Reflectance fields and transport matrices

Computational Photography

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Slides by Matt O'Toole

the superposition principle

photo with lights 1 & 2 turned on

=

photo with light 1 turned on

+

photo with light 2 turned on

photo taken under two light sources =
sum of photos taken under each source individually

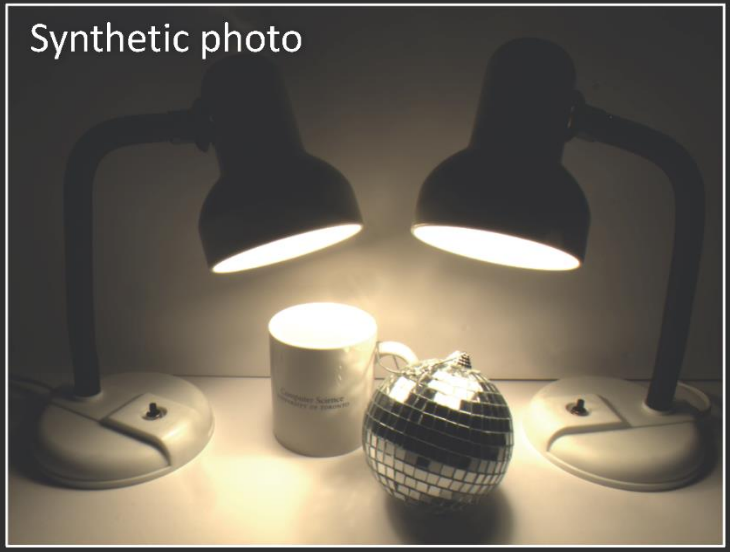
the superposition principle


Synthetic photo


Real photo

photo taken under two light sources =
sum of photos taken under each source individually

the superposition principle



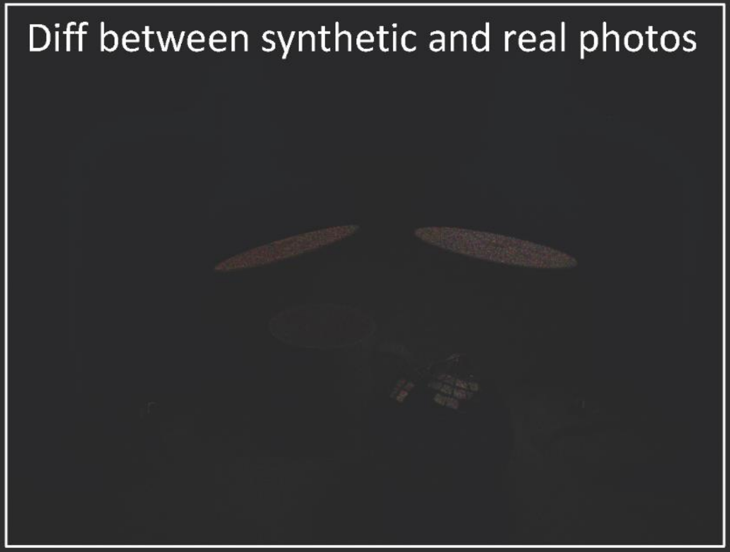


photo taken under two light sources =
sum of photos taken under each source individually

image-based relighting


Relit photo

=


photo with light 1 turned on


photo with light 2 turned on

image-based relighting

=

Weight 1

x 1

+

Weight 2

x 1

image-based relighting

=

Weight 1

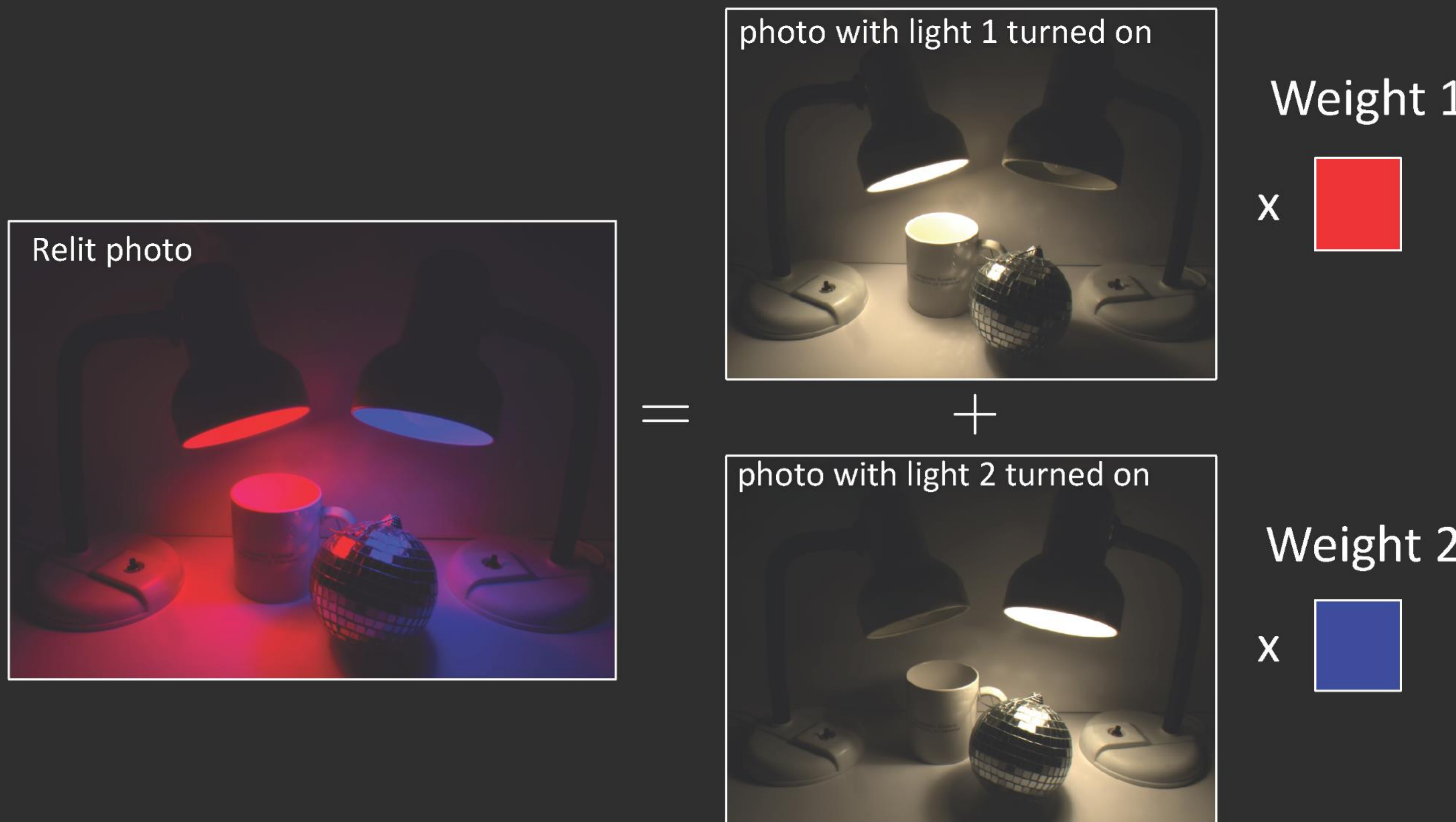
x 1

+

Weight 2

x 0

image-based relighting



$=$

Weight 1

x $\boxed{\mathbf{l_1}}$ $+$

Weight 2

x $\boxed{\mathbf{l_2}}$

$=$

Weight 1 x $\boxed{\mathbf{l}_1}$ $+$

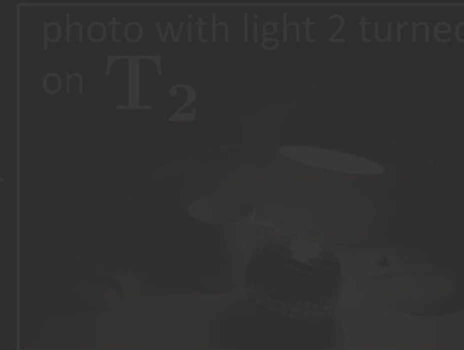
Weight 2 x $\boxed{\mathbf{l}_2}$

$$\mathbf{p} = \sum_{i=1}^{2} \mathbf{T}_i \times \mathbf{l}_i$$

$=$

Weight 1

x $\boxed{\mathbf{l_1}}$ $+$



Weight 2

x $\boxed{\mathbf{l_2}}$

$$n \quad \mathbf{p} = \sum_{i=1}^{2} \mathbf{T}_i \times \mathbf{l}_i$$

n pixel values

=

Weight 1

x $\boxed{\mathbf{l_1}}$ +

Weight 2

x $\boxed{\mathbf{l_2}}$

$$n \quad \mathbf{p} = \sum_{i=1}^{2} \mathbf{T}_i \times \mathbf{l}_i$$

n pixel values

$=$

Weight 1

x $\boxed{\mathbf{l}_1}$ $+$

Weight 2

x $\boxed{\mathbf{l}_2}$

$$\underset{n}{\boxed{\mathbf{p}}} = \sum_{i=1}^{2} \boxed{\mathbf{T}_i} \times \boxed{\mathbf{l}_i}$$

