Light Transport

CS535

Daniel G. Aliaga

Department of Computer Science

Purdue University
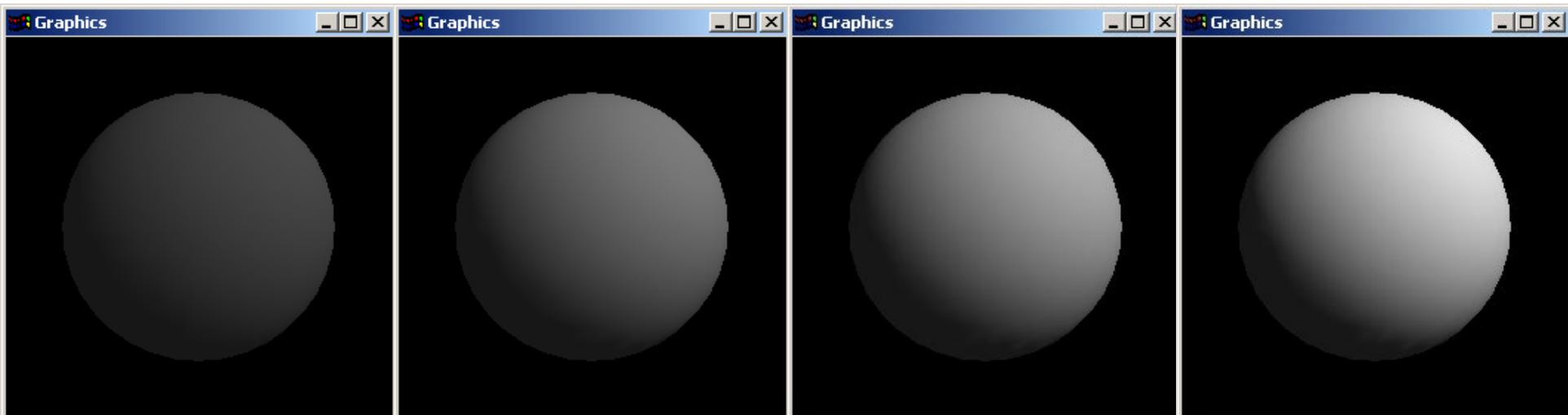
Topics

- Local and Global Illumination Models
- Helmholtz Reciprocity
- Dual Photography/Light Transport in Real-World

Diffuse Lighting

- A.k.a. Lambertian illumination
- A fraction of light is radiated in every direction
- Intensity varies with cosine of the angle with normal

Specular Lighting

- Shiny surfaces reflect predominantly in a particular direction, creating *highlights*
- Where the highlights appear depends on the viewer's position
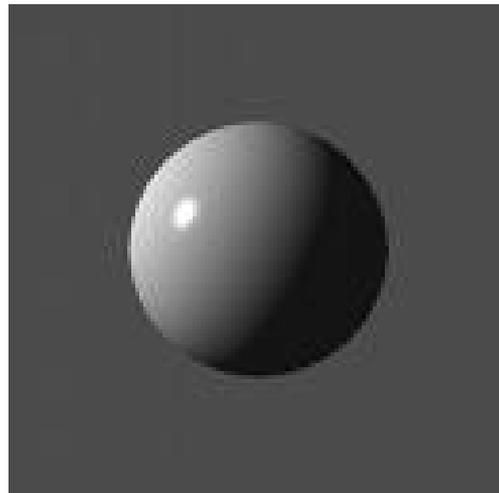
Global Illumination
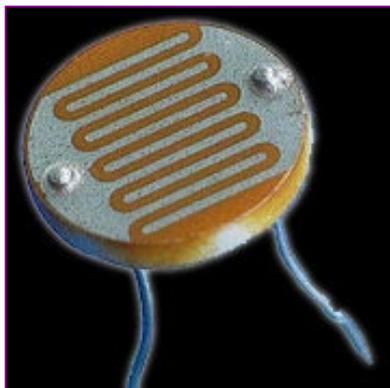
- Ray tracing

Conclusion

- Modeling illumination is hard
- "Undoing" physically-observed illumination in order to discover the underlying geometry is even harder

