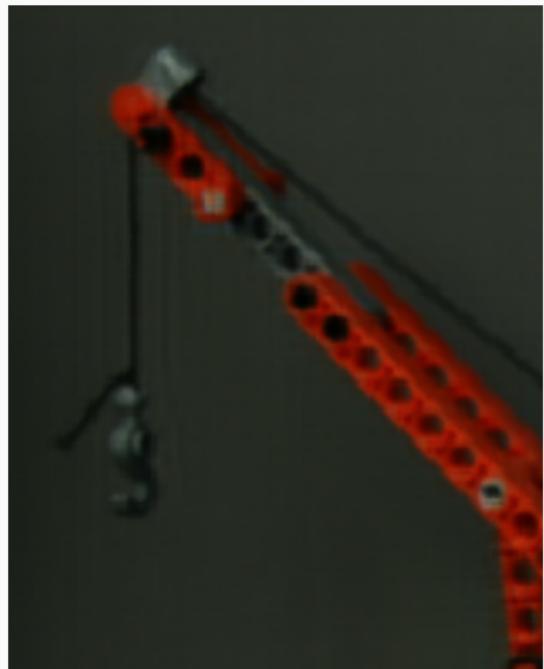


5 LAYERS

Original

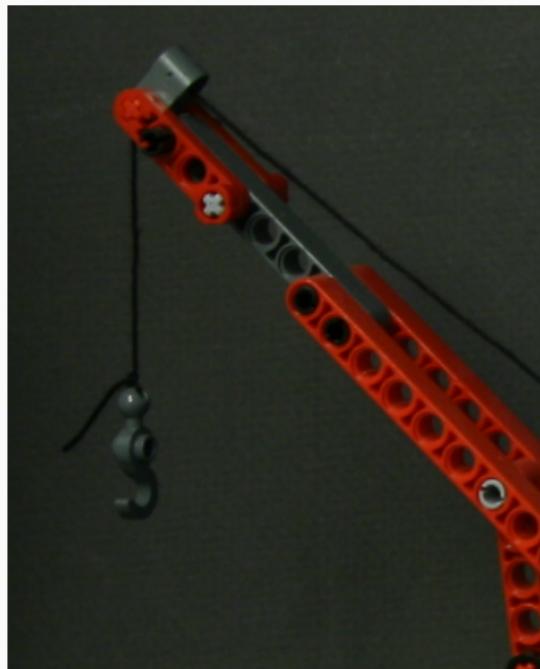


Simulation

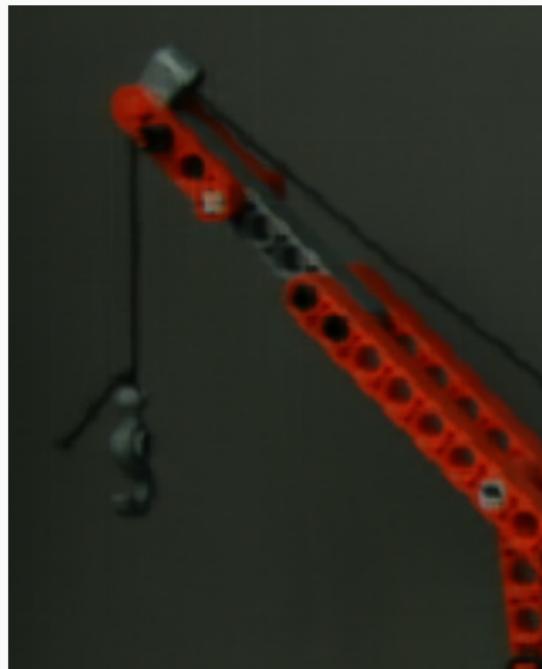


10 LAYERS

Original

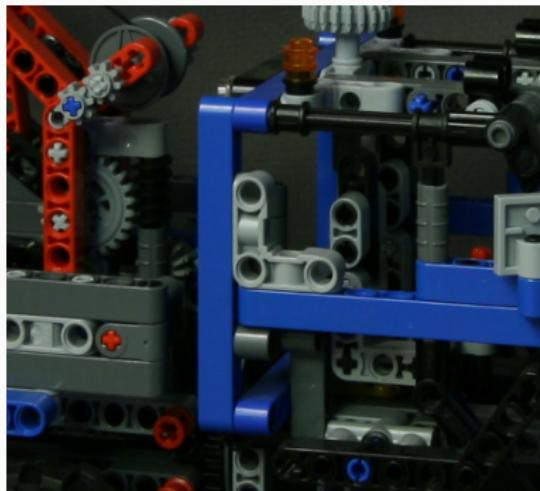


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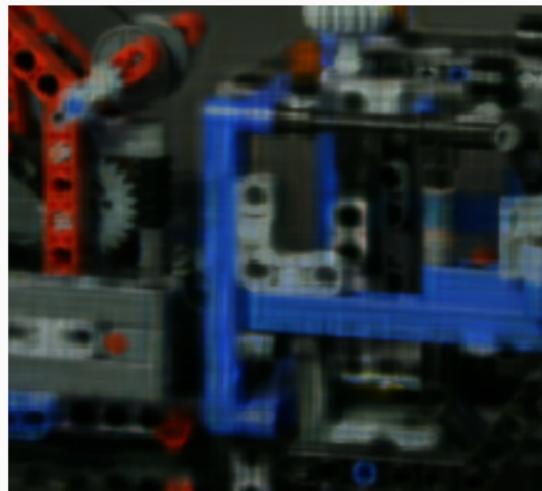


