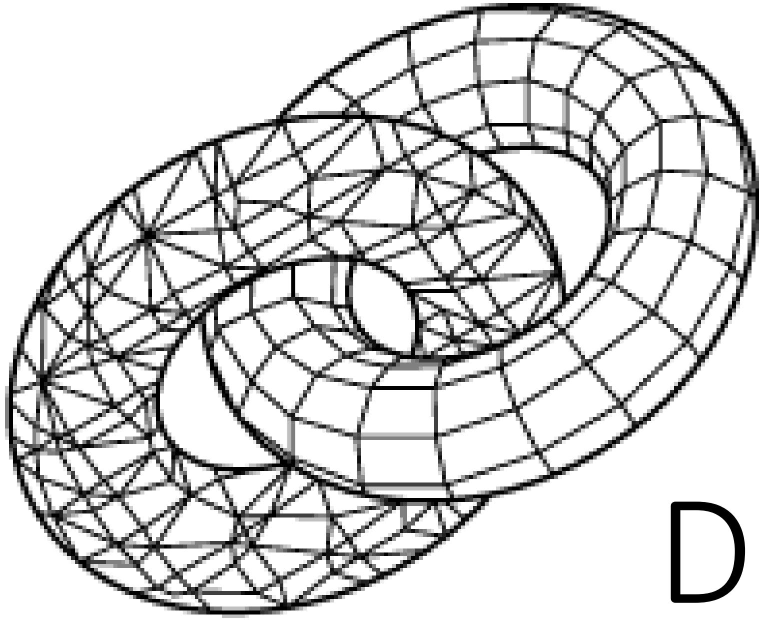


Dual Photography

3D Graphics Systems

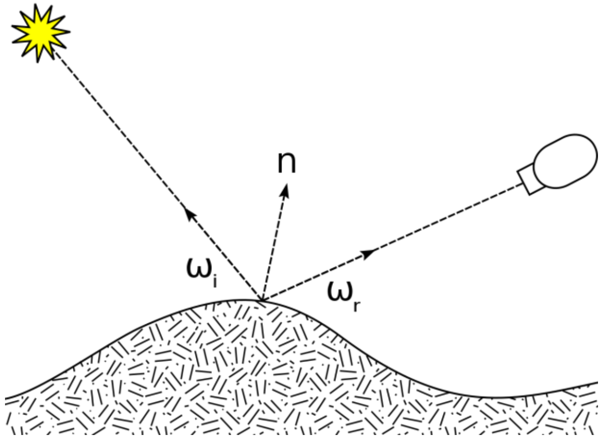
2020.1

Professor Luiz Velho

Jonas Lopes

Dual Photography is based on Helmholtz Reciprocity.

Helmholtz Reciprocity

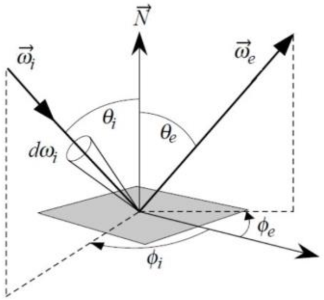


Bidirectional Reflectance Distribution Function (BRDF)

$f_r(\omega_i, \omega_o)$

(outgoing radiance / Incoming radiance)

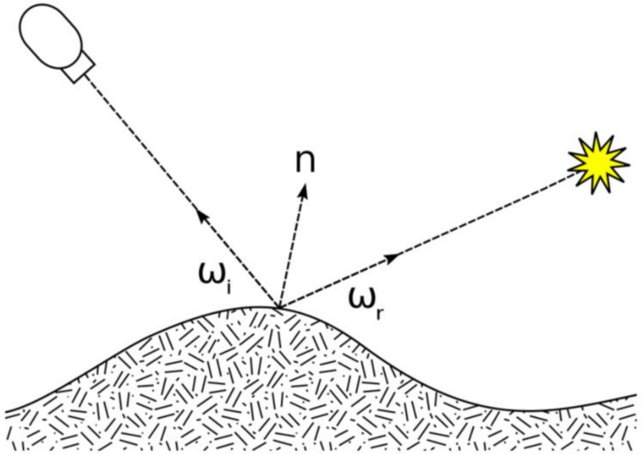
$$f_r(\omega_i, \omega_r) = \frac{d L_r(\omega_r)}{d E_i(\omega_i)} = \frac{d L_r(\omega_r)}{L_i(\omega_i) \cos\theta_i \, d\omega_i}$$



$$\rho(\vec{\omega}_i, \vec{\omega}_e) = \rho(\theta_i, \phi_i, \theta_e, \phi_e) = \frac{dL_e(\vec{\omega}_e)}{dE(\vec{\omega}_i)}$$

BRDF defines that ρ is a function with four degrees of freedom

Helmholtz Reciprocity



$$f_r(\omega_i, \omega_o) = f_r(\omega_o, \omega_i)$$

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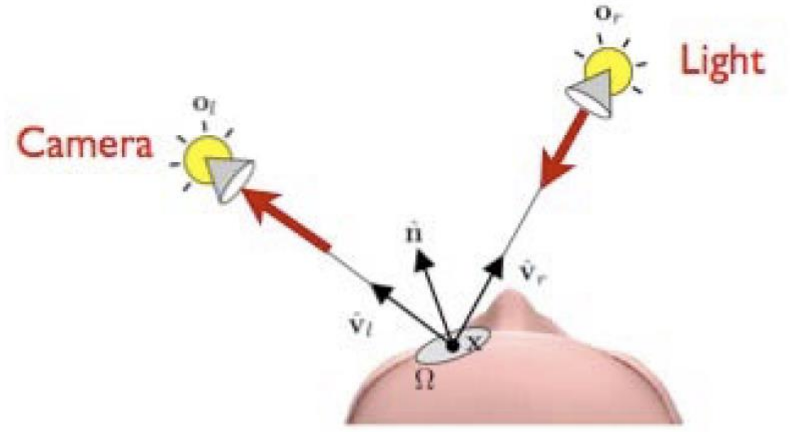
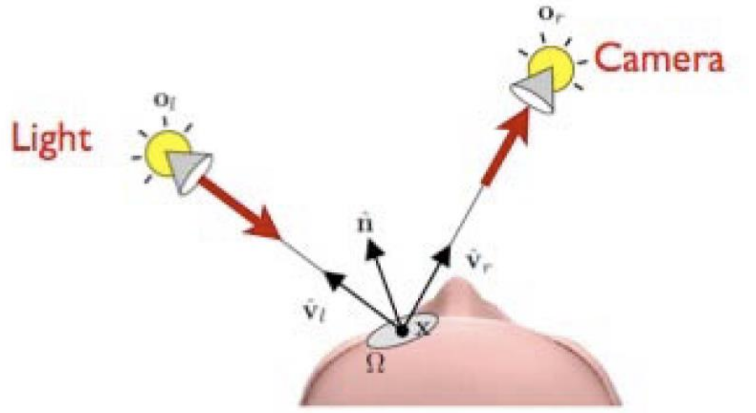
Helmholtz Reciprocity

Each ray of light can be reversed without altering its transport properties. Radiance transfer between incoming and outgoing directions is symmetric.

Interchange the lights and cameras

Dual Photography uses the concept of **Helmholtz Reciprocity** to interchange the lights and cameras in a scene.