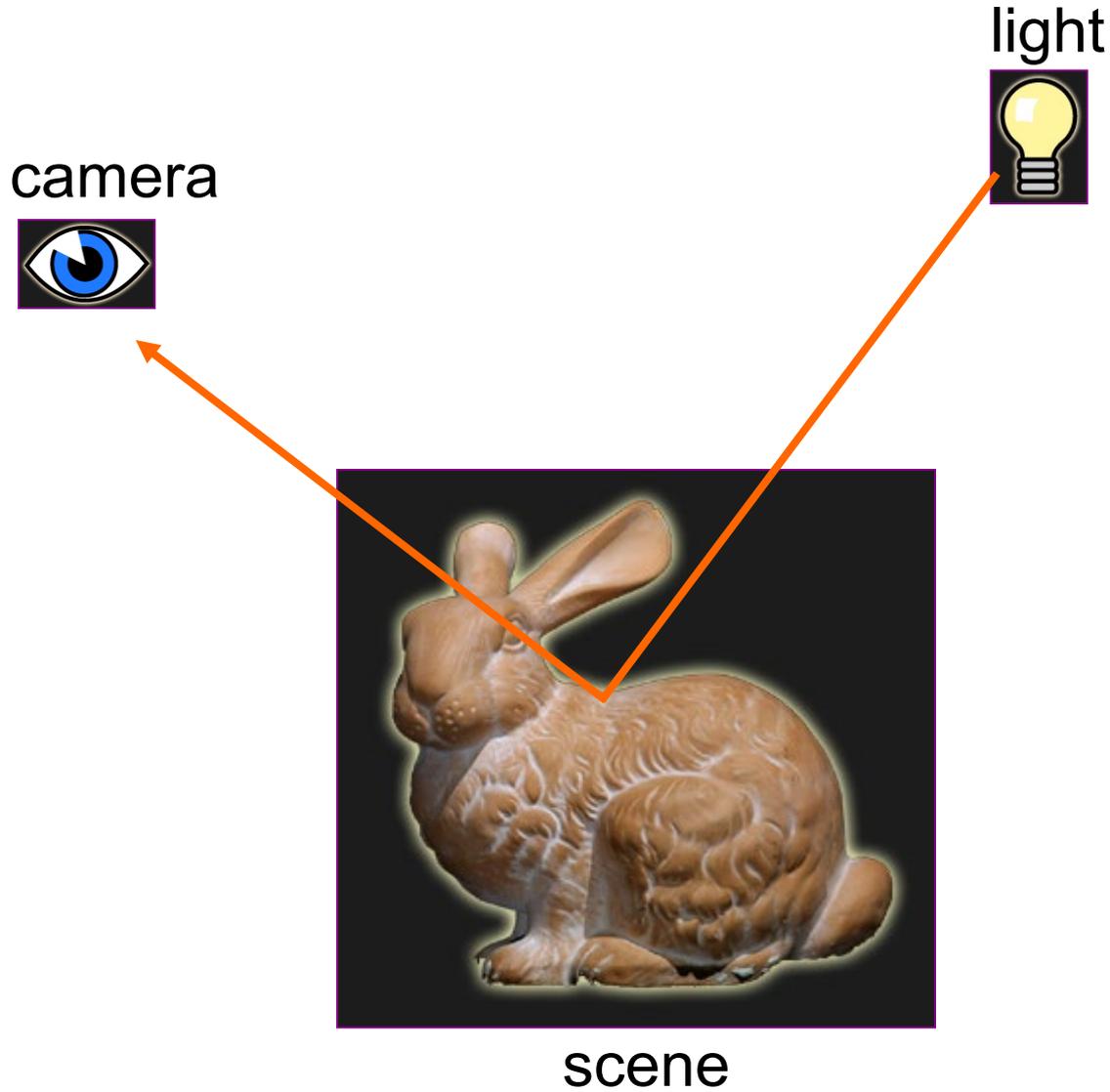- Insight: let's sample it and "re-apply" it!