3 LAYERS

Original

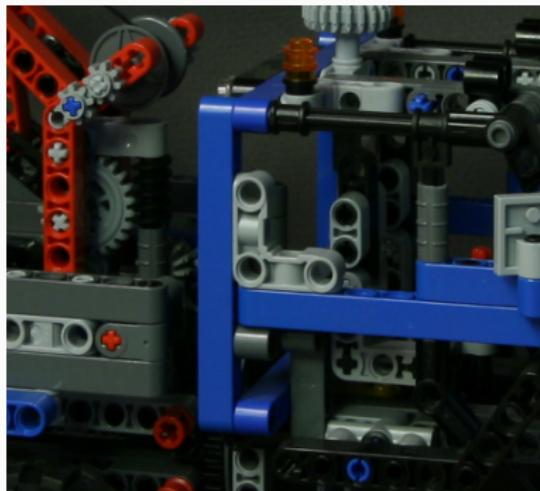


Simulation

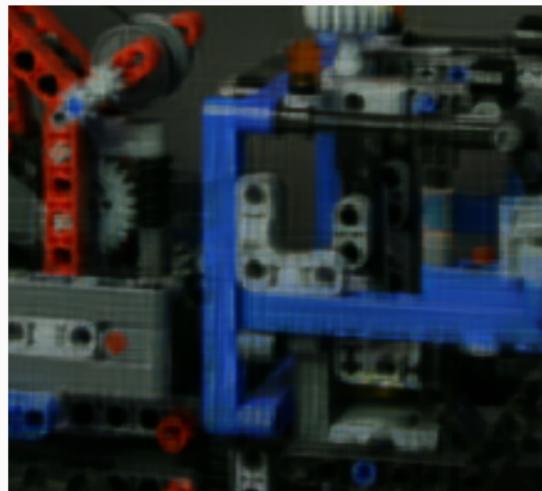


5 LAYERS

Original

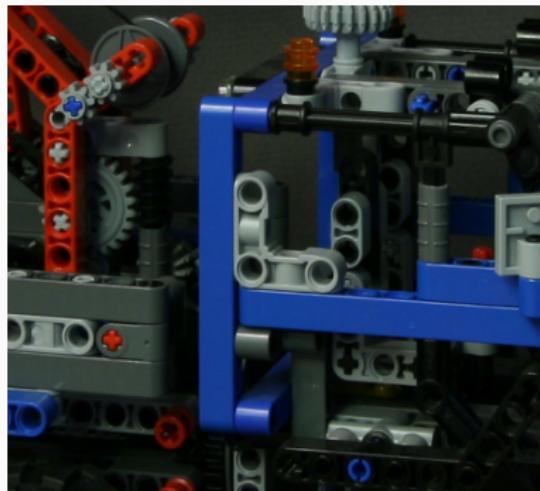


Simulation

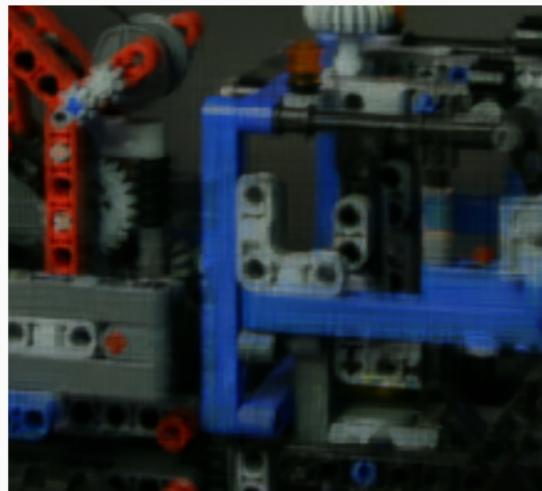


10 LAYERS

Original

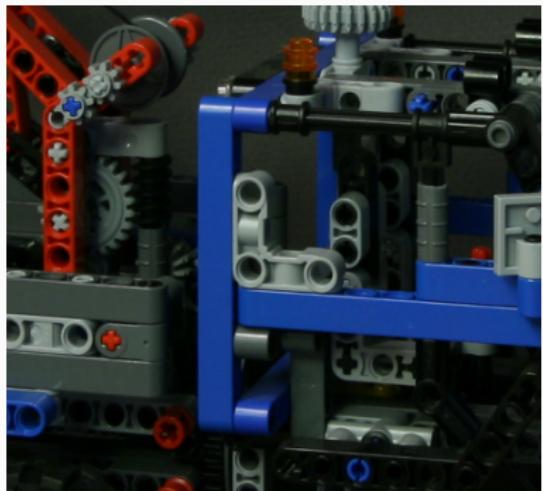


Simulation

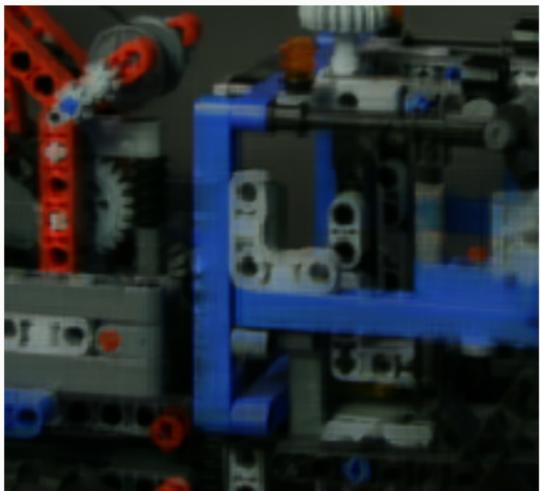


10 LAYERS, HIGHER ANGULAR RESOLUTION

Original



Simulation



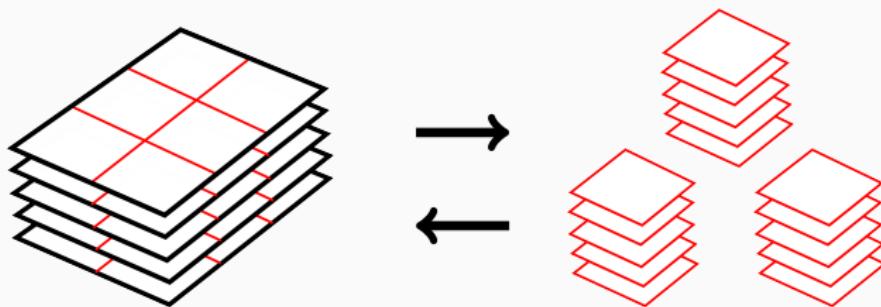
EXAMPLE: LEGO TRUCK