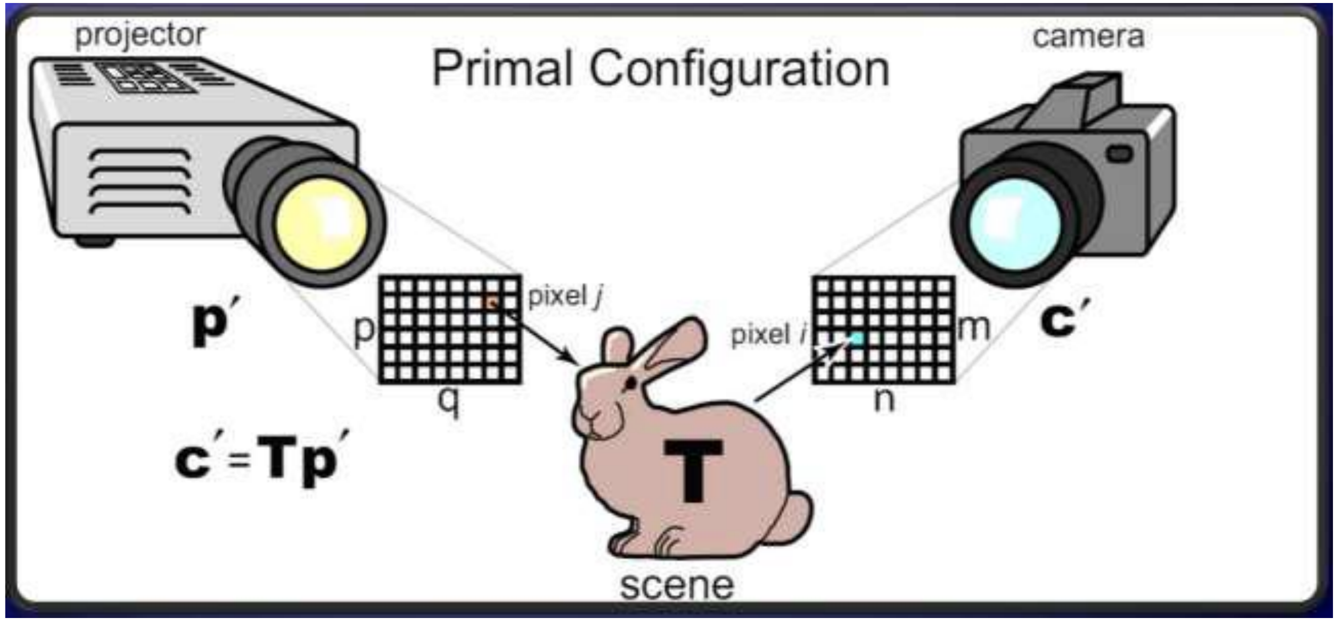


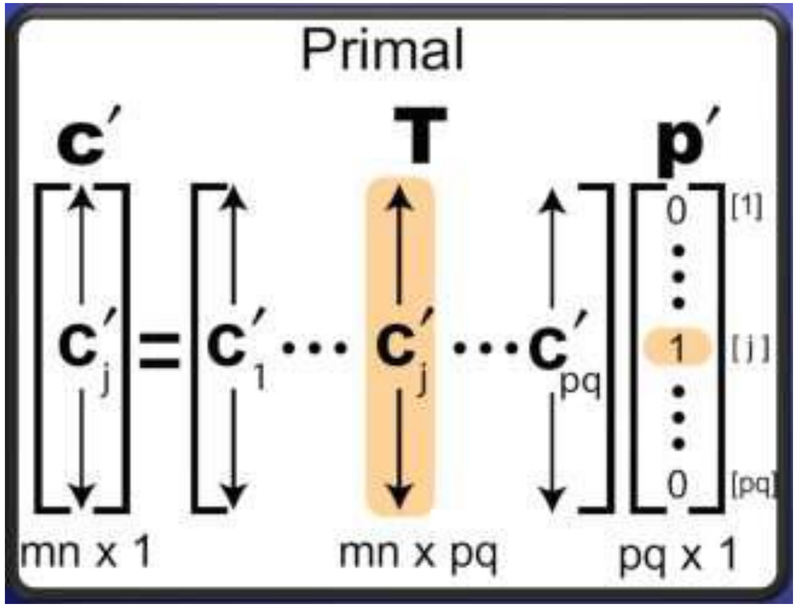


This means that we can effectively exchange the positions of the camera and the projector.

We can **generate an image** from the point of view of the projector.

Primal Configuration



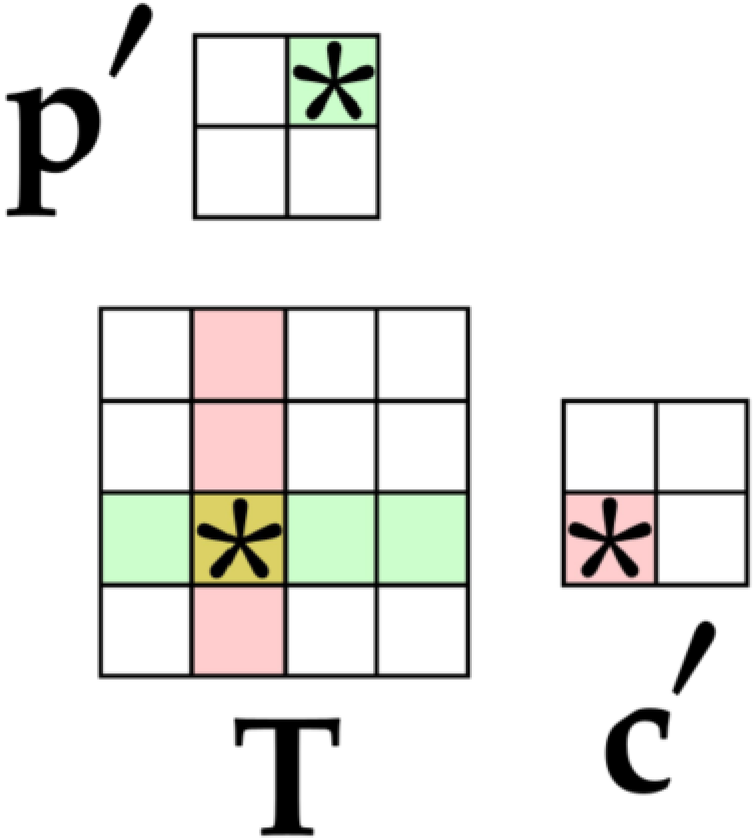


The light transport matrix **T**

$$c' = Tp'$$

- Each element of **T** describes the transmission in the optical path between a pixel in the projector and a pixel in the camera.

$$f_r(\omega_i, \omega_o) = f_r(\omega_o, \omega_i)$$



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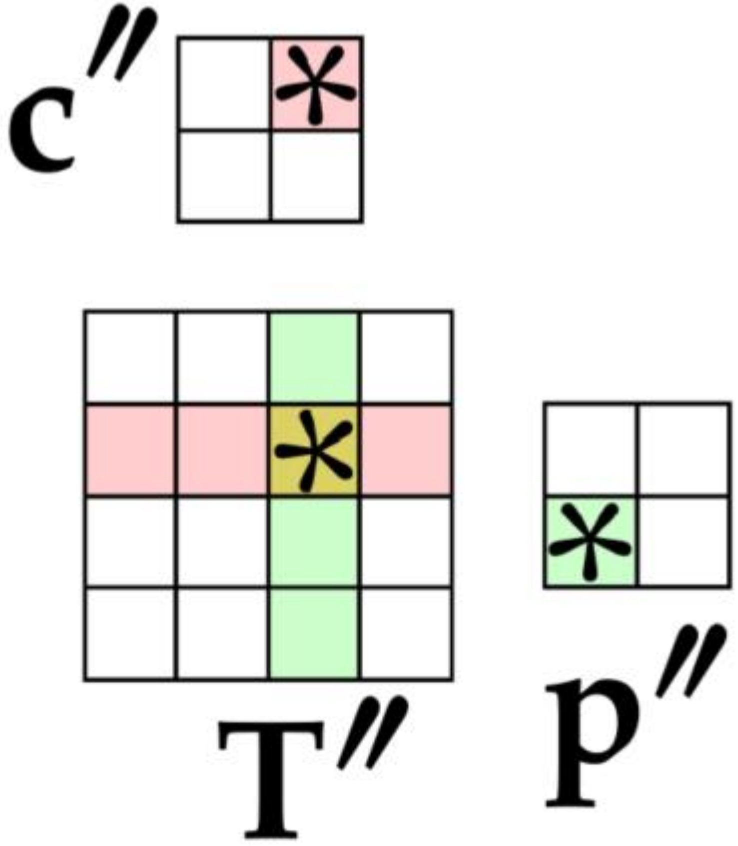
The light transport matrix T”

p”=T”c”