Contribution of the source

n pixel values

$=$

Weight 1

x $\boxed{\mathbf{l_1}}$ $+$

Weight 2

x $\boxed{\mathbf{l_2}}$

Number of controllable sources

Contribution of each source

n

$$\mathbf{p} = \sum_{i=1}^{2} \mathbf{T}_i \times \mathbf{l}_i$$

n pixel values

Relit photo $\mathbf{p}$

$=$

photo with light 1 turned on $\mathbf{T_1}$

Weight 1

x $\boxed{\mathbf{l_1}}$ $+$

photo with light 2 turned on $\mathbf{T_2}$

Weight 2

x $\boxed{\mathbf{l_2}}$

Number of controllable sources

Contribution of each source

$$n \quad \mathbf{p} = \sum_{i=1}^{2} \mathbf{T}_i \times \boxed{\mathbf{l}_i}$$

n pixel values

Relit photo $\mathbf{p}$

$=$

photo with light 1 turned on $\mathbf{T_1}$

Weight 1 x $\boxed{\mathbf{l_1}}$ $+$

photo with light 2 turned on $\mathbf{T_2}$

Weight 2 x $\boxed{\mathbf{l_2}}$

Number of controllable sources

Contribution of each source

$$\mathbf{p} = \sum_{i=1}^{m} \mathbf{T}_i \times \mathbf{l}_i$$

n

n pixel values

Relit photo $\mathbf{p}$

$=$

photo with light 1 turned on $\mathbf{T_1}$

Weight 1

x $\boxed{\mathbf{l_1}}$ $+$

photo with light 2 turned on $\mathbf{T_2}$

Weight 2

x $\boxed{\mathbf{l_2}}$

$$\mathbf{p} = \mathbf{T}\,\mathbf{l}$$

n

m

n pixel values

$n \times m$

m independent illumination degrees of freedom

the light transport matrix

Sloan et al 02, Ng et al 03, Seitz et al 05,Sen et al 05, …

transport matrix represents the set of photos under all possible (controllable) lighting conditions

$$\mathbf{p} = \mathbf{T} \, \mathbf{l}$$

n

m

n pixel values

$n \times m$

m independent illumination degrees of freedom

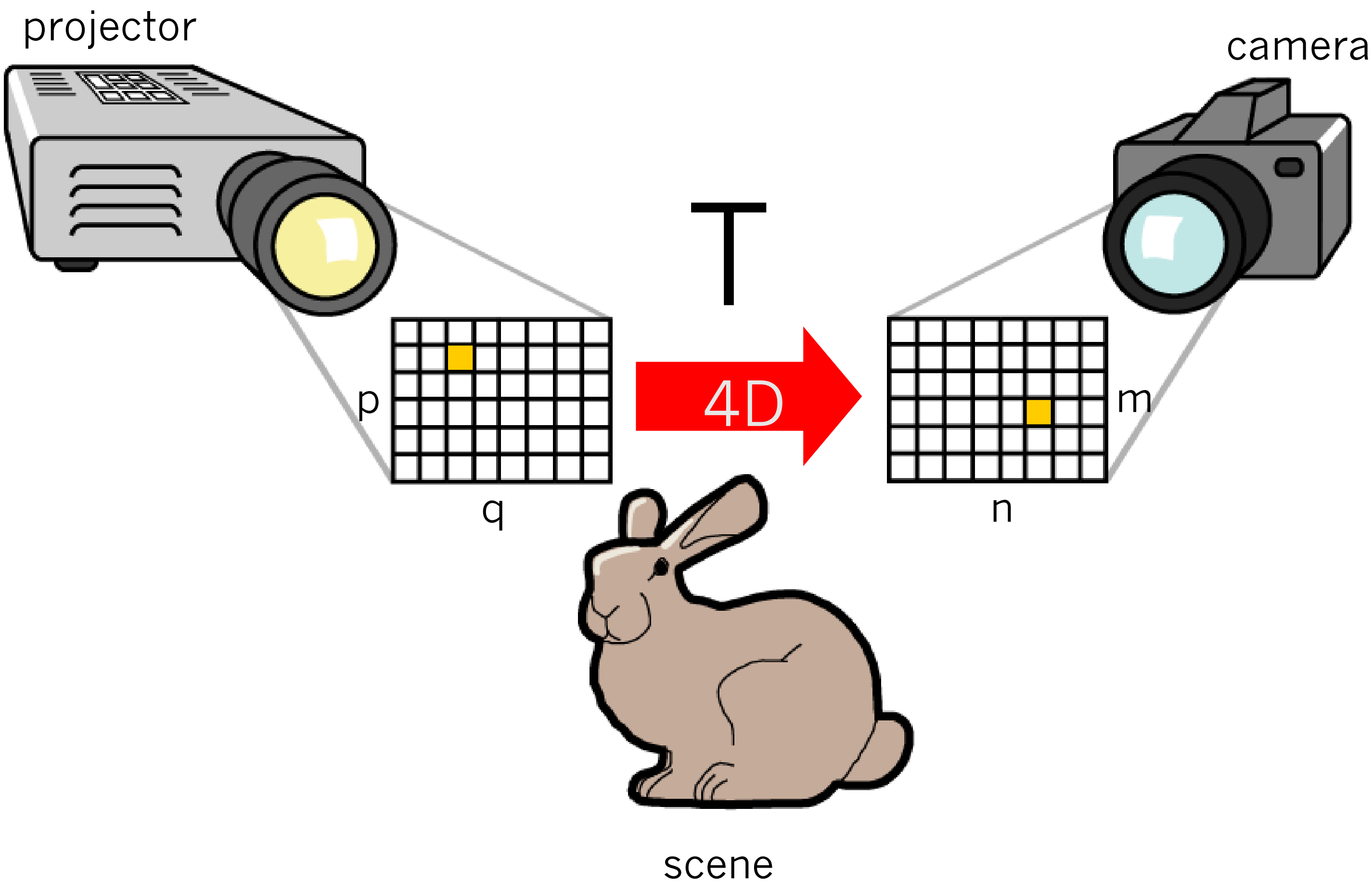
Acquiring the Reflectance Field [Debevec et al. 2000]

image-based rendering & relighting

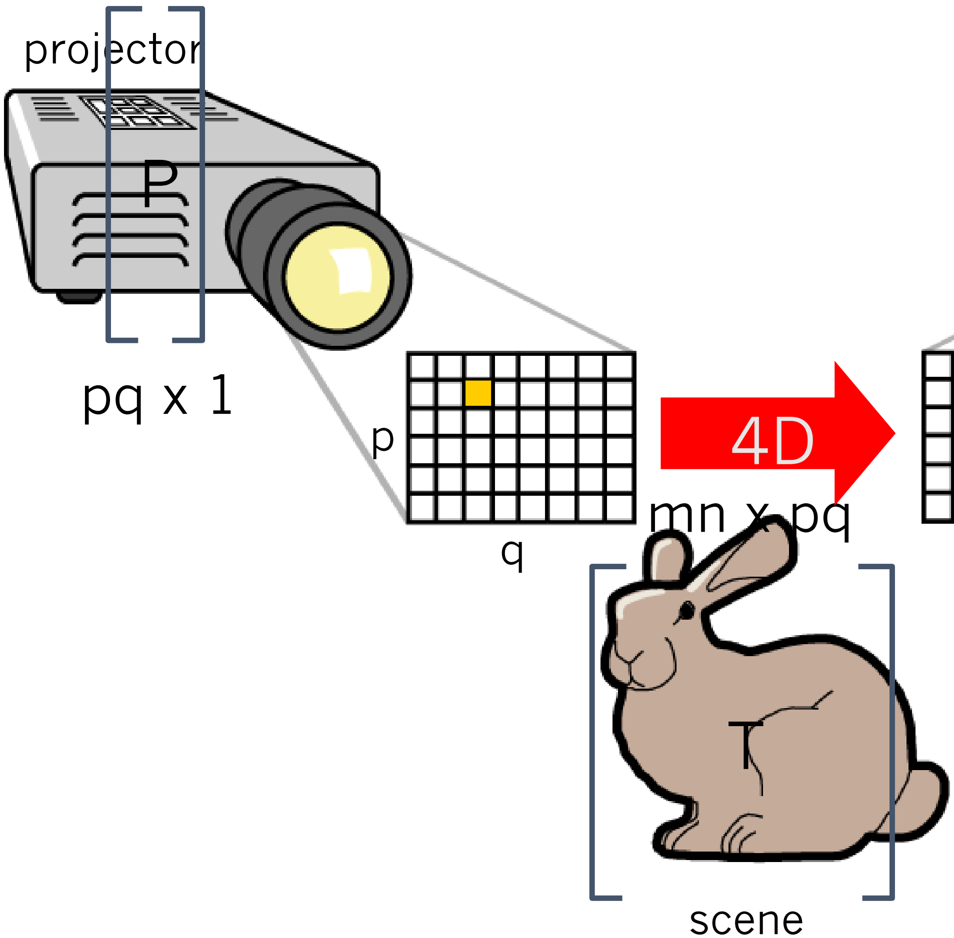
Reflectance field

Performance Relighting [Peers2007]