- A lot of memory is needed:
 - Light field (uncompressed)
 - Propagation matrix (? nnz entries)
 - Additional matrices for solver
- Memory usage grows with resolution
- Solution: Slice the attenuator

ATTENUATOR TILING

1. Slice attenuator into smaller pieces
2. Solve optimization problem for every slice
3. Reconnect the slices



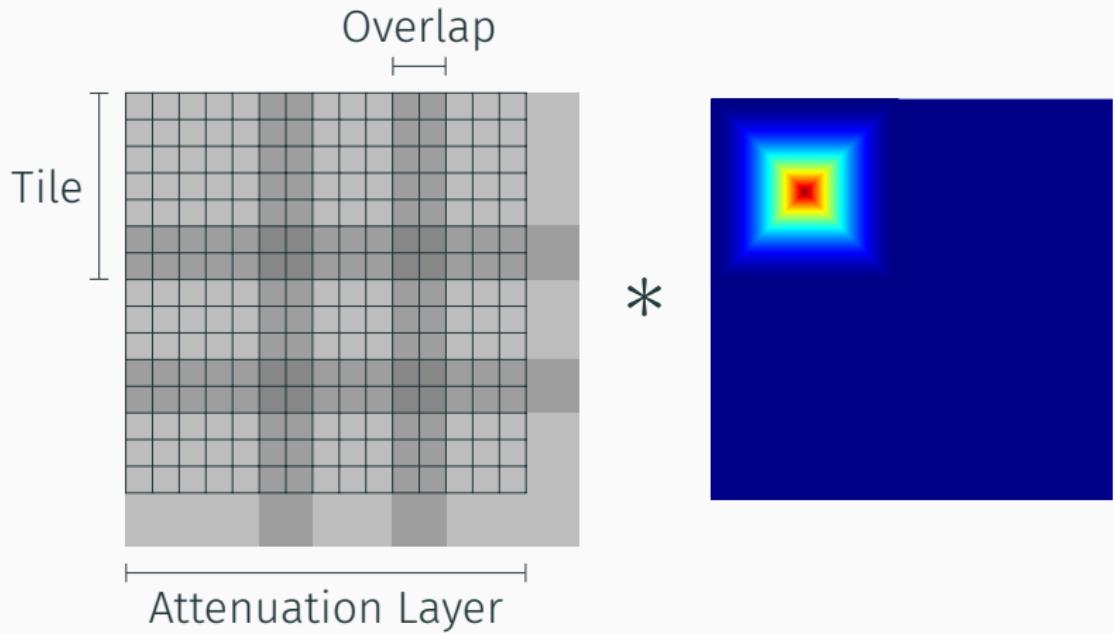
ATTENUATOR TILING

- Problem: Rays can overlap with multiple slices at borders
- Slices need to overlap too
- Blend slices with mask