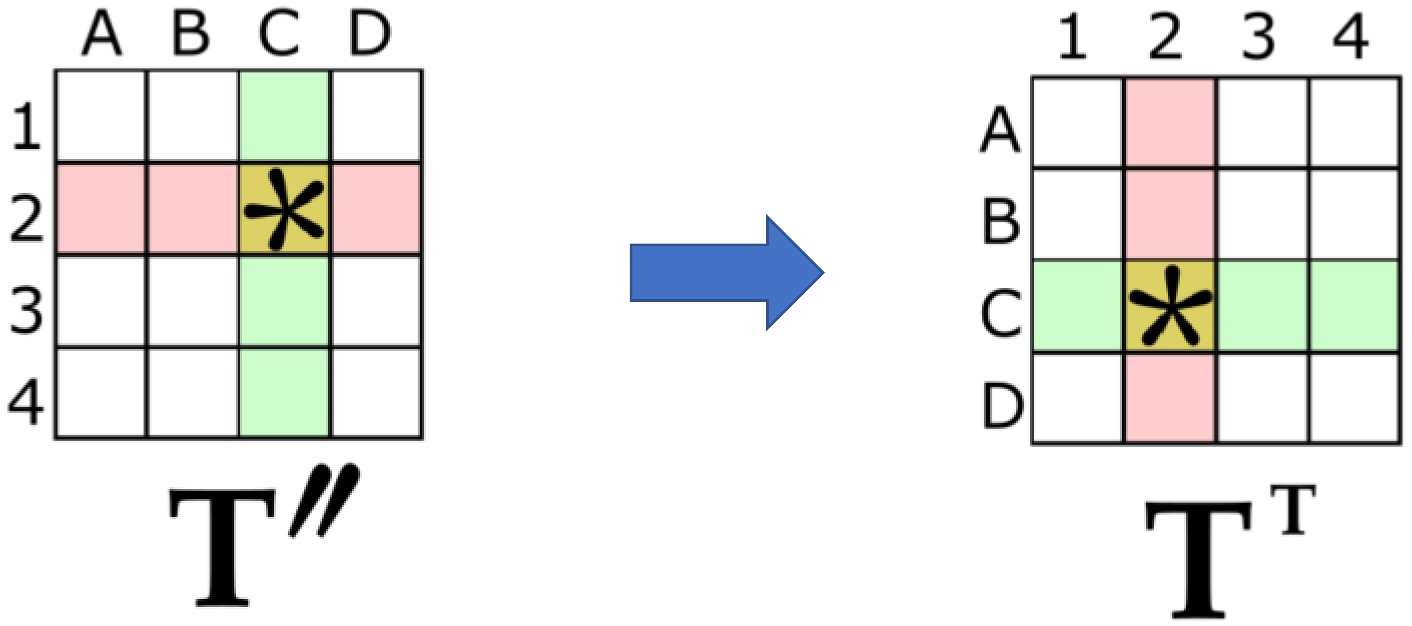
- Each element of **T** describes the transmission in the optical path between a pixel in the projector and a pixel in the camera.

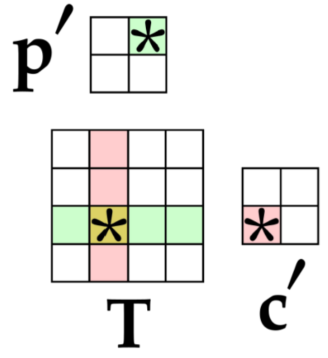
$$f_r(\omega_i, \omega_o) = f_r(\omega_o, \omega_i)$$



The light transport matrix $\mathbf{T}^T$

p"=T"c"





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$$f_r(\omega_i, \omega_o) = f_r(\omega_o, \omega_i)$$