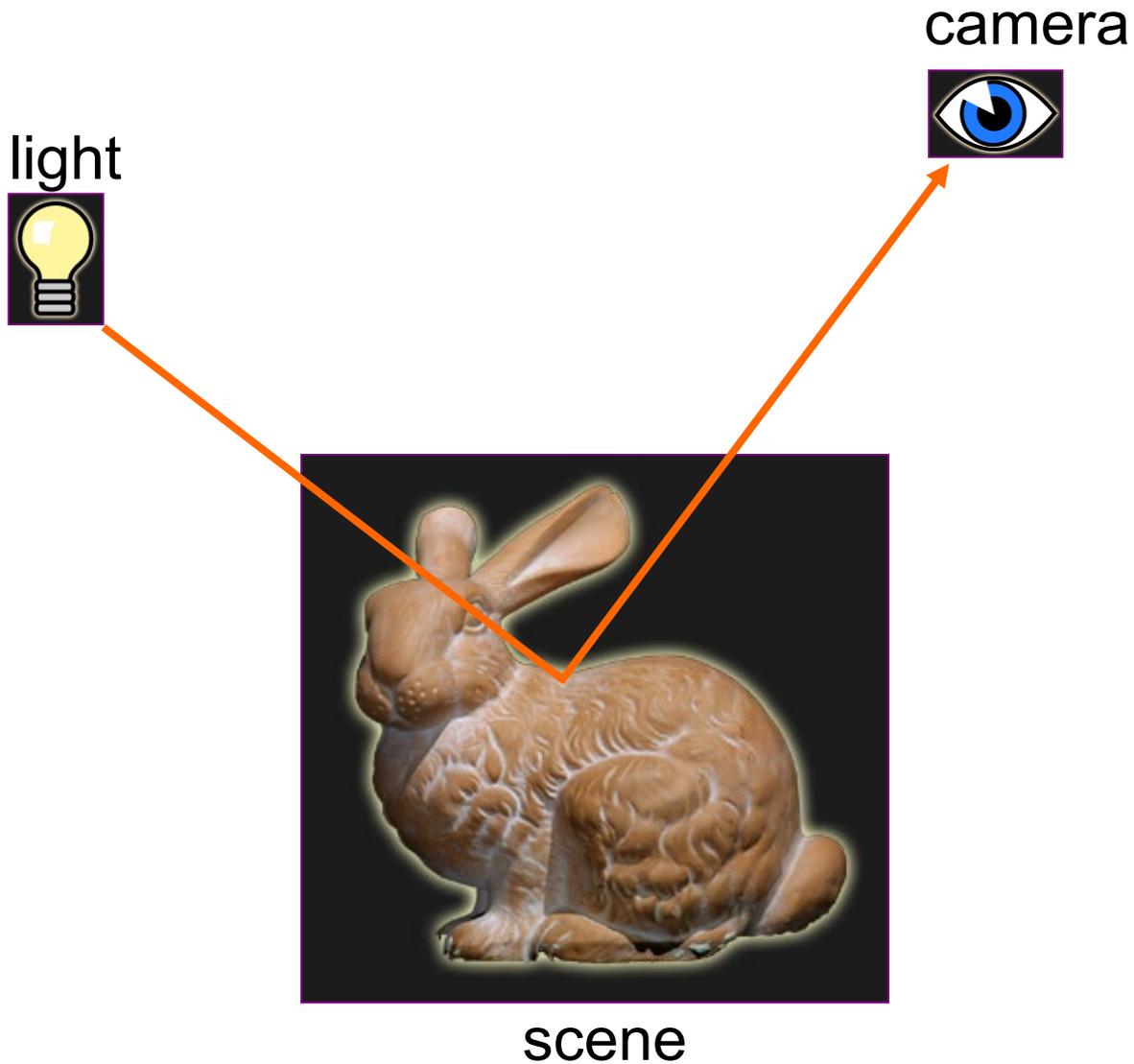# Dual Photography

Sen et al., SIGGRAPH 2005

(slides courtesy of M. Levoy)

Helmholtz Reciprocity

light

camera

scene
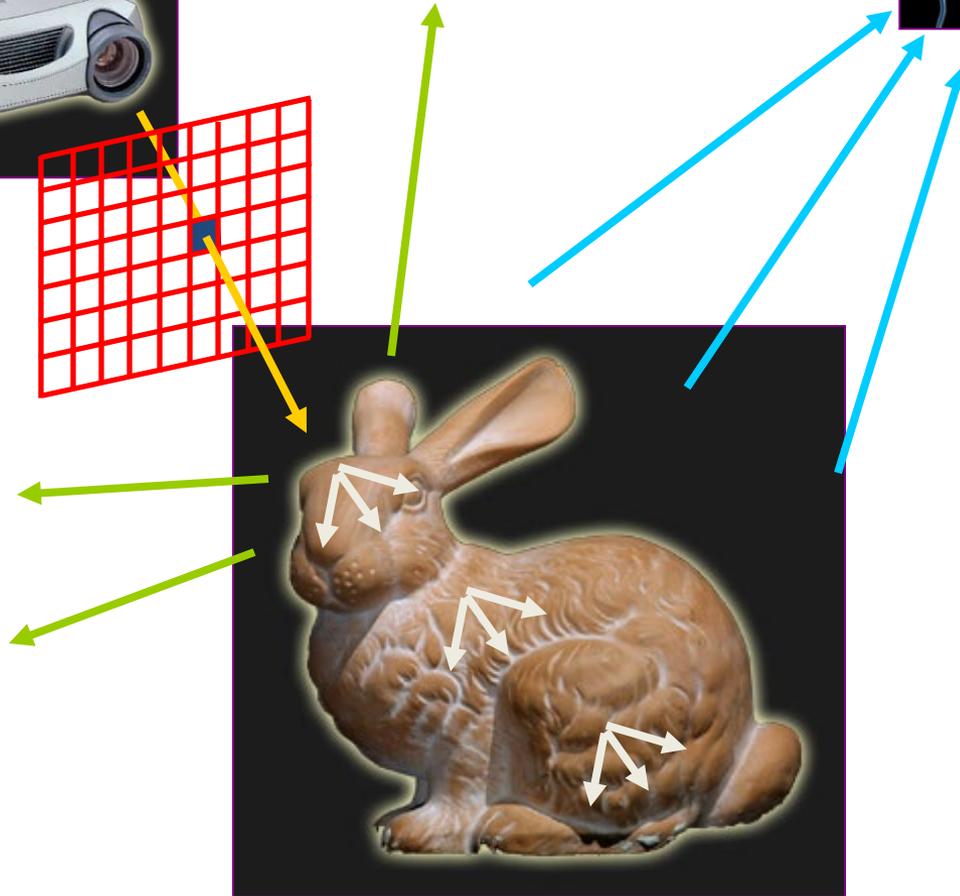
Helmholtz Reciprocity
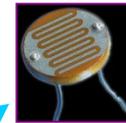
camera