Pixel-to-Pixel Transport

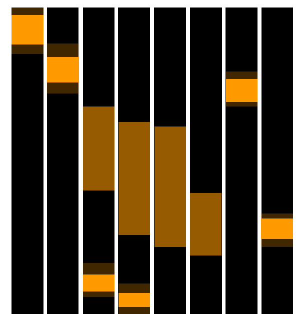


Mathematical Notation



Mathematical Notation

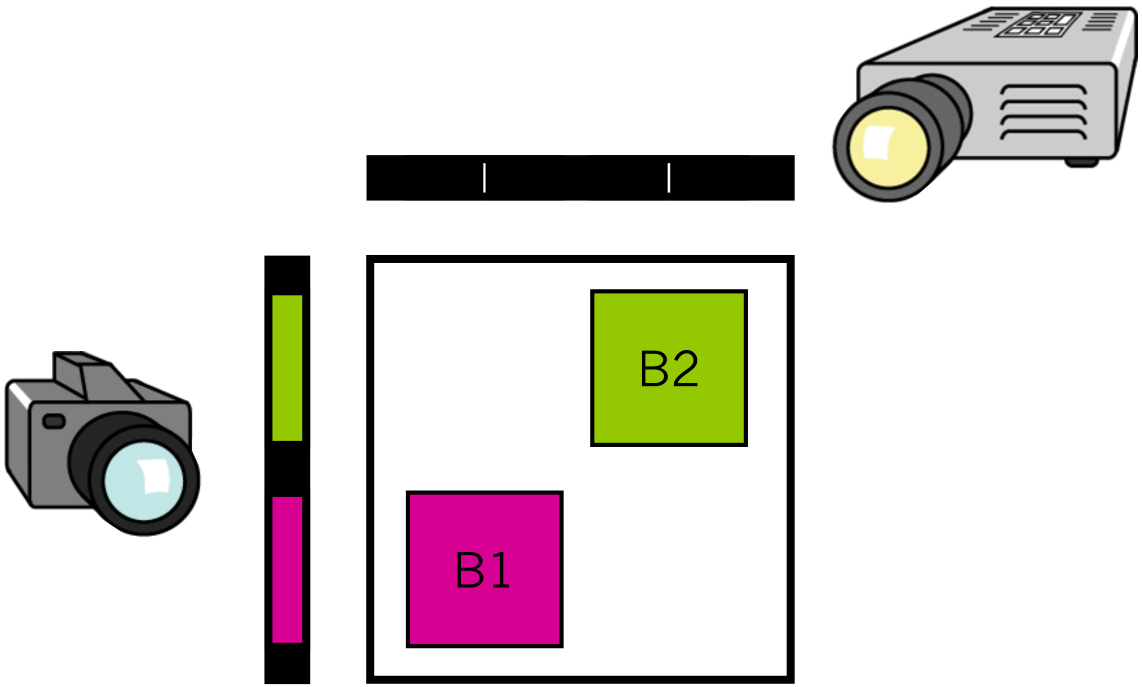
$$\underset{pq \times 1}{\begin{bmatrix} P \end{bmatrix}} = \underset{mn \times pq}{\begin{bmatrix} T \end{bmatrix}} \underset{mn \times 1}{\begin{bmatrix} C \end{bmatrix}}$$



- Matrix properties
  - little interreflection ↔ T rather sparse
  - many interreflections ↔ T rather dense

Adaptive Parallel Acquisition

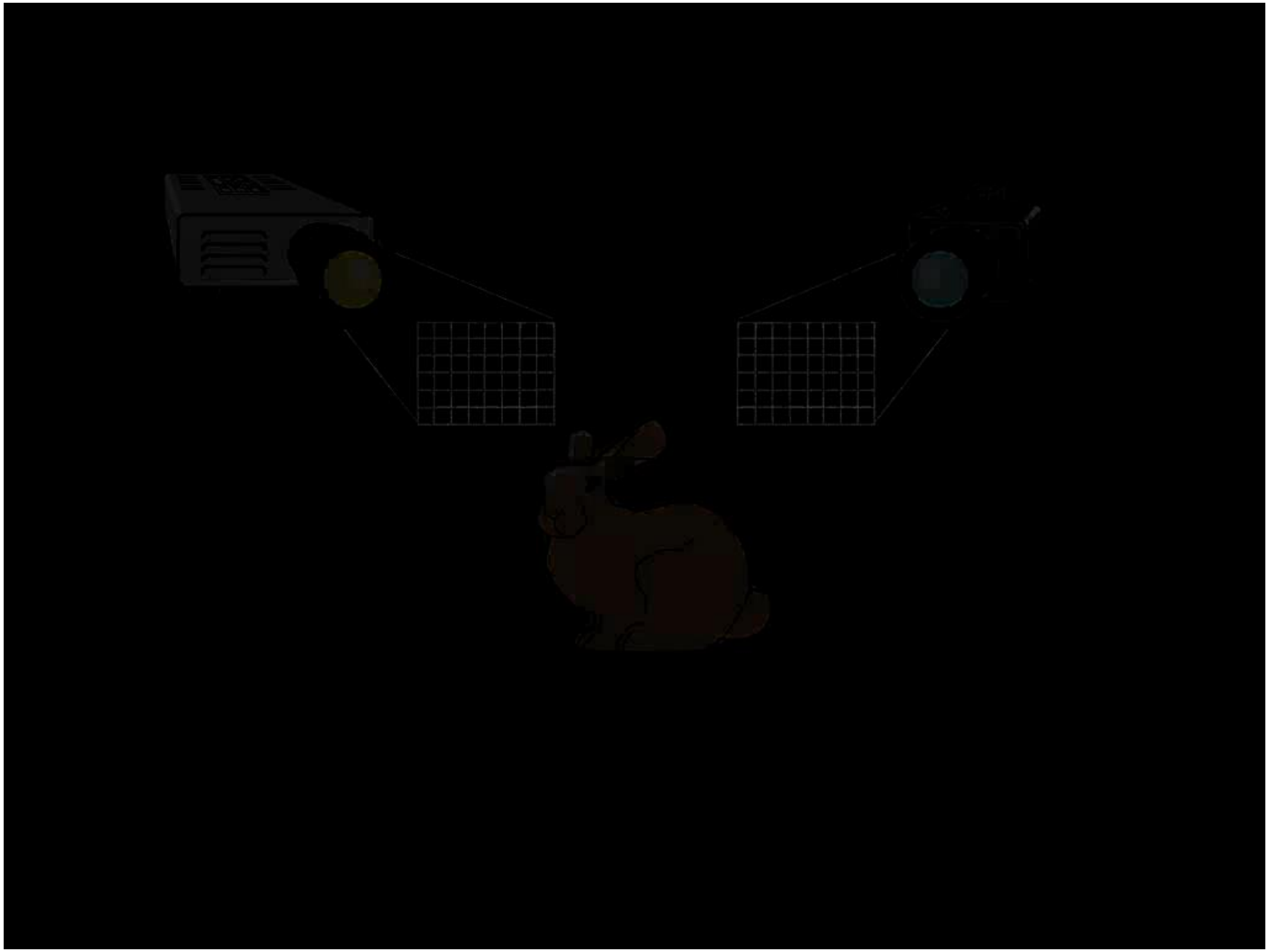
- assumption: sparse matrix
- radiometrically independent blocks can be sensed in parallel



[Sen et al., Dual Photography, SIGGRAPH 2005]