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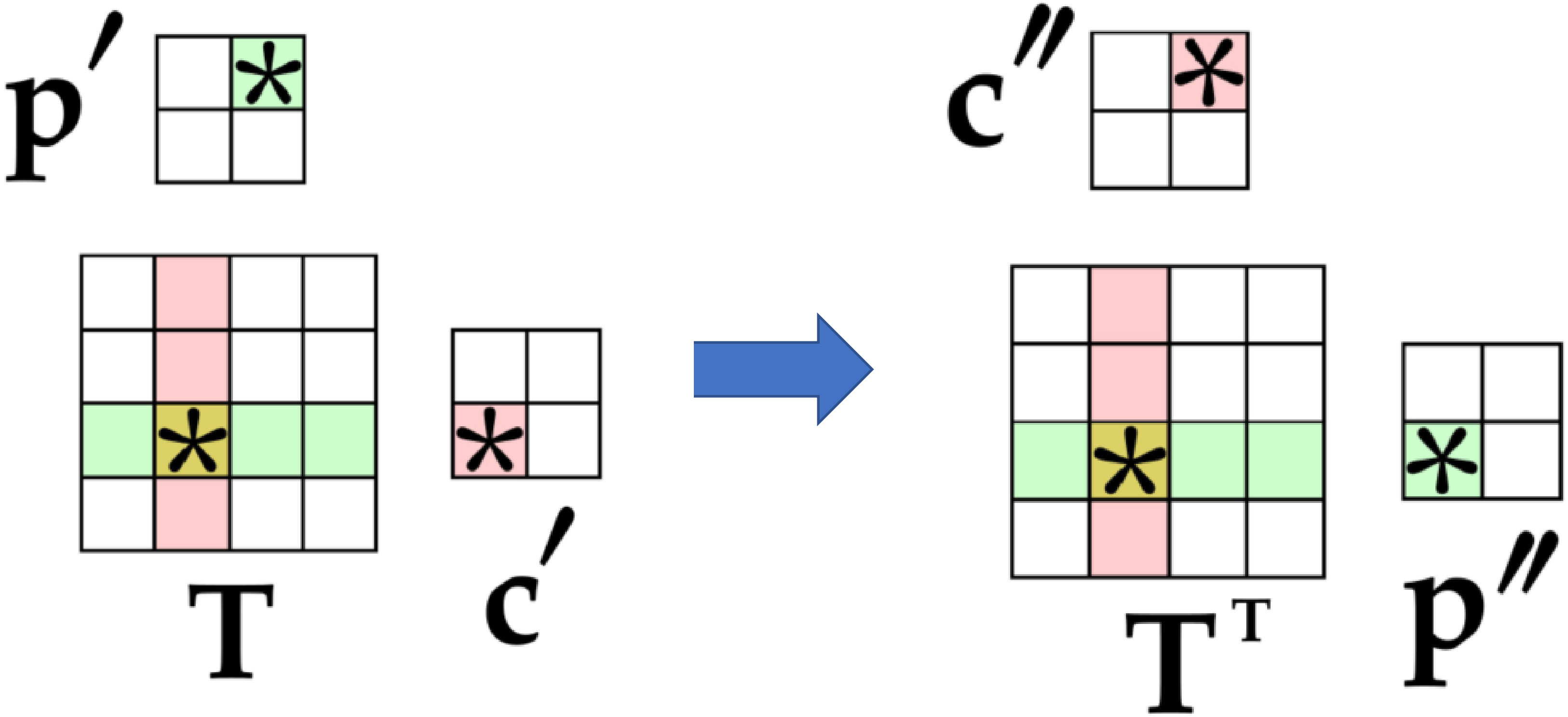
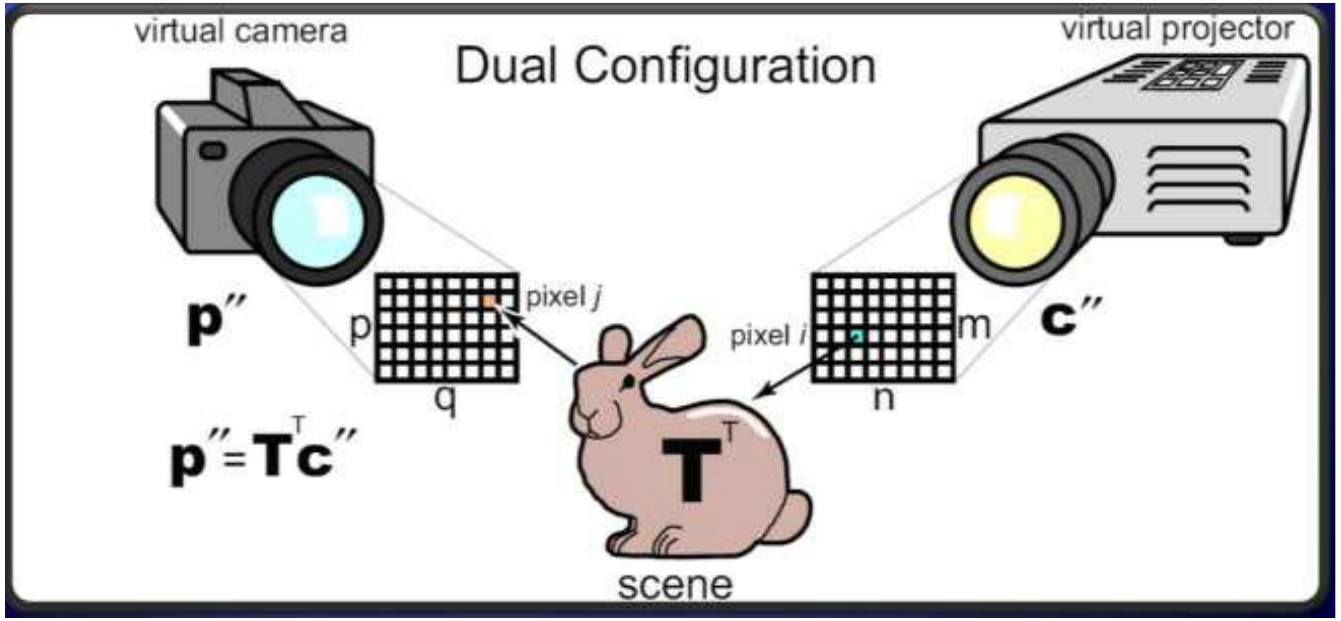
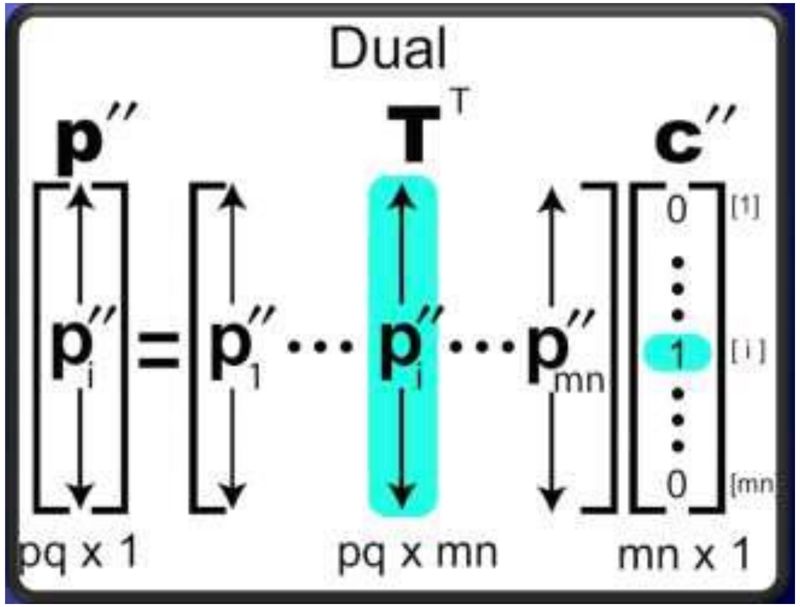
The light transport matrix $\mathbf{T}^T$

$$\mathbf{p''=T^Tc''}$$

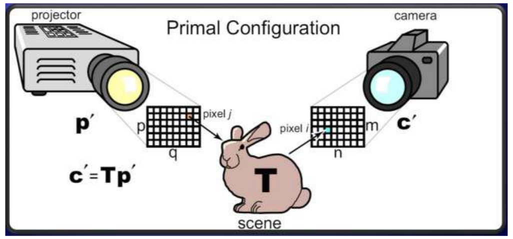


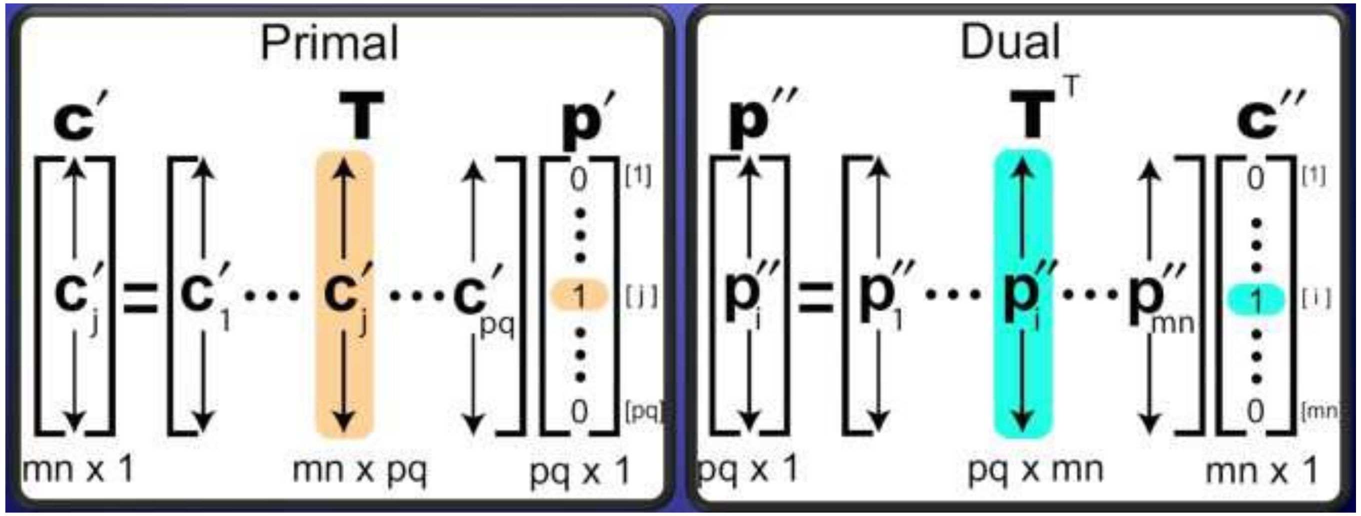
Dual Configuration

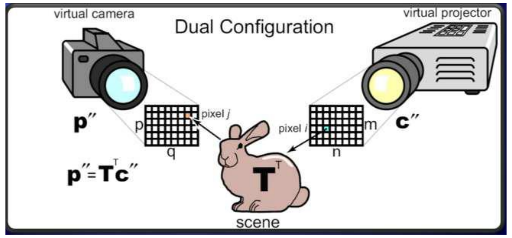




Transport Matrix







T’’ = T^T due to Helmholtz Reciprocity

Each column of **T** is the image seen by the camera when only one pixel of the projector is turned on.