light

scene

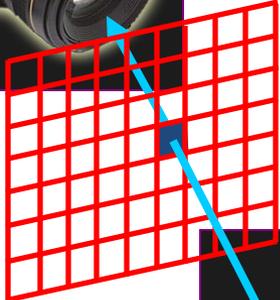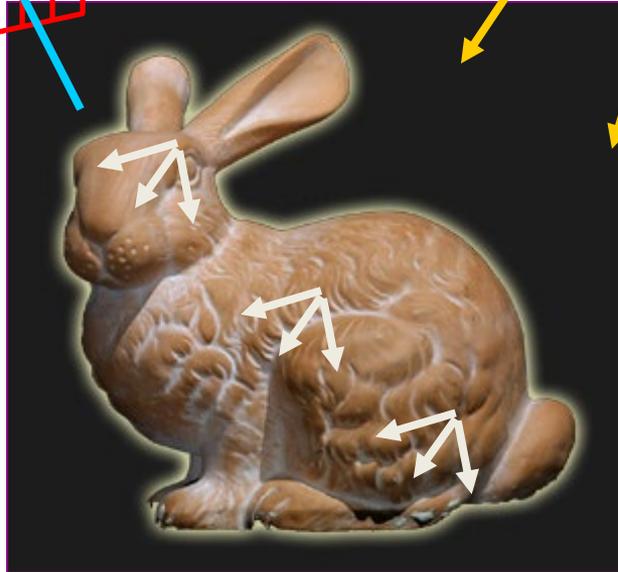# Measuring transport along a set of paths

projector

photocell

scene
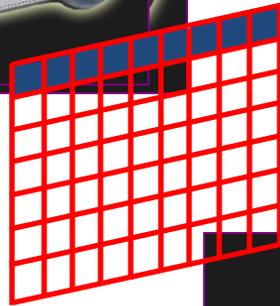
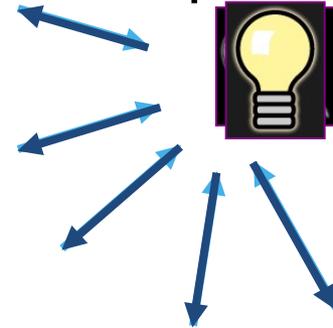# Reversing the paths

camera

point light

scene

Forming a dual photograph

"dual" camera
projector

"dual" light
photocell
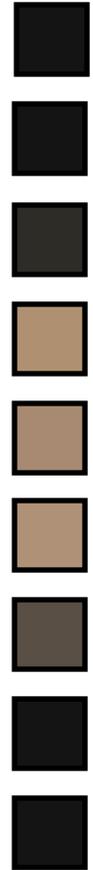
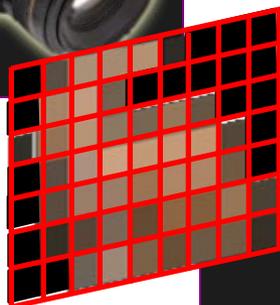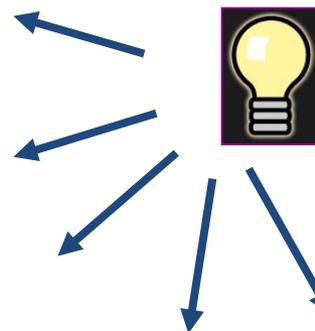scene

Forming a dual photograph

"dual" camera

"dual" light

image of scene

scene

Physical demonstration

- light replaced with projector
- camera replaced with photocell
- projector scanned across the scene
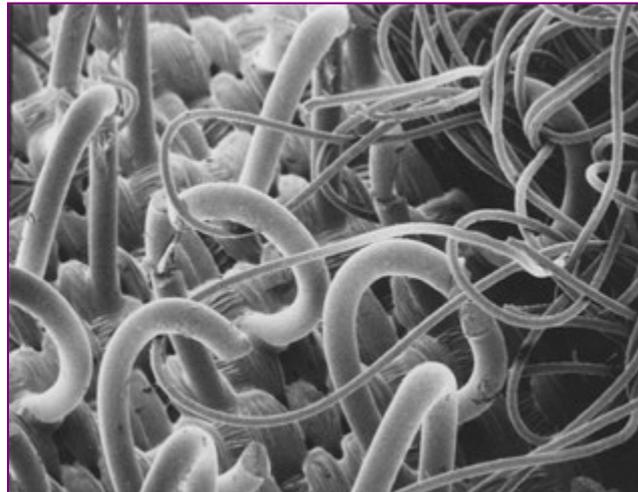

conventional photograph,
with light coming from right

dual photograph,
as seen from projector's position
and as illuminated from photocell's position

Related imaging methods

- time-of-flight scanner
  - if they return reflectance as well as range
  - but their light source and sensor are typically coaxial

- scanning electron microscope

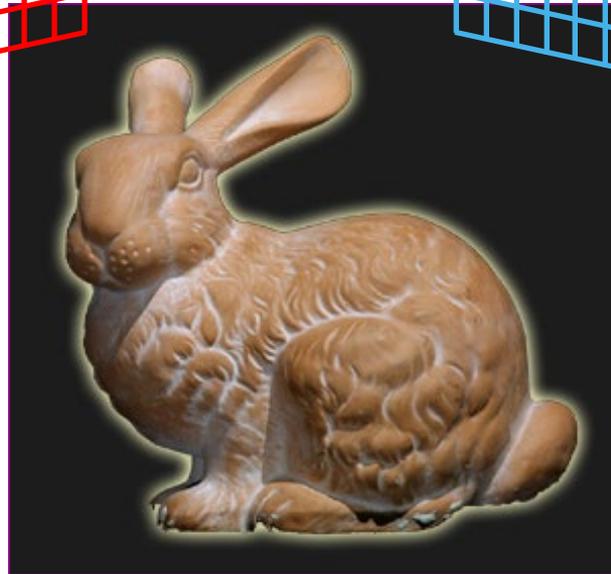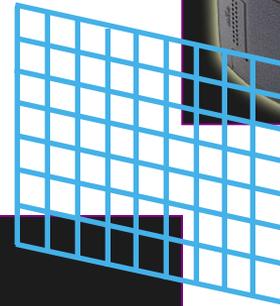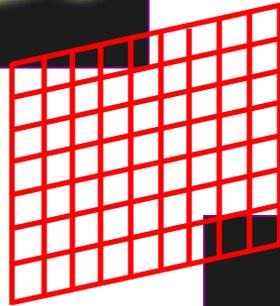Velcro® at 35x magnification,
Museum of Science, Boston