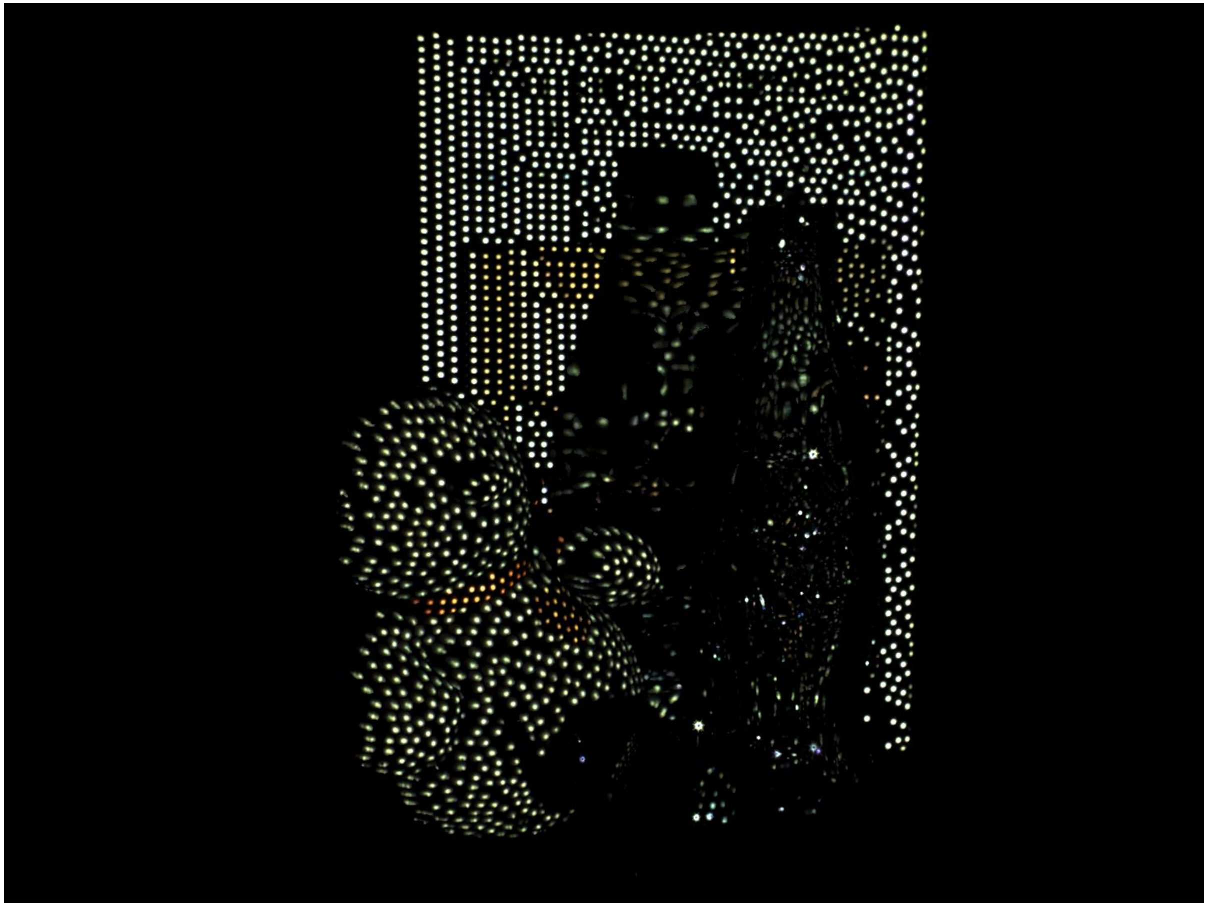
Adaptive Multiplexed Acquisition

- Parallel investigation possible if regions do not overlap in camera image



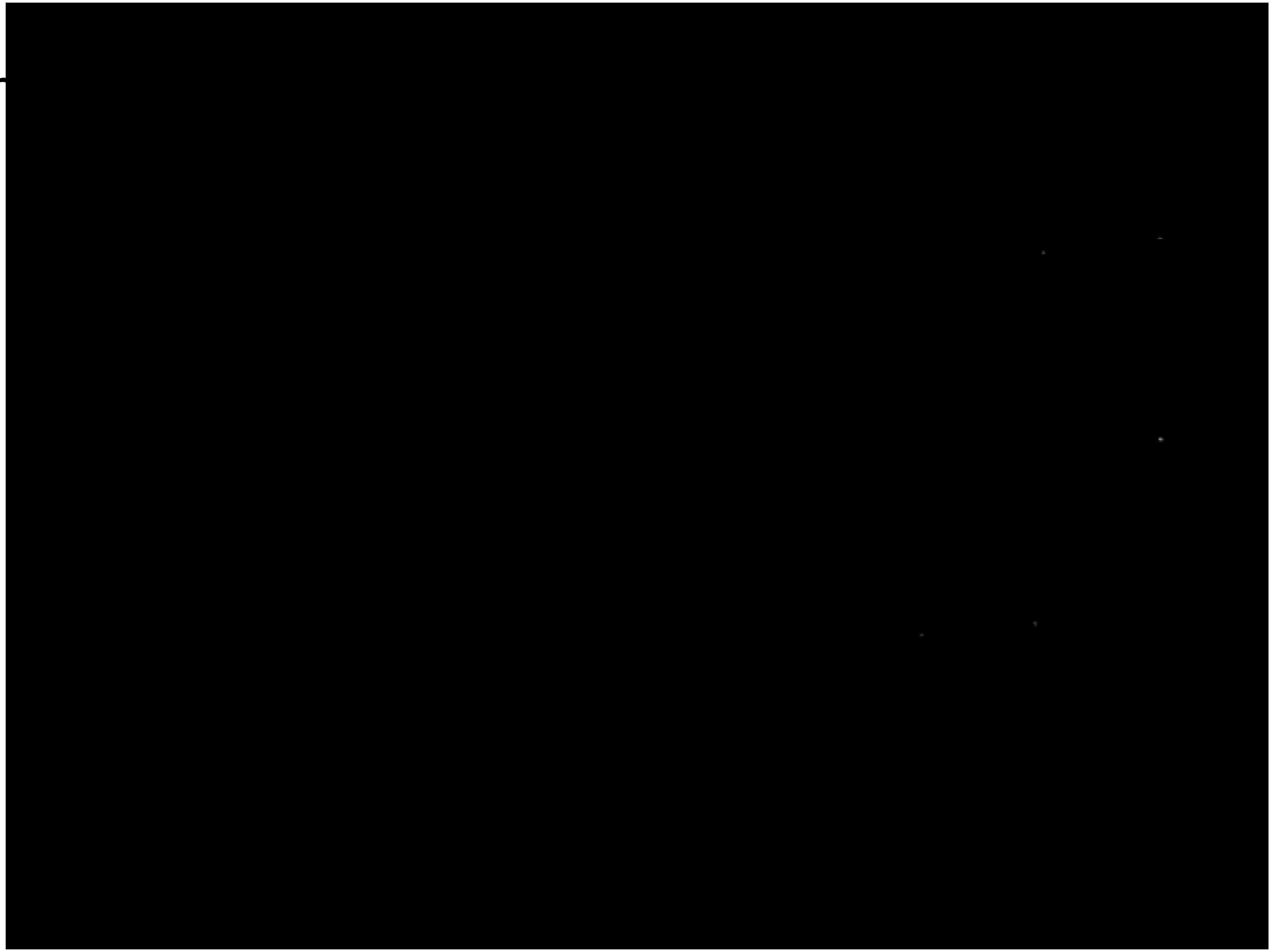
Adaptive Acquisition

- parallel investigation if regions do not overlap in camera image

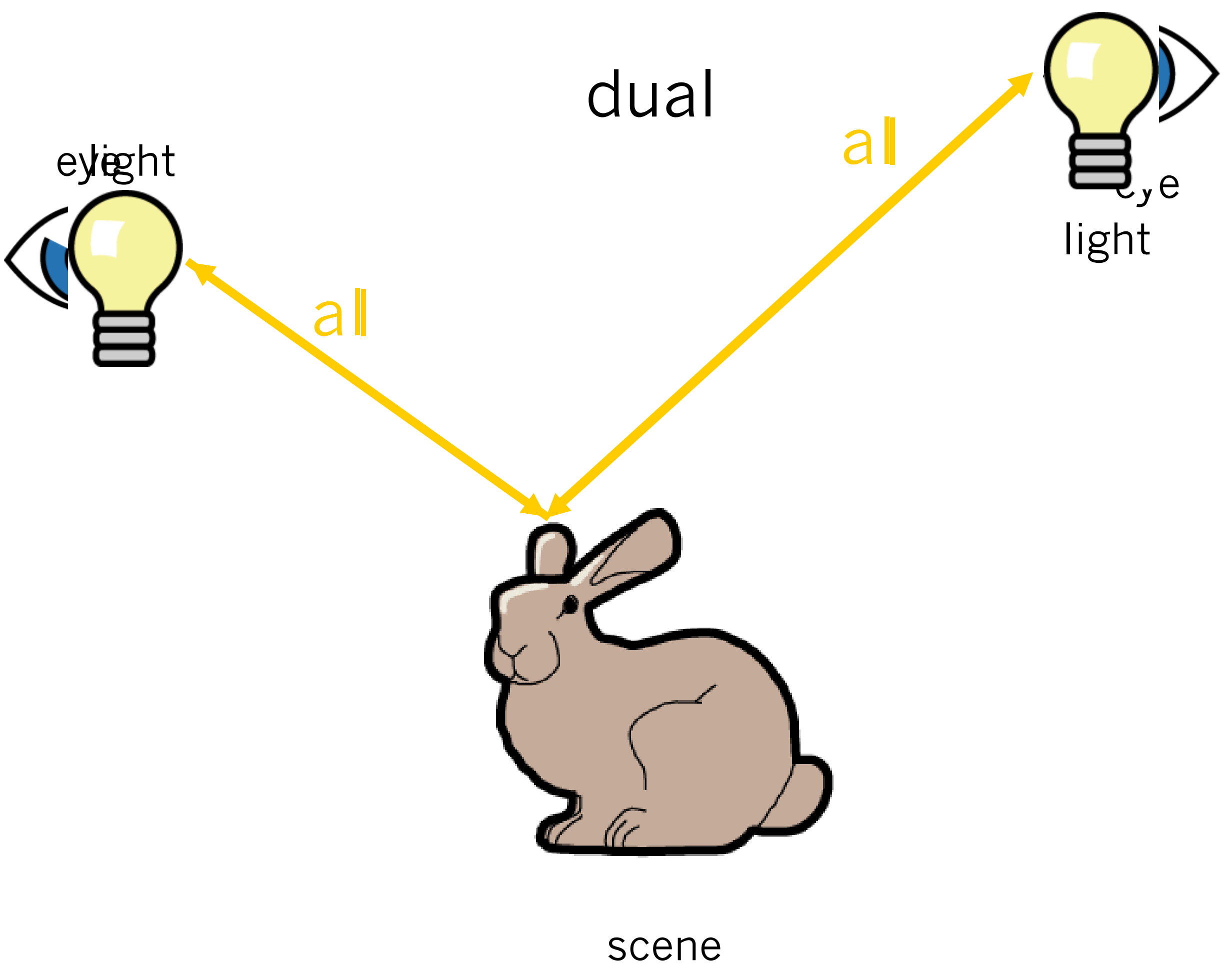