Dual Photography is the act of multiplying the **transposed matrix** by a desired **lighting image vector**.

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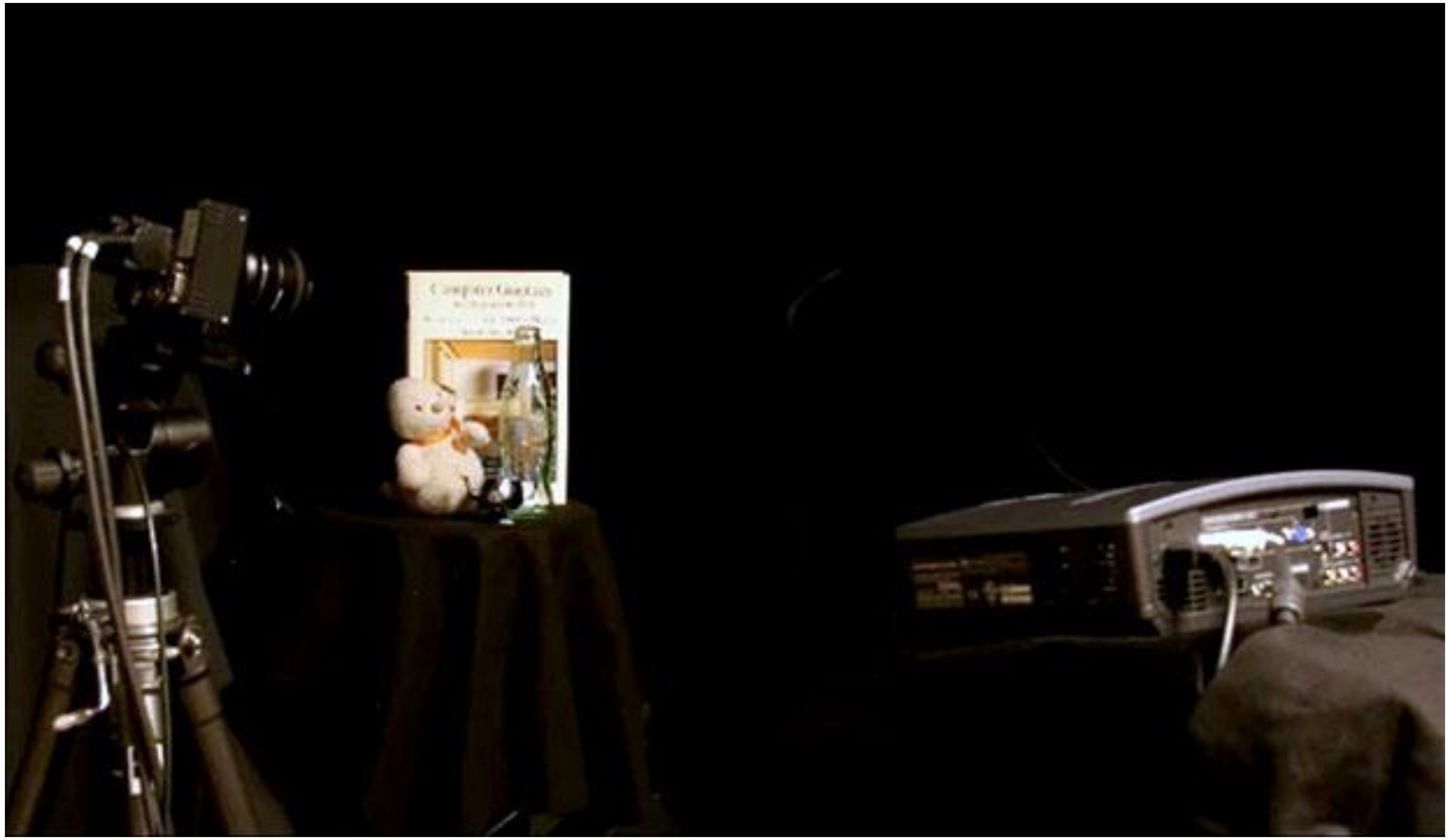
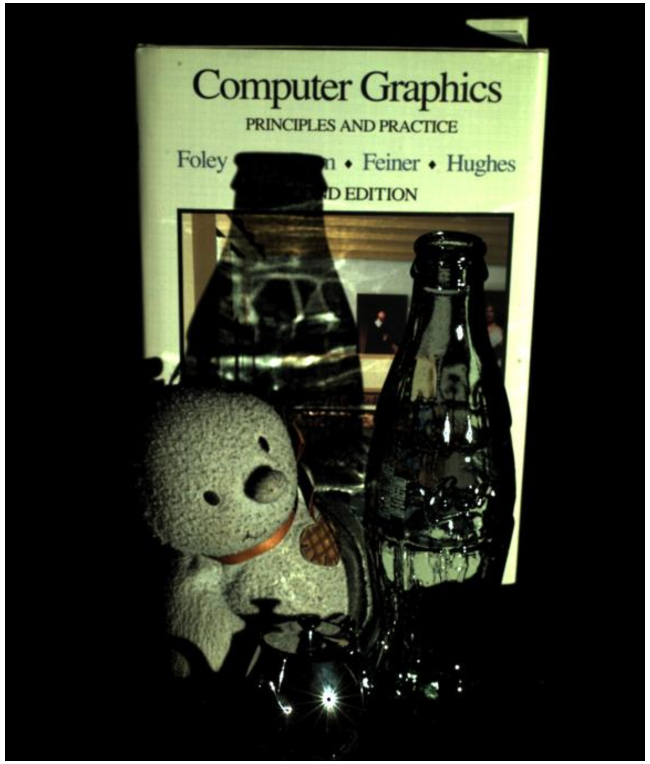
Experiments

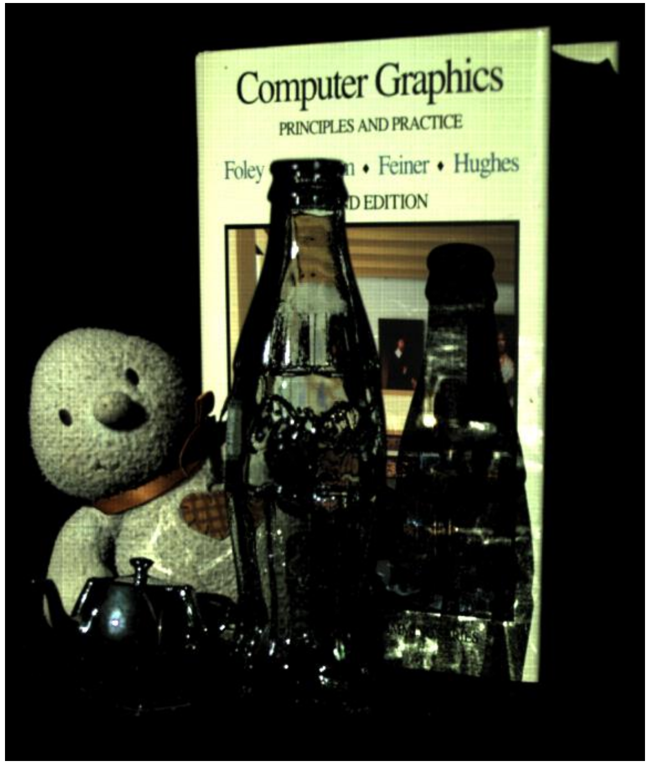


Two photographs captured of the scene without touching anything in the setting

Primal Image



Synthesized Dual Image



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Measuring T

- Brute Force
- Fixed Pattern Scanning
- Adaptive Multiplexed Illumination
- Hierarchical Assembly of the Transport Matrix
- Compressive Sensing