The 4D transport matrix

projector

camera

scene

The 4D transport matrix

projector

P

pq x 1

camera

C

mn x 1

mn x pq

T

scene

The 4D transport matrix

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

The 4D transport matrix

$$\begin{bmatrix} C \end{bmatrix} = \begin{bmatrix} \blacksquare \quad T \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

mn x pq

mn x 1   pq x 1

The 4D transport matrix

mn x pq

$$\begin{bmatrix} C \end{bmatrix} = \begin{bmatrix} \quad T \quad \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

mn x 1   **pq x 1**

$$\begin{bmatrix} C \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

mn x pq

mn x 1   pq x 1

The 4D transport matrix

$$\mathbf{C} = \mathbf{T} \; \mathbf{P}$$

mn x pq

mn x 1   **pq x 1**

The 4D transport matrix

$$mn \times pq$$

$$[C] = [T][P]$$

$$mn \times 1 \qquad\qquad pq \times 1$$

applying Helmholtz reciprocity...

$$pq \times mn$$

$$[C'] = [T^T][P']$$

$$pq \times 1 \qquad\qquad mn \times 1$$

Example
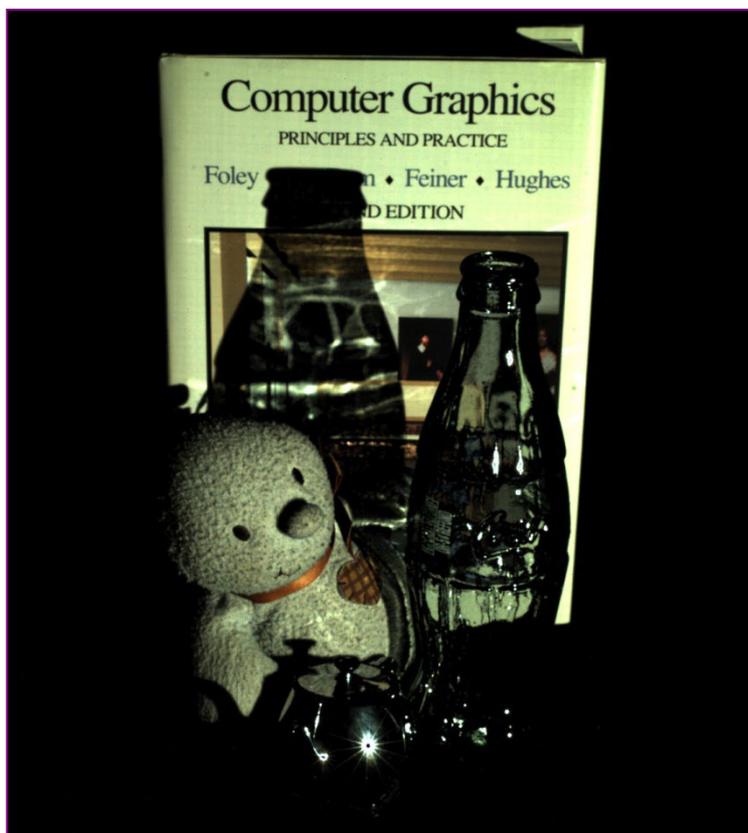
conventional photograph
with light coming from right
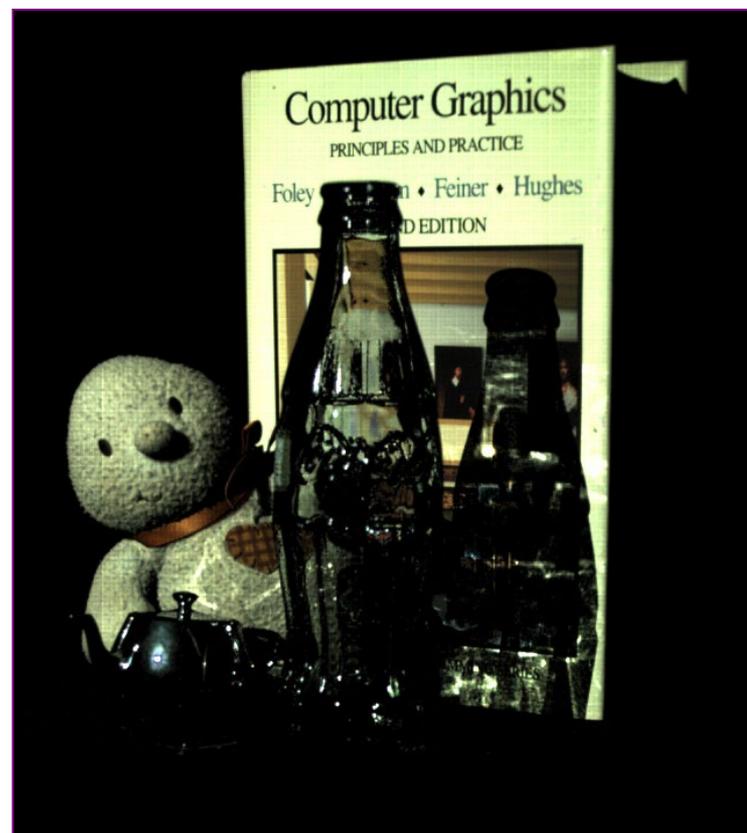
dual photograph
as seen from projector's position