Relighting with 2D Patterns

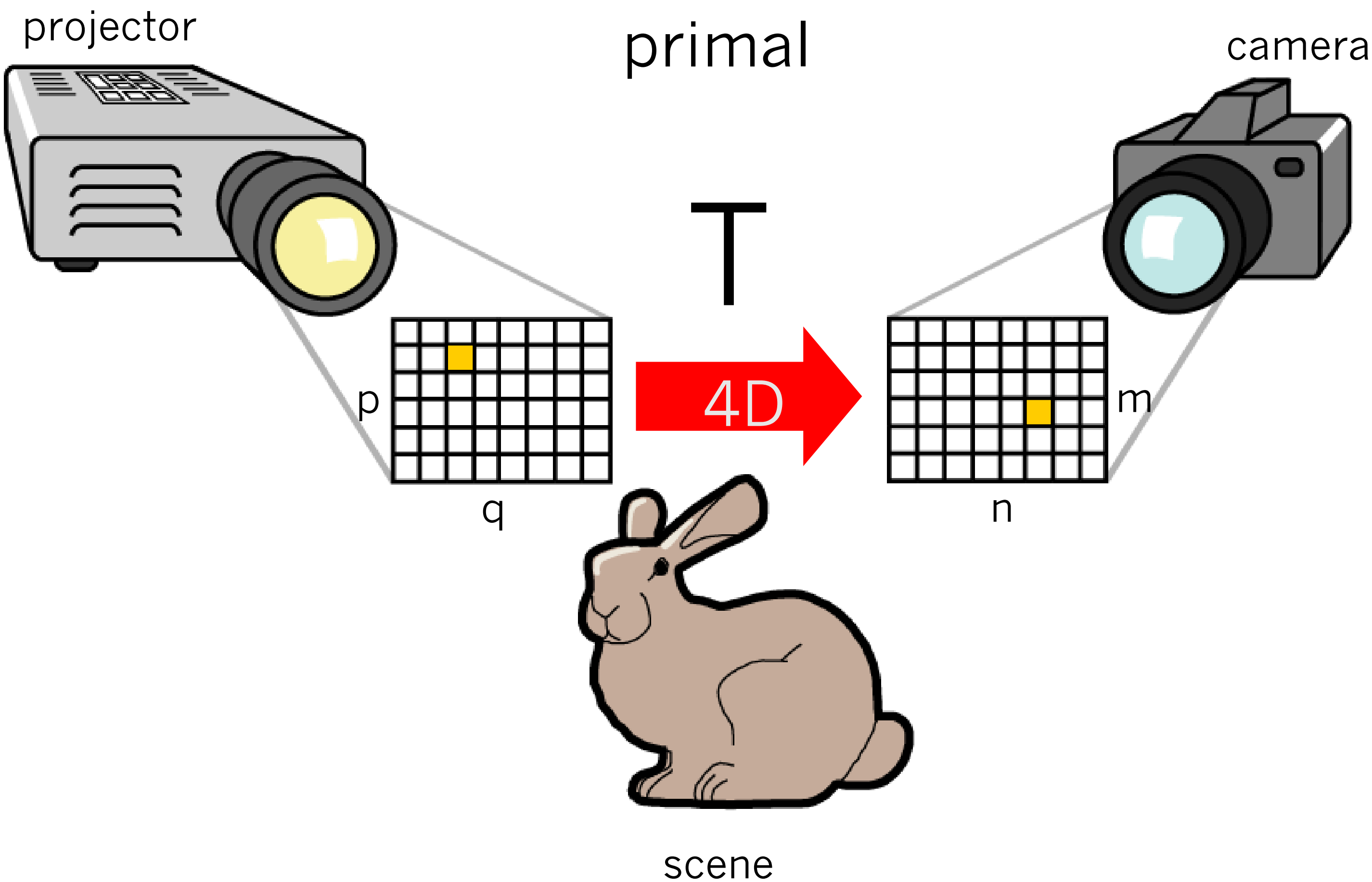
[Sen



Helmholtz Reciprocity



Dual Photography for Relighting



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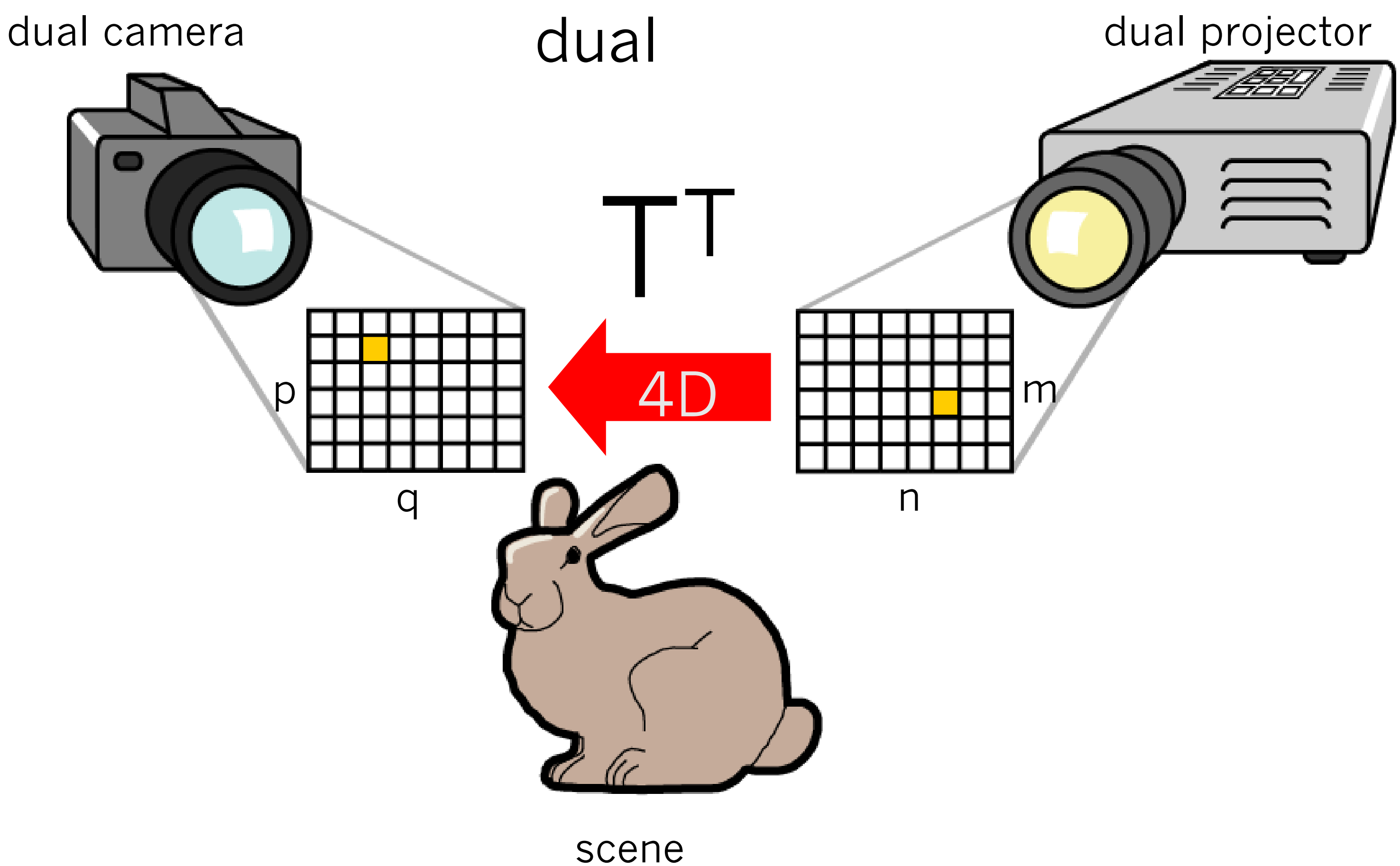
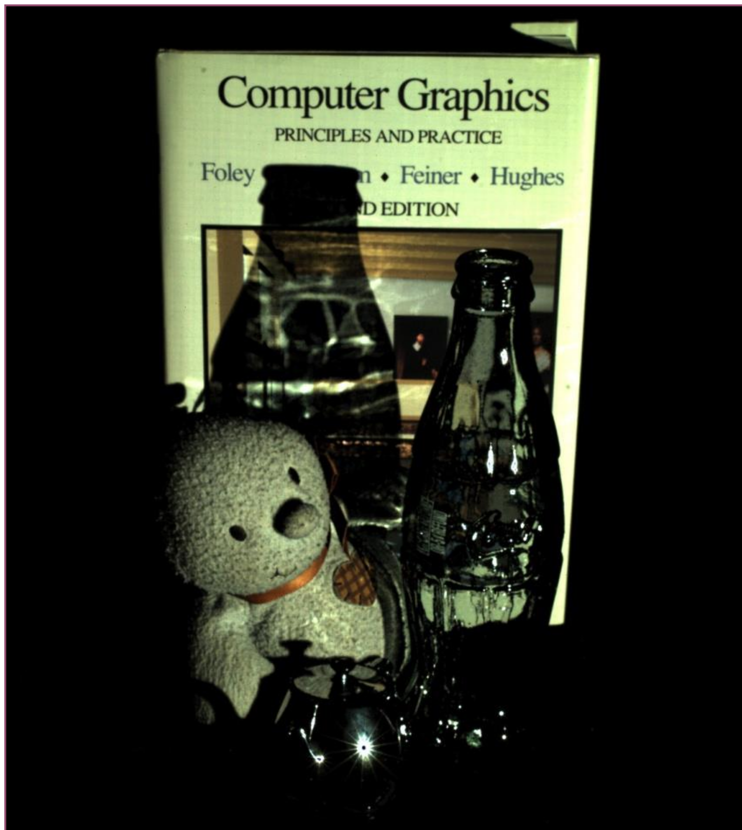
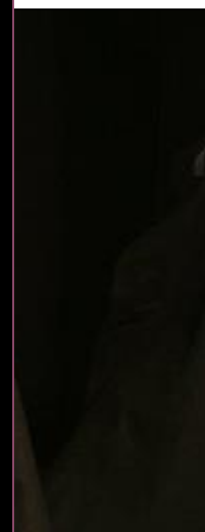
Dual Photography for Relighting