Measuring T by Brute Force

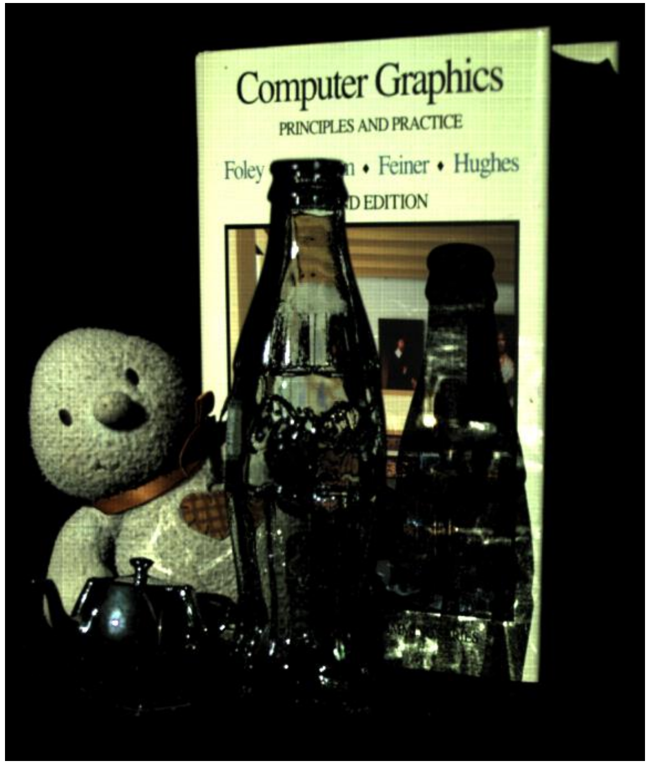
The trivial way to construct the T matrix is to turn on one pixel of the projector at a time. Each picture you take is a column of T. This is called the “brute-force” pixel scan. Unfortunately…

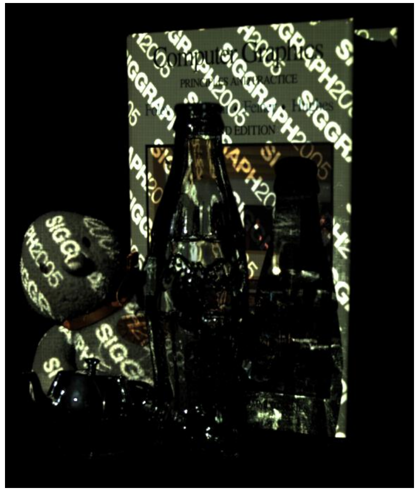
- Need to take as many pictures as there are projector pixels
- The image when only one pixel is lit can be quite dim
- Projector and Camera each have $O(n^6)$ pixels
- Full T matrix would have $O(n^{12})$ elements

Measuring T by Brute Force

Size: 5.4 TB

Days: 10.9





Scan a single pixel per captured camera frame

Measuring T efficiently: Hierarchical Assembly of the Transport Matrix

Instead of capturing pixel level matrix T, capture a sequence of matrices T_k at different scales, then upscale and combine them.

$$\mathbf{p}'' = \sum_k f(\mathbf{T}_k{}^T \mathbf{c}'')$$

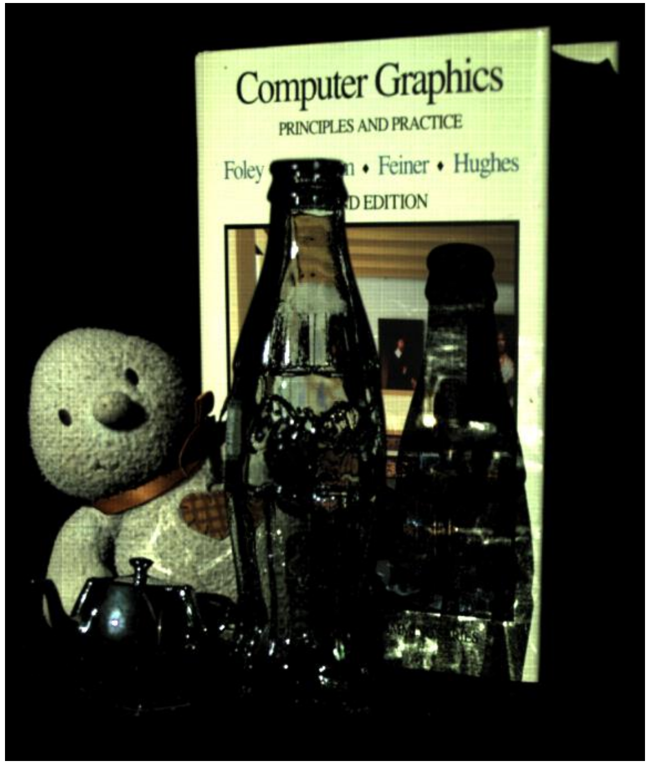
Experimentally demonstrated that this works in: O(log pq)

pq = Projector Pixels

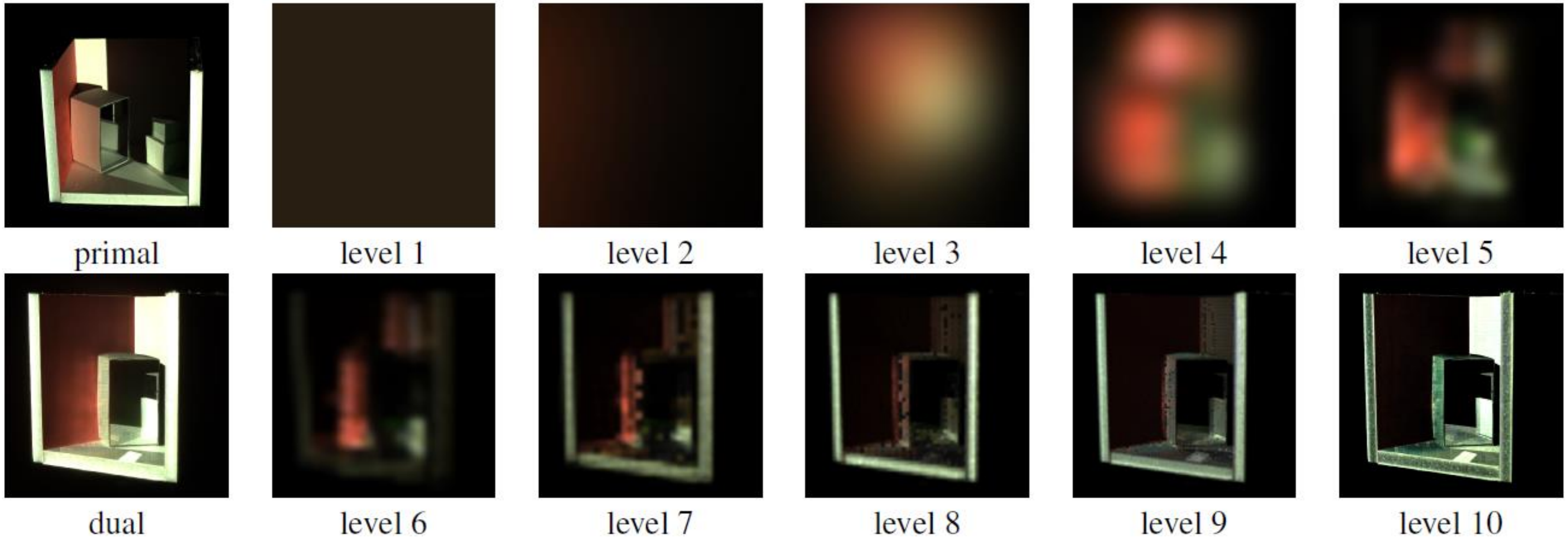
Measuring T efficiently: Hierarchical Assembly of the Transport Matrix