Properties of the transport matrix

- little inter-reflection

  → sparse matrix

- many inter-reflections

  → dense matrix

- convex object

  → diagonal matrix

- concave object
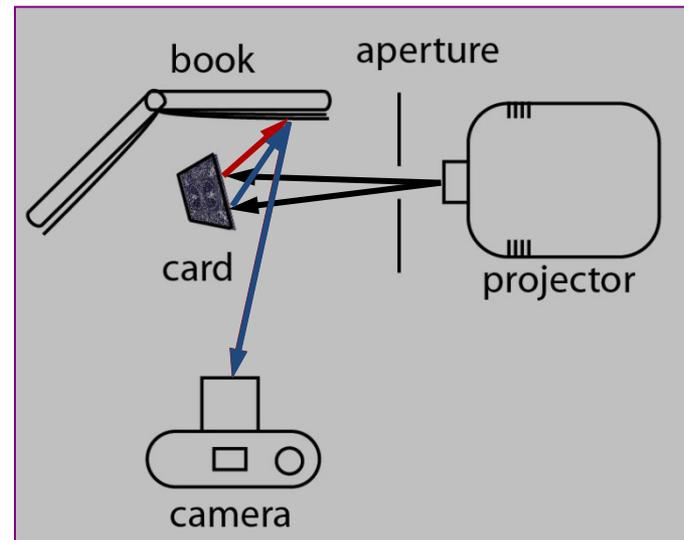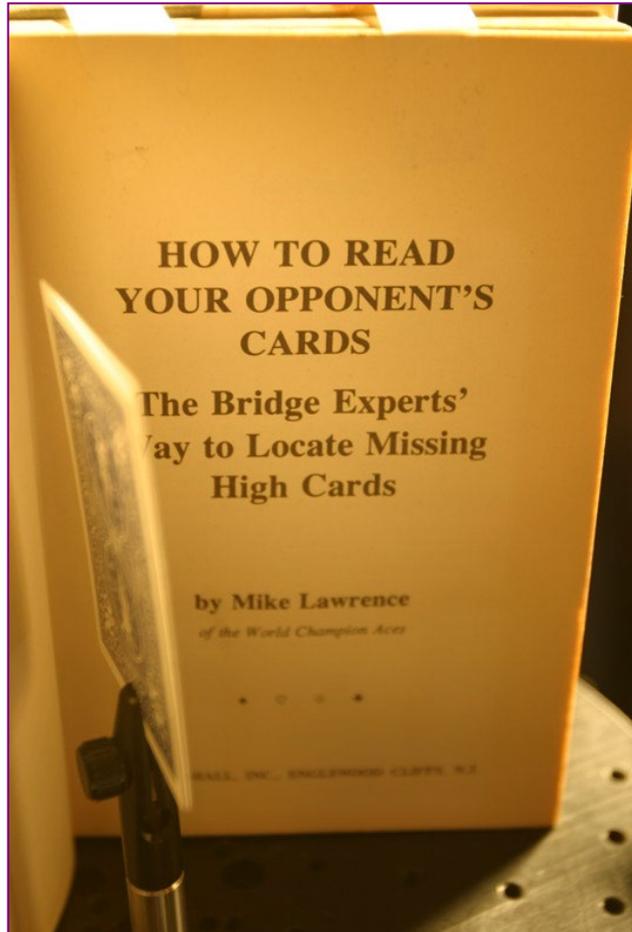
  → full matrix

Can we create a dual photograph entirely from diffuse reflections?
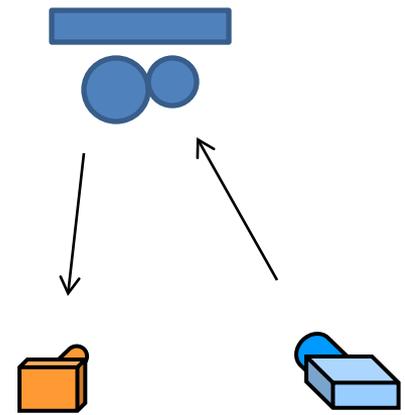
Dual photography
from diffuse reflections