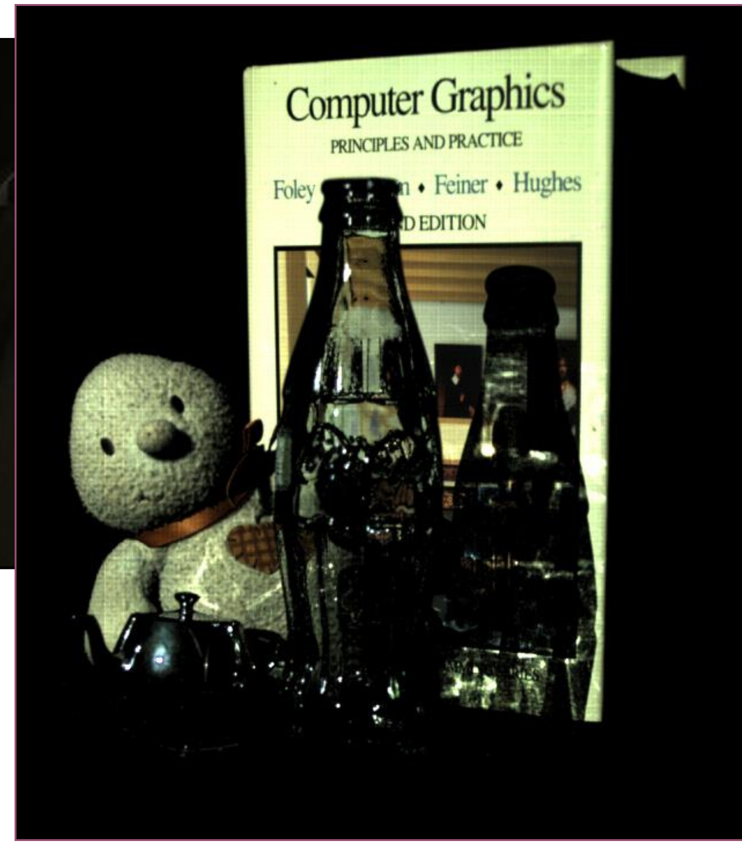
Using the Transposed T Matrix

standard photograph
from camera





dual photograph
from projector

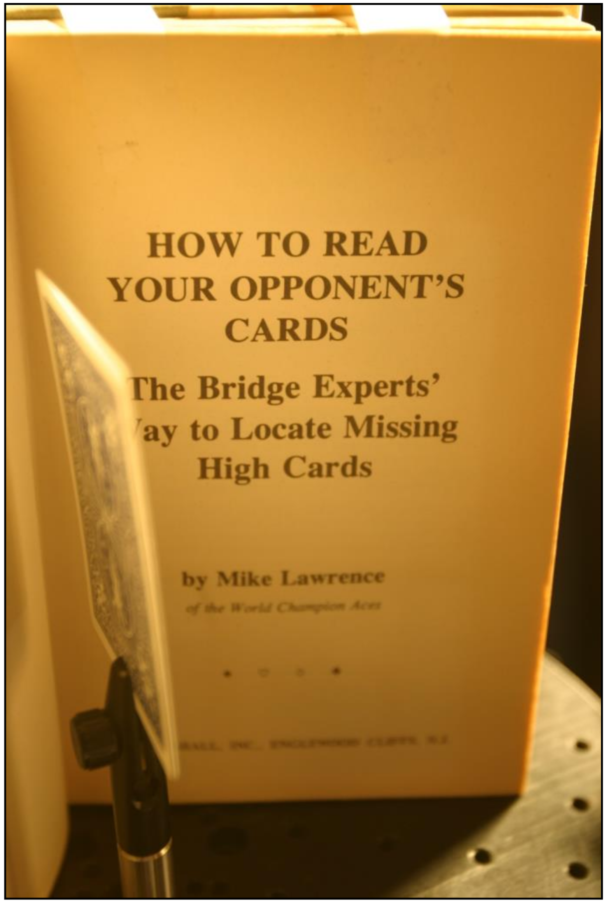


Sample Results

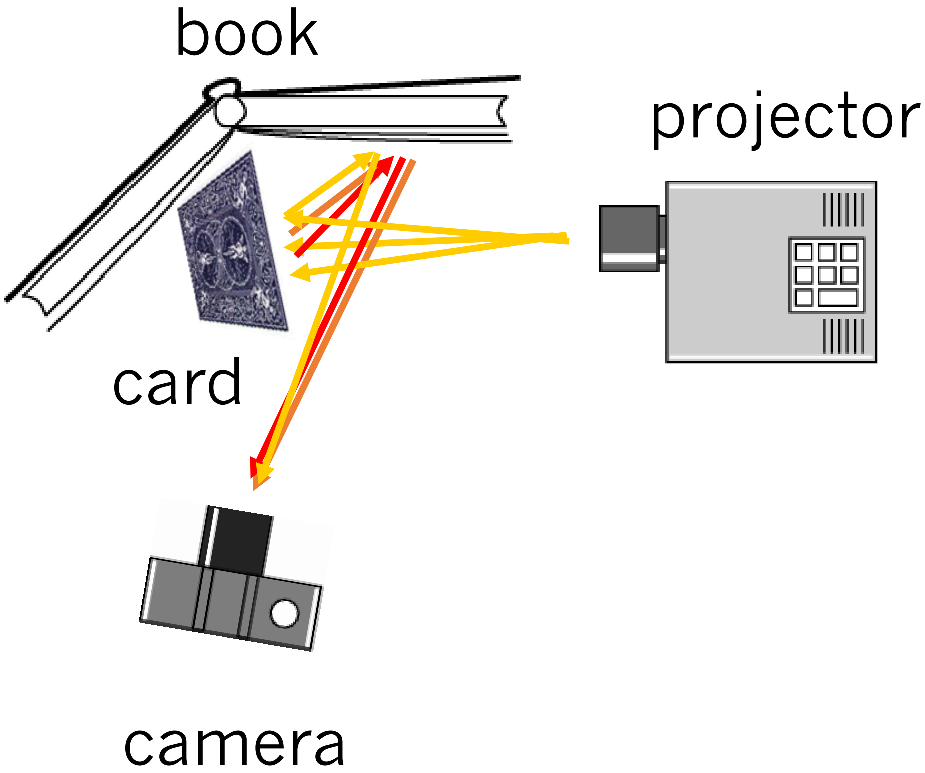
primal

dual

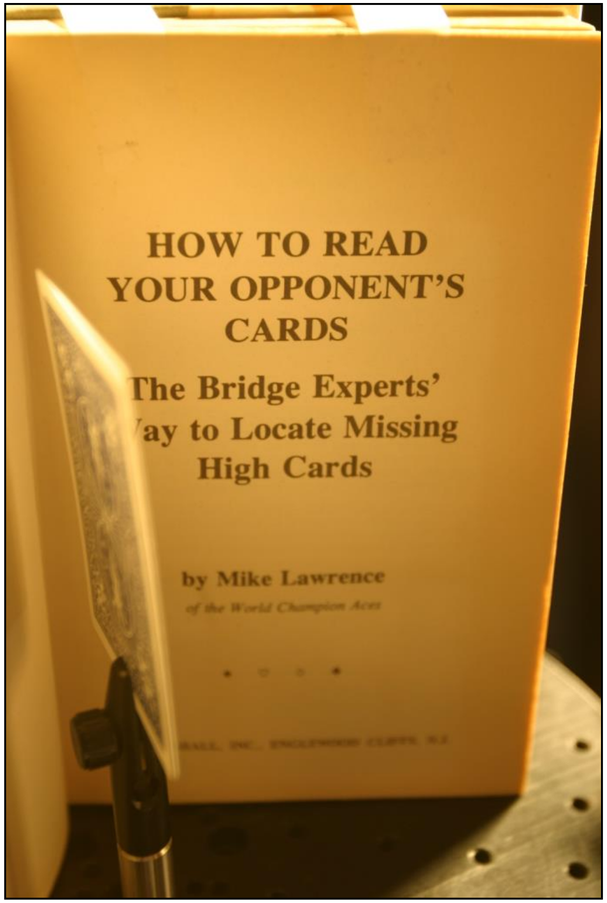
Card Experiment



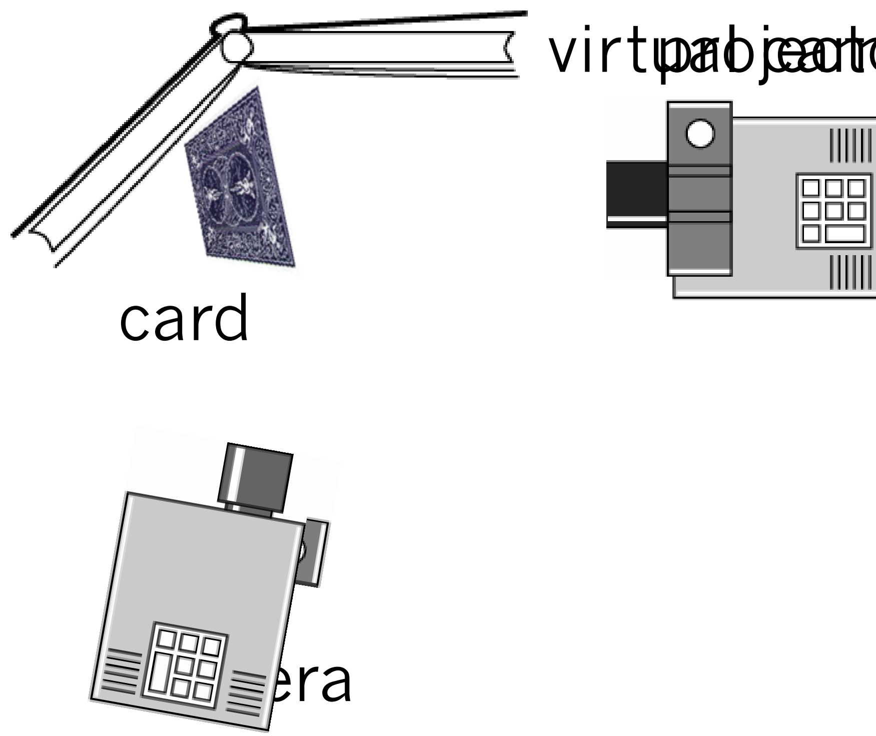
primal



Card Experiment

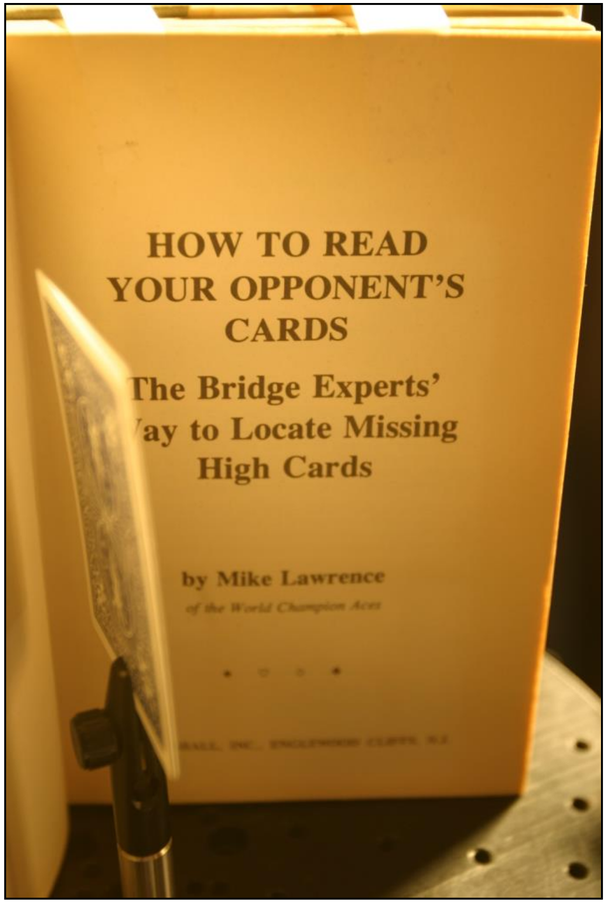


primal



virtual projector

Card Experiment



primal

dual

Optical Computing [O'Toole 2010]