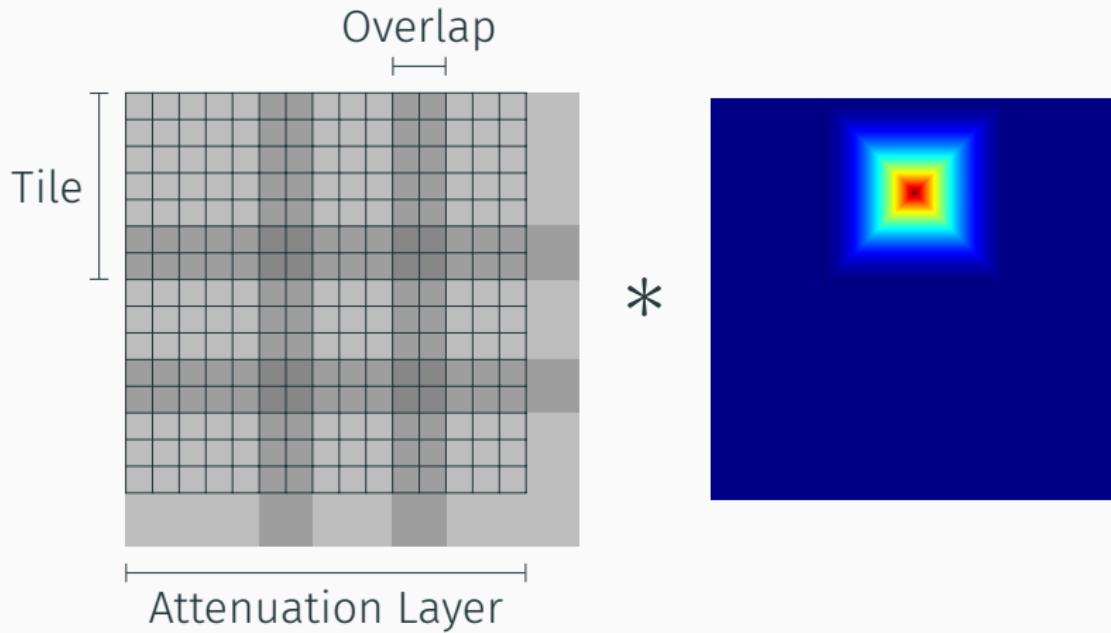


Simulation

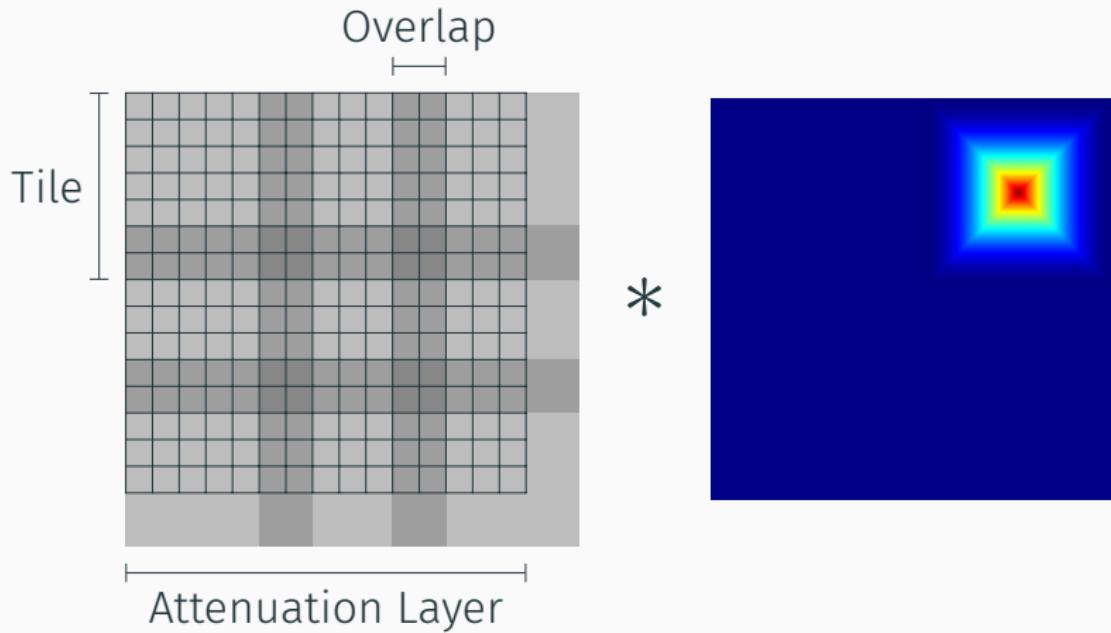
TILE BLENDING



TILE BLENDING



TILE BLENDING



TILE BLENDING



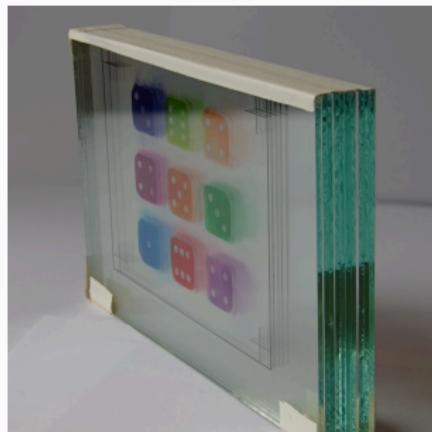
No overlap



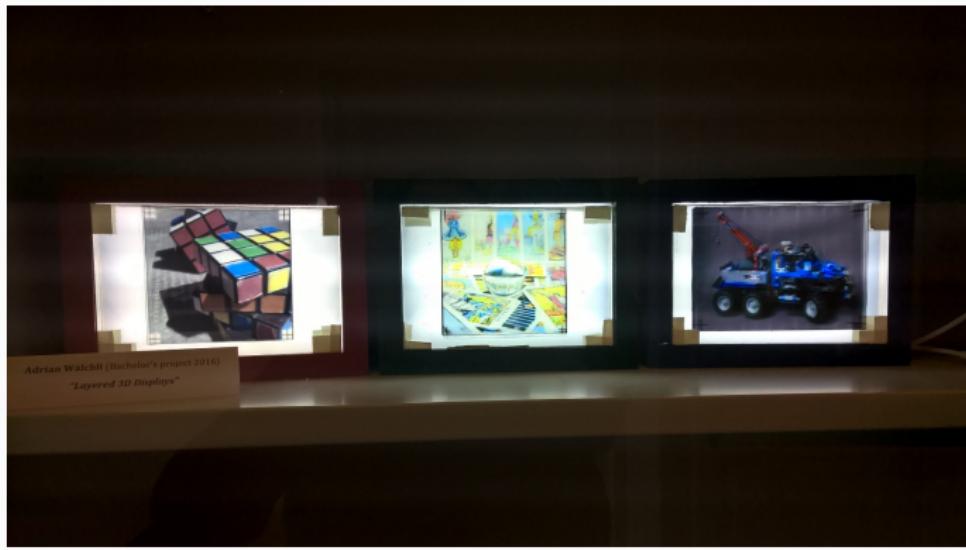
30% overlap

THE FINISHED PRODUCT