the camera's view

book   aperture

card

projector

camera

Light Transport Based Methods

- Can encode light (or projector) to camera "transport" in a large matrix T

Camera c Projector p

$$\begin{bmatrix} c \end{bmatrix} = \begin{bmatrix} T \end{bmatrix}\begin{bmatrix} p \end{bmatrix}$$
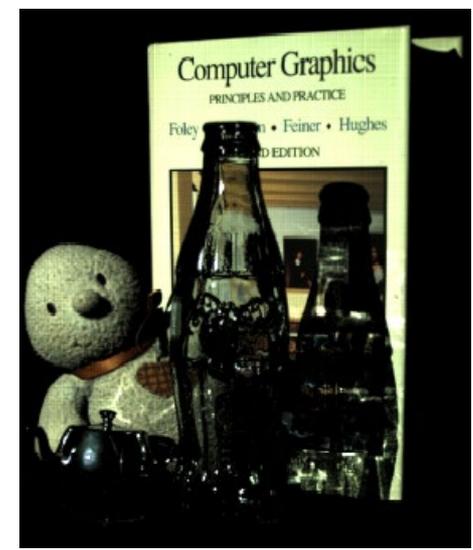
$$\begin{bmatrix} p \end{bmatrix} = \begin{bmatrix} T^t \end{bmatrix}\begin{bmatrix} c \end{bmatrix}$$

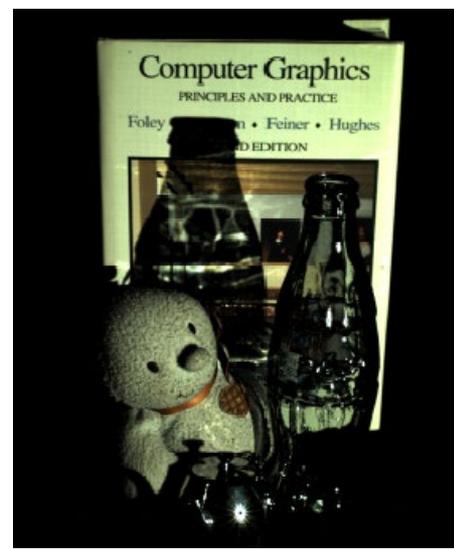As seen from camera…   As seen from projector!!!

Light Transport Based Methods

- Can encode light (or projector) to camera "transport" in a large matrix T
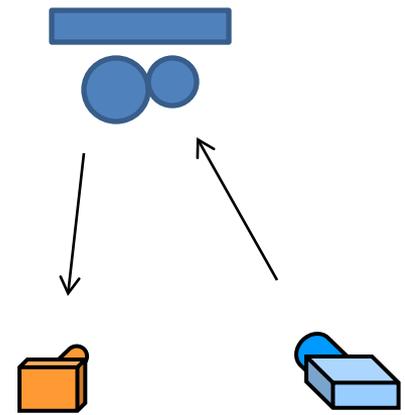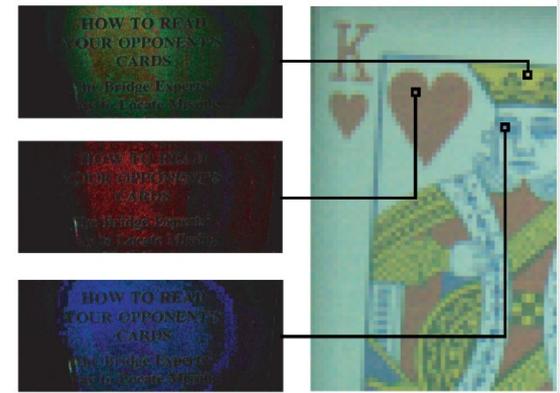

Camera c Projector p
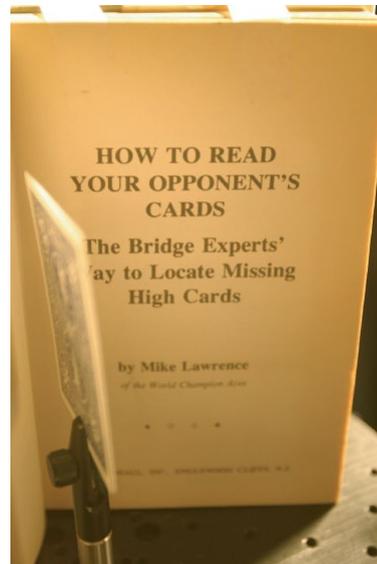
$$\begin{bmatrix} c \\ \\ \end{bmatrix} = \begin{bmatrix} \\ T \\ \end{bmatrix}\begin{bmatrix} p \\ \\ \end{bmatrix}$$

$$\begin{bmatrix} p \\ \\ \end{bmatrix} = \begin{bmatrix} \\ T^{\,t} \\ \end{bmatrix}\begin{bmatrix} c \\ \\ \end{bmatrix}$$