Size: 272 MB

Min: 136



Measuring T efficiently:
Hierarchical Assembly of the Transport Matrix



The primal and dual image show diffuse to diffuse inter-reflections which could only be captured by use of the hierarchical acquisition.

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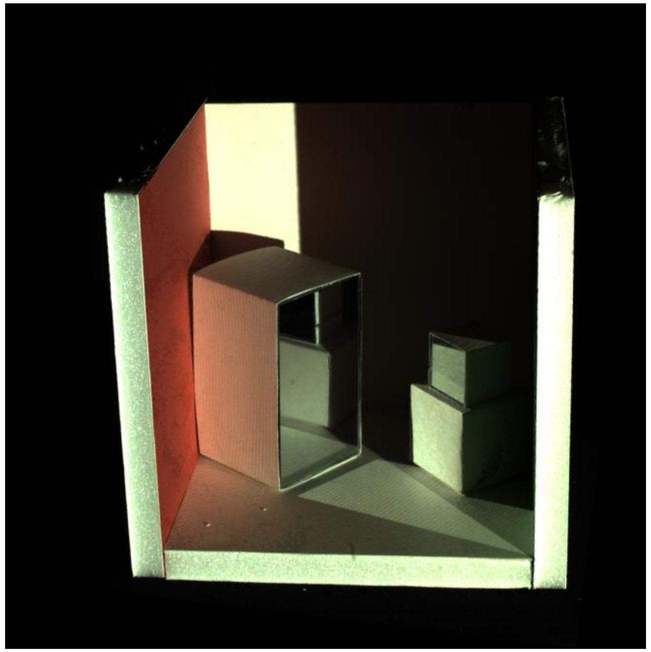
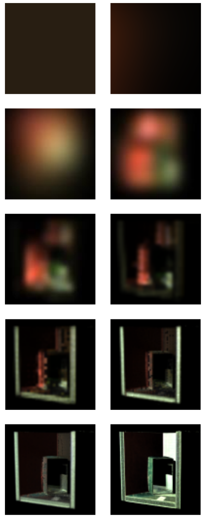
Measuring T efficiently:
Hierarchical Assembly of the Transport Matrix

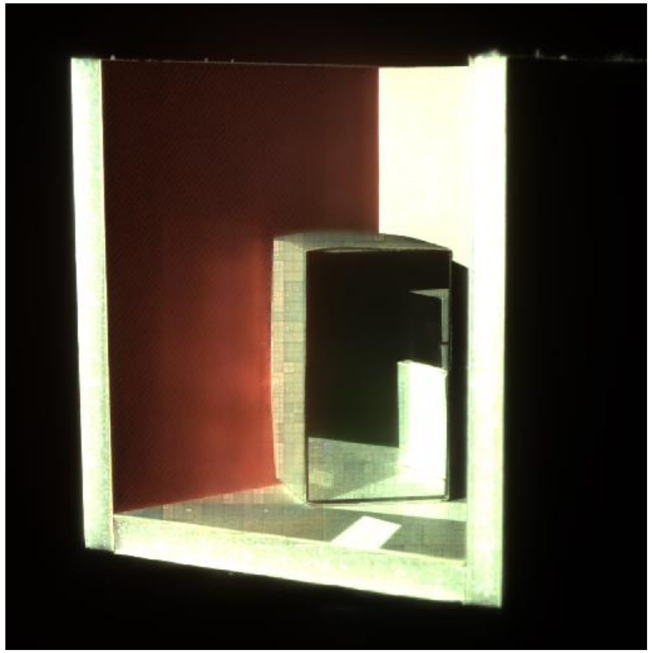
Primal Image



Levels



Synthesized Dual Image



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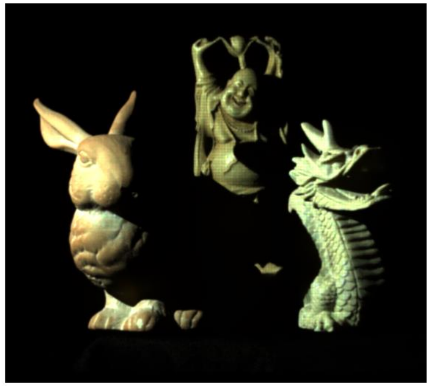
Measuring T efficiently: Hierarchical Assembly of the Transport Matrix