- Finally, print images on transparent sheets
- Glass plates hold sheets in place
- Combine with backlight



THE FINISHED PRODUCT

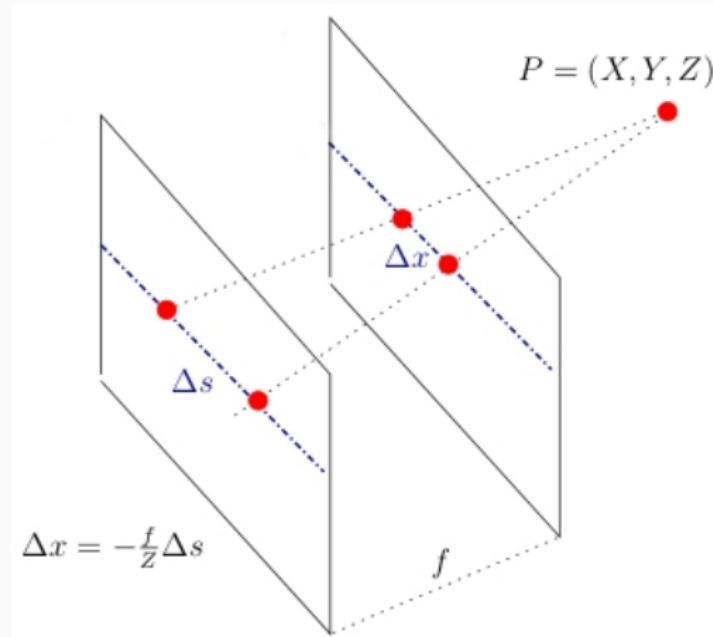


QUESTIONS

- Impact of more layers?
- Does thickness of display matter?
- What are the limitations?