- Krylov subspace method for eigenspace computation
- Capture Tl, T^2l, T^3l, ... (converges to T's principal eigenvector)

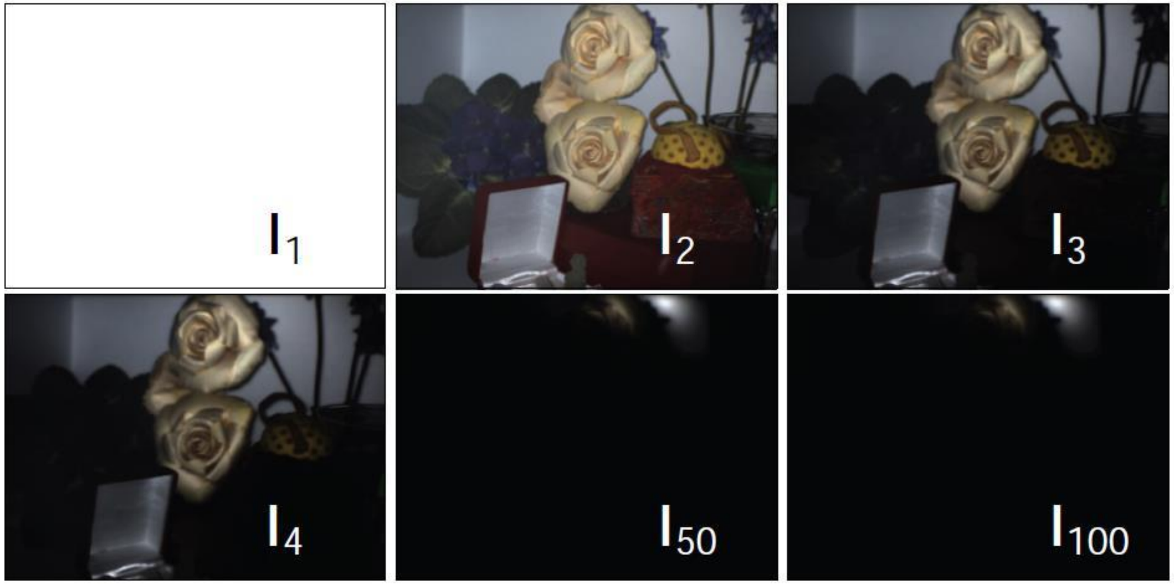
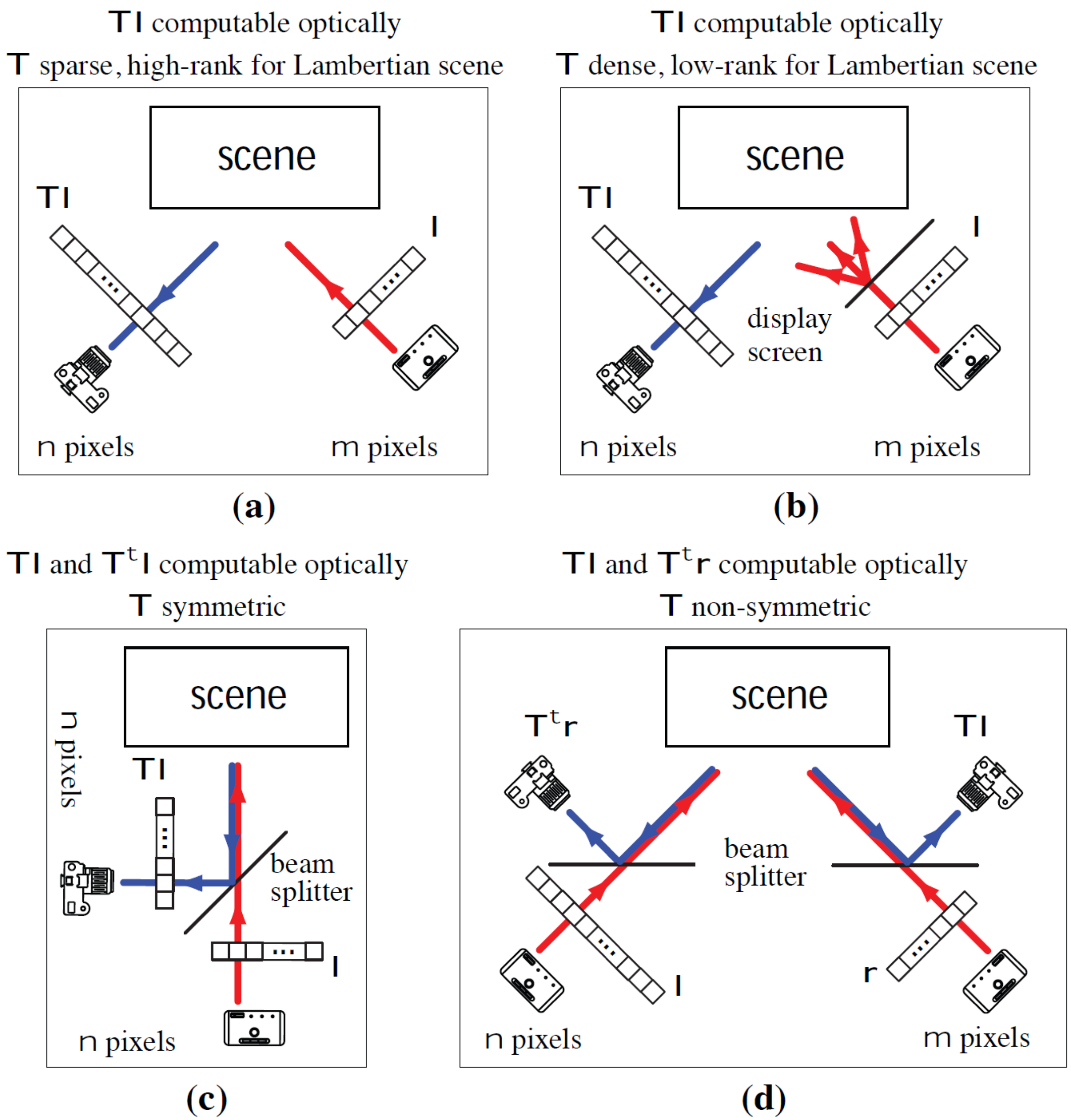


Figure 4: ***Optical power iteration in action.*** *We used the coaxial arrangement of Figure 2(c) for this example, where a camera and a projector share the same viewpoint and* T *is symmetric. We started with a constant illumination vector* l_1*, shown above, so the first photo of the scene was captured under constant illumination. That photo became the next illumination vector,* l_2*, also shown above. The illumination vectors change very little after about 50 captured photos, indicating that a good approximation of* T*'s principal eigenvector has already been found.*