Primal Image

Synthesized Dual Image

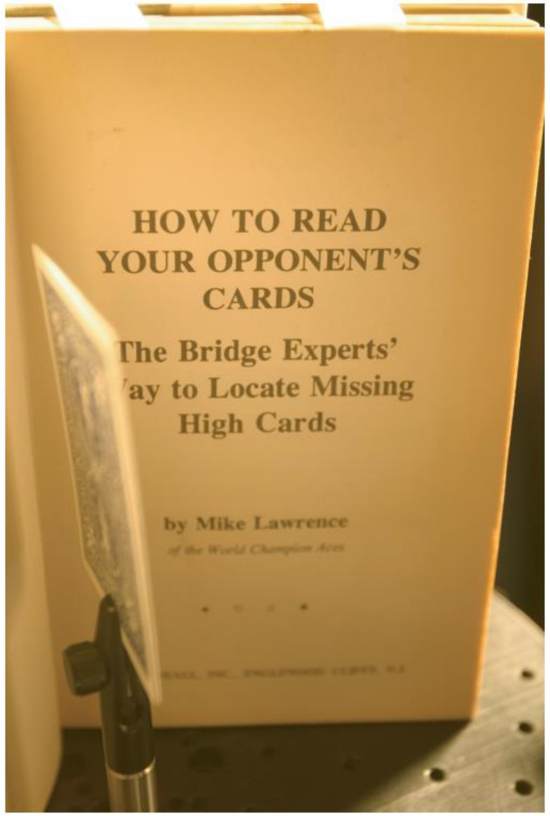


Measuring T efficiently: Hierarchical Assembly of the Transport Matrix

Synthesized Dual Image

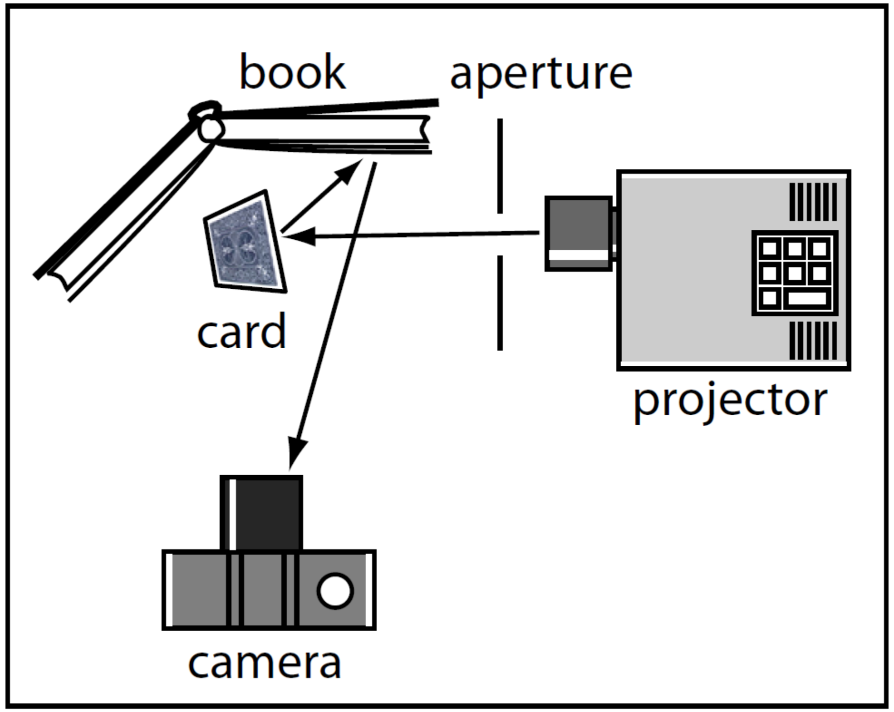
Dual Photography with indirect light transport

How to read your opponent's card?



Dual photography with indirect light transport

Indirect light transport!



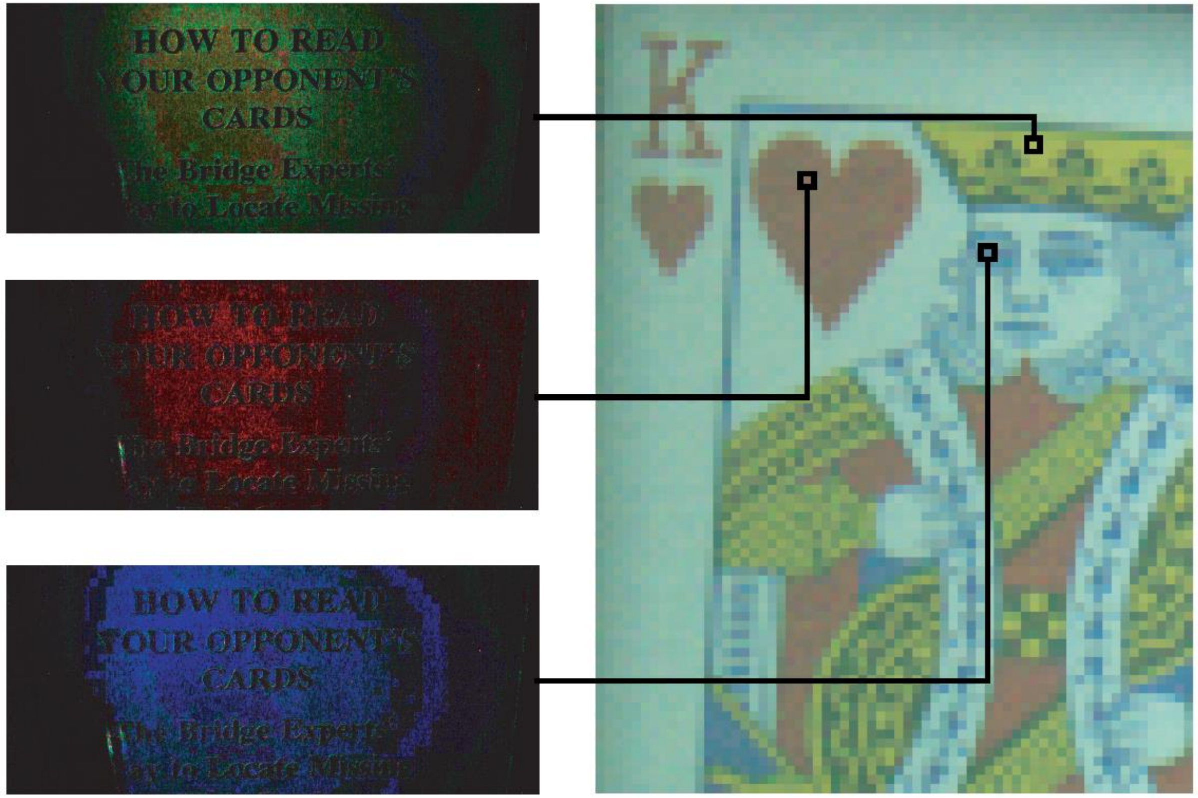
Dual photography with indirect light transport

Synthesized Dual Image

It shows the playing card from the perspective of the projector being indirectly lit by the camera.

Dual photography with indirect light transport

The resulting image has been automatically antialiased over the area of each projector pixel



Sample images acquired when the projector scanned the indicated points on the card. The dark level has been subtracted and the images gamma corrected to amplify the contrast. We see that the diffuse reflection changes depending on the color of the card at the point of illumination. After acquiring the T matrix in this manner, we can reconstruct the floodlit dual image.

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Measuring T **more** efficiently: Compressive Sensing

- Compressive sensing exploits sparsity to recover images using few random samples. In 2009, the authors wrote paper that greatly speeds up the dual photography process.
- Compared to the adaptive methods, compressive sensing does not require time consuming computation in real time between captures since it uses a fixed set of patterns.

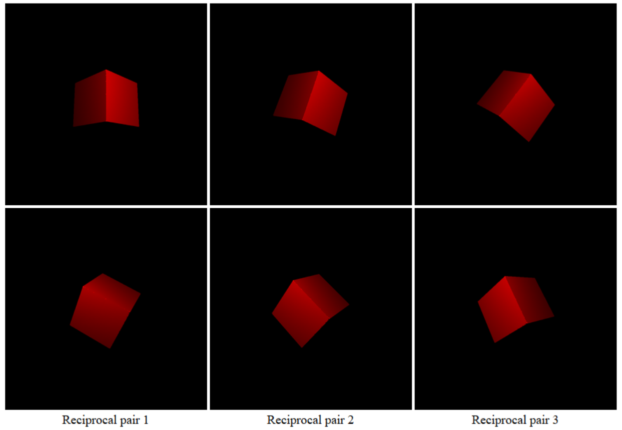
- **Peers, Pieter, et al. “Compressive light transport sensing.” ACM Transactions on Graphics (TOG) 28.1 (2009): 3.**
- Sen, Pradeep, and Soheil Darabi. “Compressive dual photography.” Computer Graphics Forum. Vol. 28. No. 2. Blackwell Publishing Ltd, 2009.

Measuring T **more** efficiently: Compressive Sensing

- An Introduction To Compressive Sampling https://authors.library.caltech.edu/10092/1/CANieeespm08.pdf
- Compressive Sensing: New Paradigms for Image Aquisition and Compression http://w3.impa.br/~aschulz/CS/index.html
- Compressive Sensing, 27o Colóquio Brasileiro de Matemática https://impa.br/wp-content/uploads/2017/04/PM_31.pdf

Other studies!

- Deep learning for real-time single-pixel video
  https://www.nature.com/articles/s41598-018-20521-y
- Helmholtz Stereopsis: A Surface Reconstruction Method -- A method for 3D surface reconstruction (depth and normals)
  http://pages.cs.wisc.edu/~vishala/helmholtz/



Future works!

- Dual Photography + Compressive Sensing + Machine Learning + 3D

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References

- Adriana Schulz http://w3.impa.br/~aschulz/CS/index.html
- Dual Photography - Stanford Computer Graphics https://graphics.stanford.edu/papers/dual_photography/

Thank you!