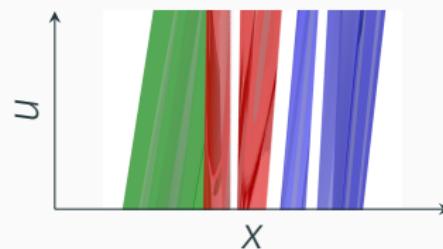
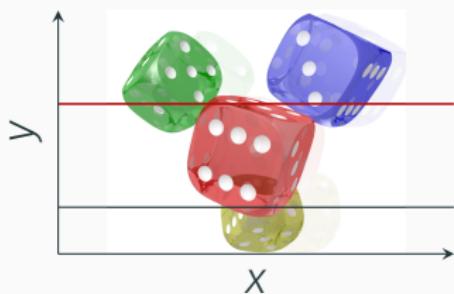
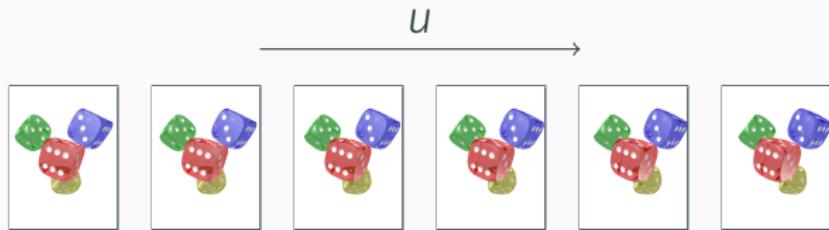
SPECTRAL ANALYSIS

EPIPOLAR PLANE GEOMETRY

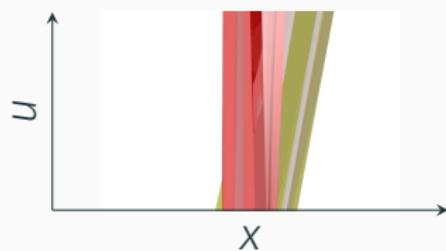
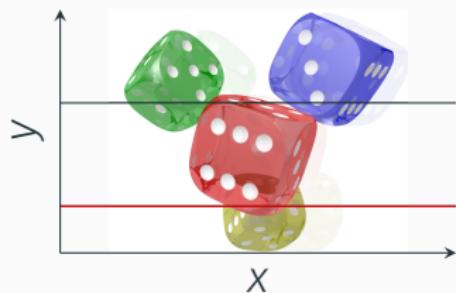
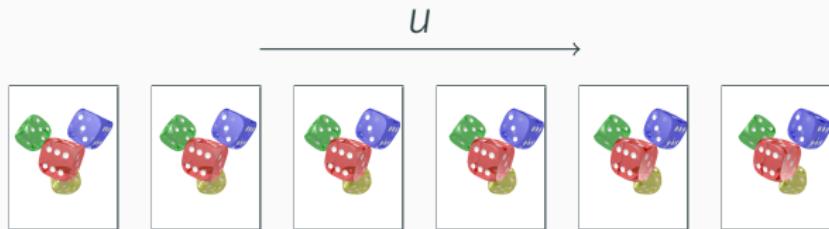


Source: klimt.iwr.uni-heidelberg.de

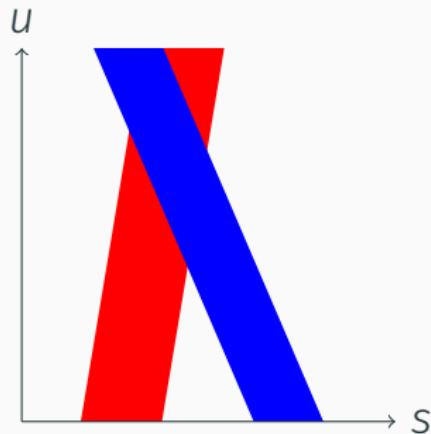
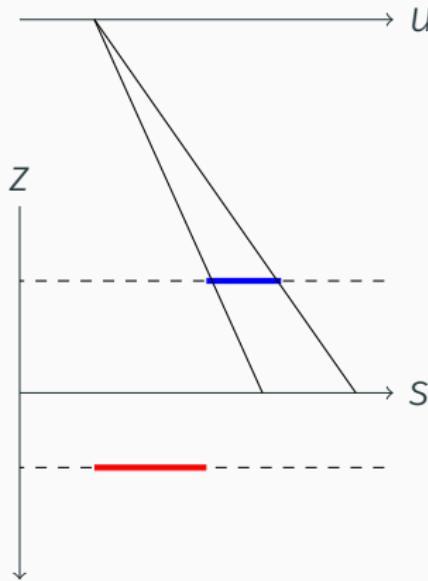
EPIPOLAR PLANE IMAGE



EPIPOLAR PLANE IMAGE

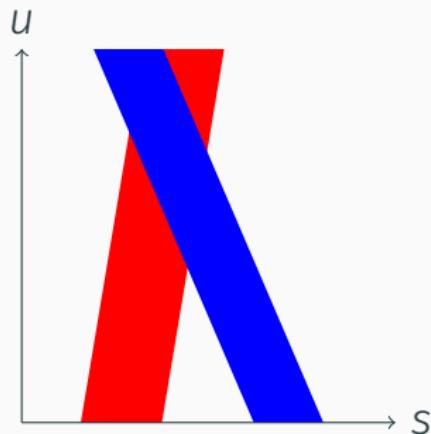
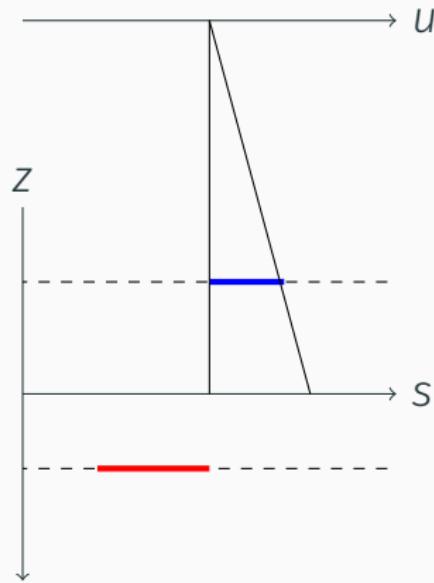