Optical Computing



Optical Computing

Exploiting light transport properties for photography

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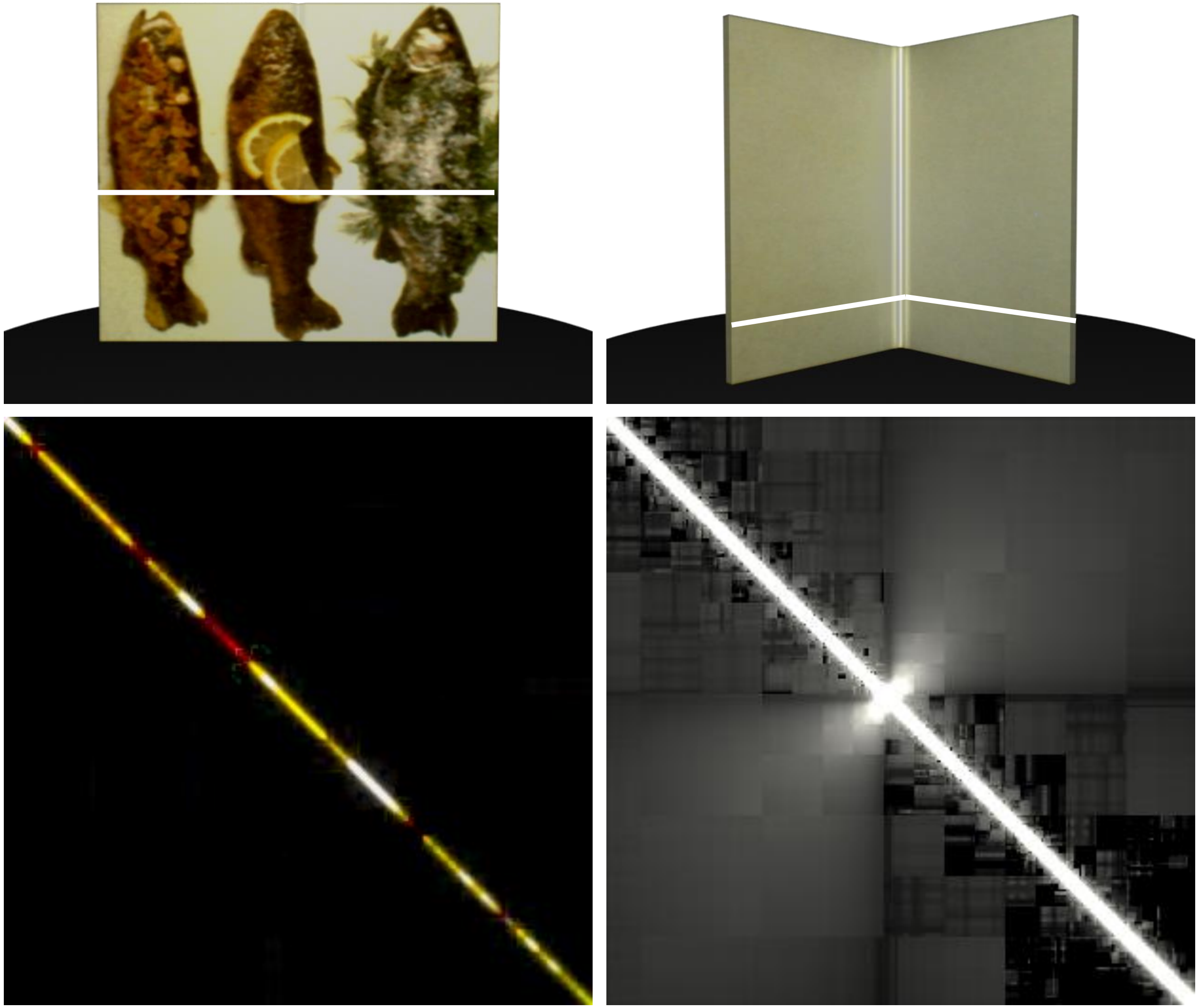
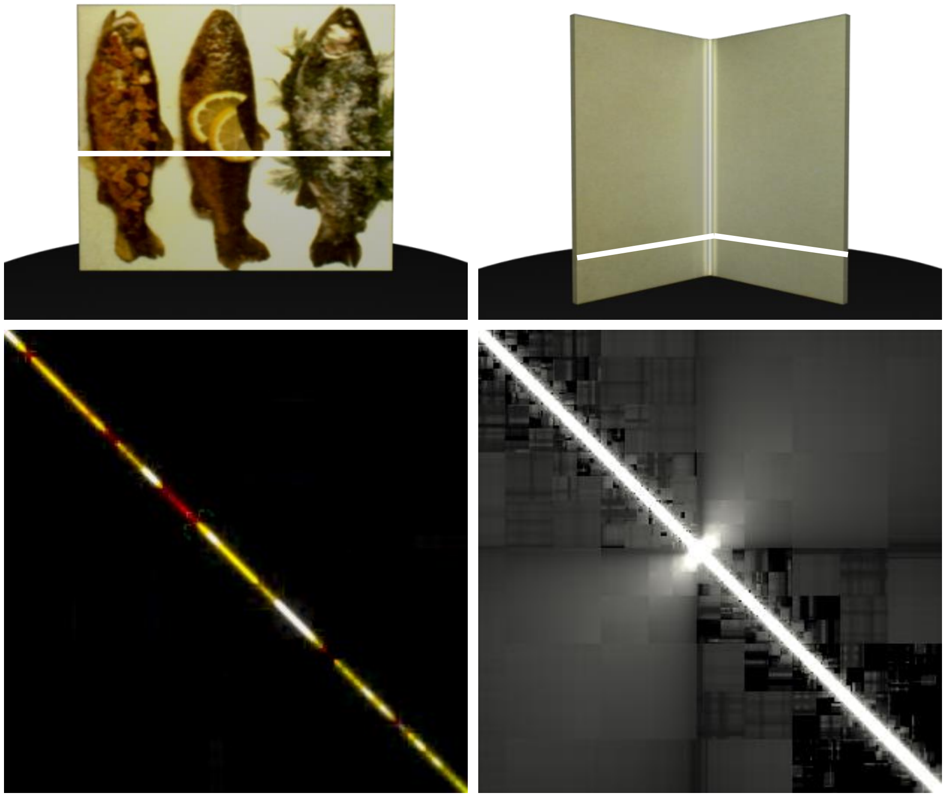
Light Transport Matrix

Local vs. Global Reflections



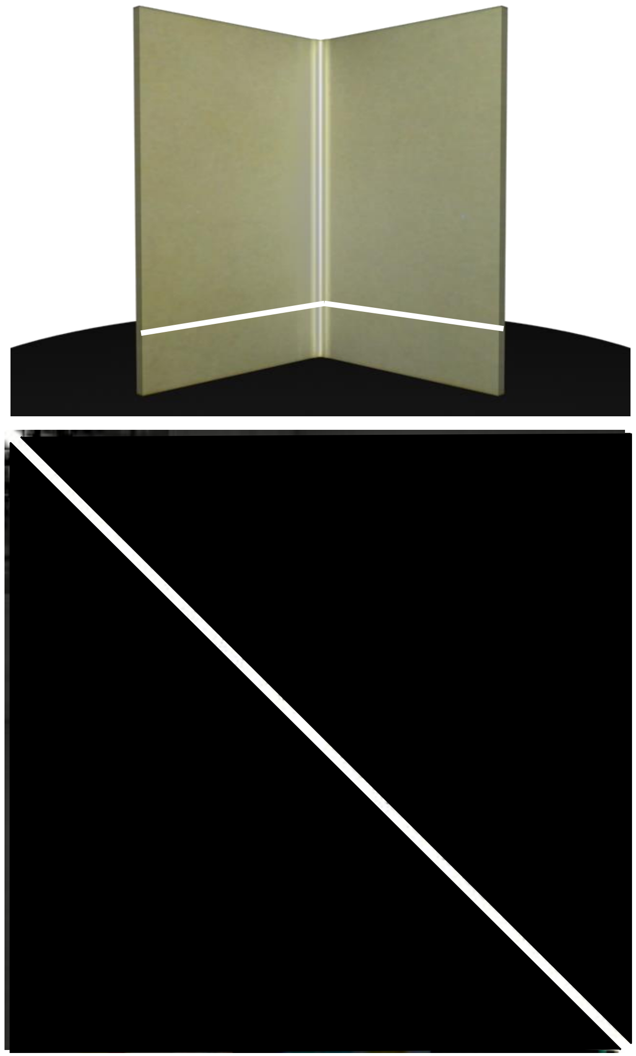
[Garg, Talvala, Levoy, Lensch · EGSR 2006]

Local vs. Global Reflections



- We are interested in the direct reflections.
- Indirect reflections correspond to smooth regions in the matrix.

Getting Rid of Global Effects



- Remove off-diagonal components
- Diagonal entries might still contain global components

Fast Separation of Direct and Global Effects

- Main idea: global illumination effects dampen high frequencies
  - illuminate with shifted high frequency patterns
  - only the local illumination will change
  - global illumination will be invariant to phase shifts

image

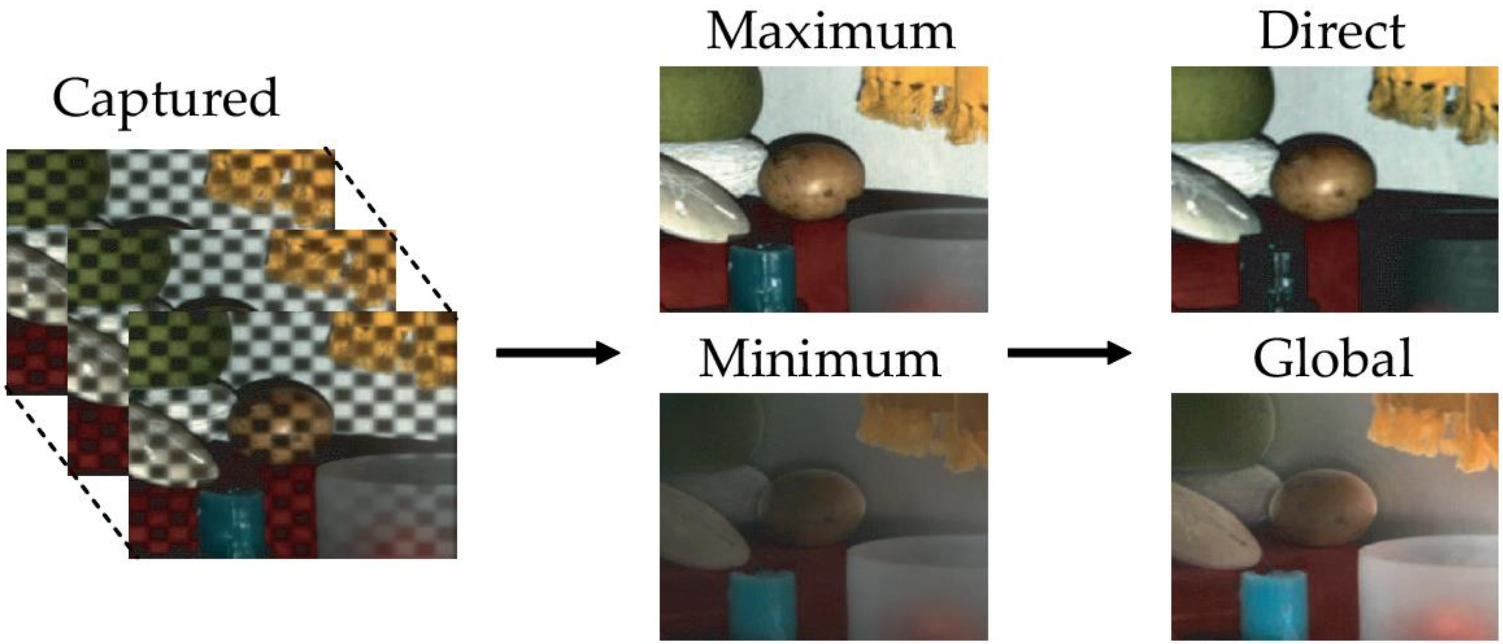
direct

global component

[Nayar et al. SIGGRAPH 2006]

Fast Separation of Direct and Global Effects

- shifted periodic patterns (e.g. checker board)
- record per-pixel minimum and maximum
- approximation:
  - $L_g = L_{\min}, \quad L_d = L_{\max} - L_{\min}$



[Nayar et al. SIGGRAPH 2006]

References

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- Garg et al., Symmetric Photography: Exploiting Data-sparseness in Reflectance Fields, EGSR 2006

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