EPIPOLAR PLANE IMAGE



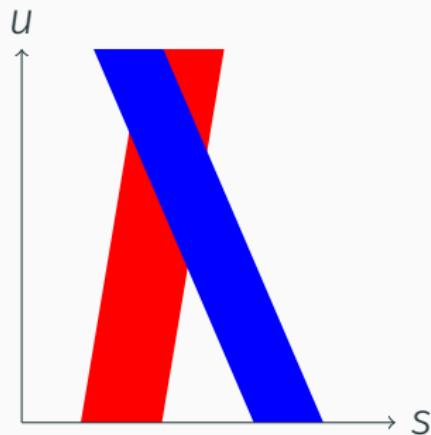
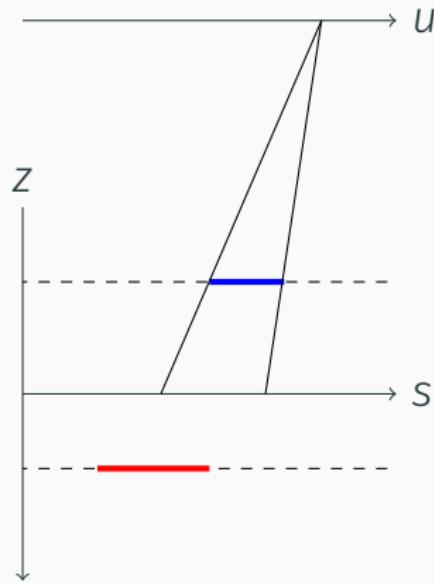
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

EPIPOLAR PLANE IMAGE



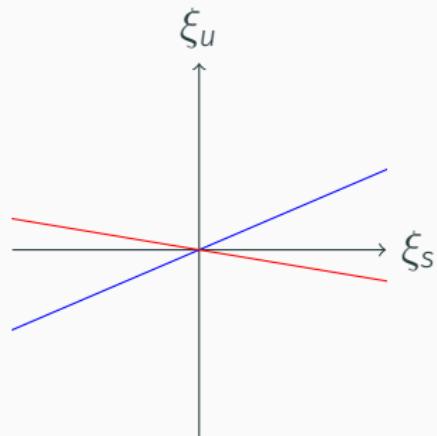
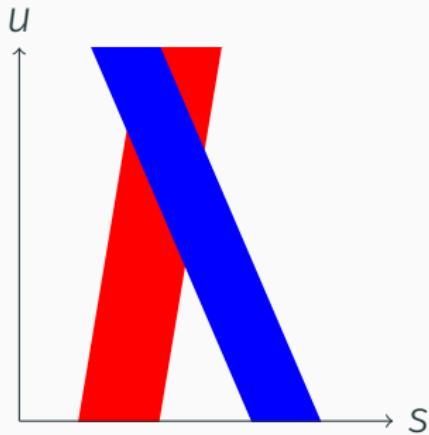
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

EPIPOLAR PLANE IMAGE



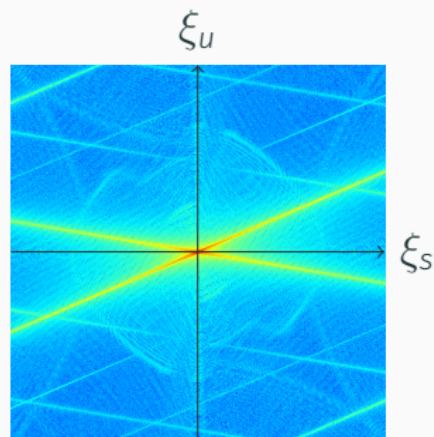
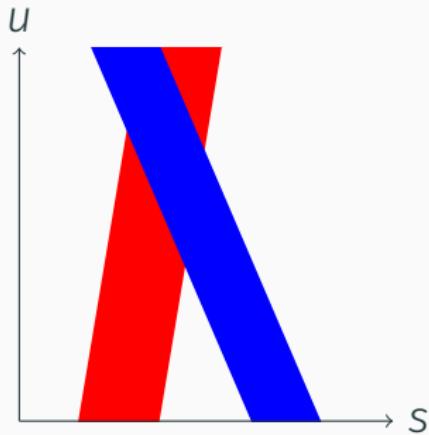
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

SPECTRAL PROPERTIES OF LIGHT FIELDS



Frequency Response
(Amplitude)

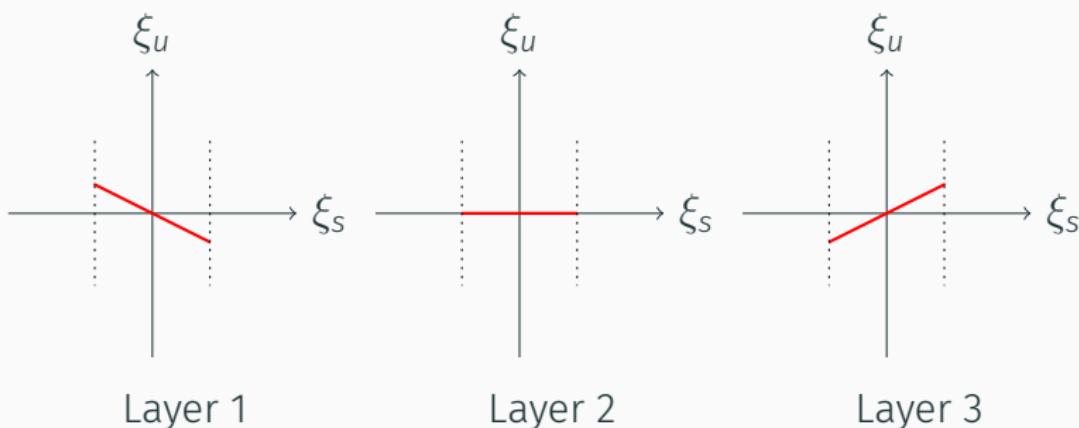
SPECTRAL PROPERTIES OF LIGHT FIELDS



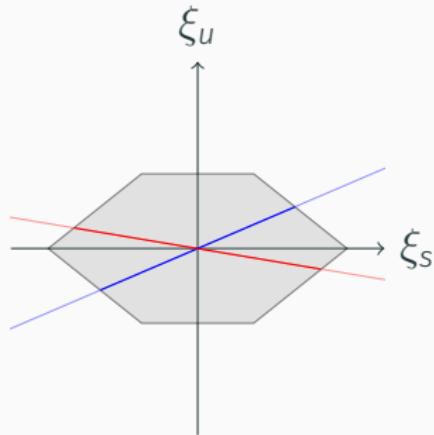
Frequency Response
(Amplitude)

SPECTRAL PROPERTIES OF DISPLAY

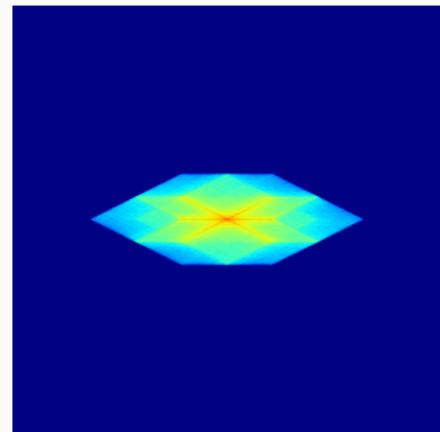
- Every layer creates a light field L_n
- Stack of layers creates $L' = L_0 \cdot L_1 \cdots L_N$
- What does L' look like in frequency domain?



SPECTRAL PROPERTIES OF DISPLAY



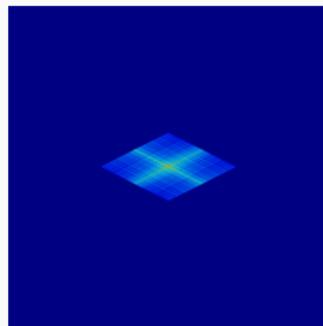
Spectral Support



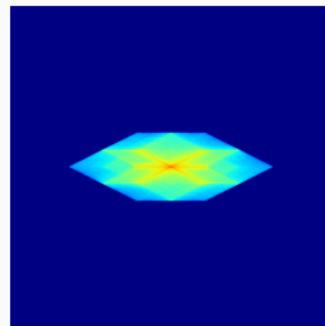
Frequency Response
(Amplitude)

SPECTRAL PROPERTIES OF DISPLAY

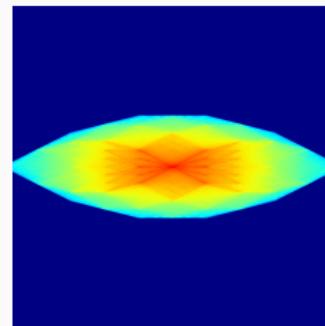
- Spectral support increases with more layers
- Highest response in center



2 Layers



3 Layers



5 Layers

CONCLUSION

THE GOOD

THE BAD

SUMMARY

Your Questions

ACKNOWLEDGEMENTS

Supervision by

Prof. Dr. Matthias Zwicker
Siavash Bigdeli

MORE INFORMATION

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Thesis and Resources

github.com/awaelchli/bachelor_thesis

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