As seen from camera...   As seen from projector!!!
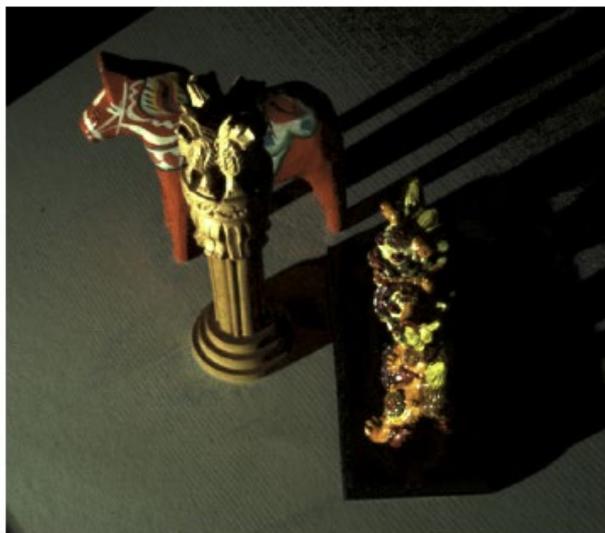
Relighting

With Dual Photography…

Relighting

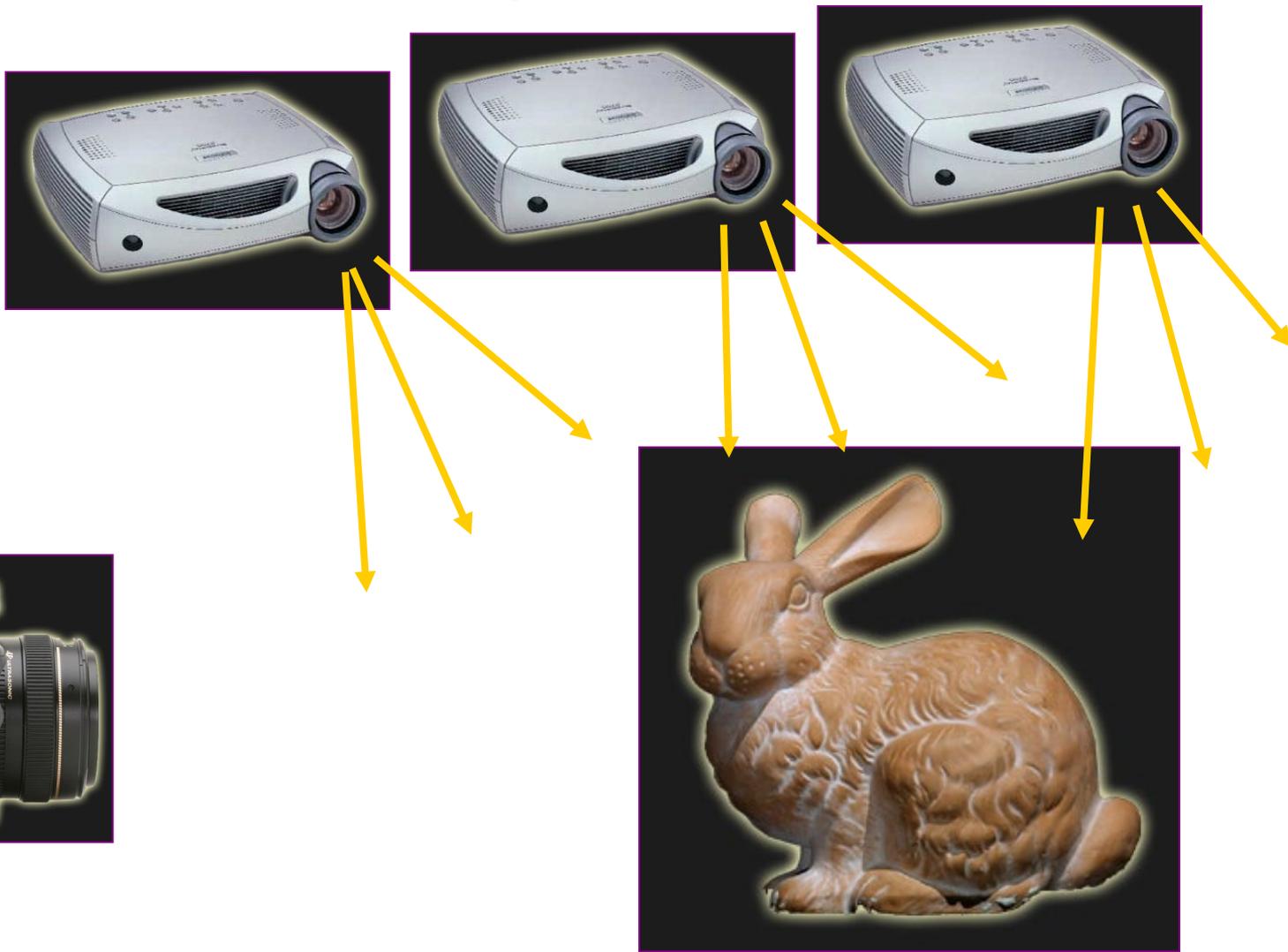With Dual Photography…

Relighting

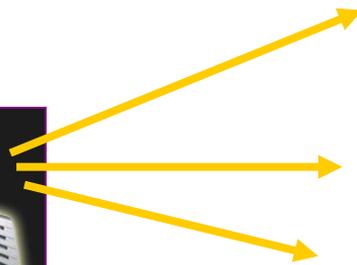

(a)

(b)

With Dual Photography…

The 6D transport matrix

The 6D transport matrix

Measuring the 6D transport matrix

projector

camera array

scene

Relighting with complex illumination

projector
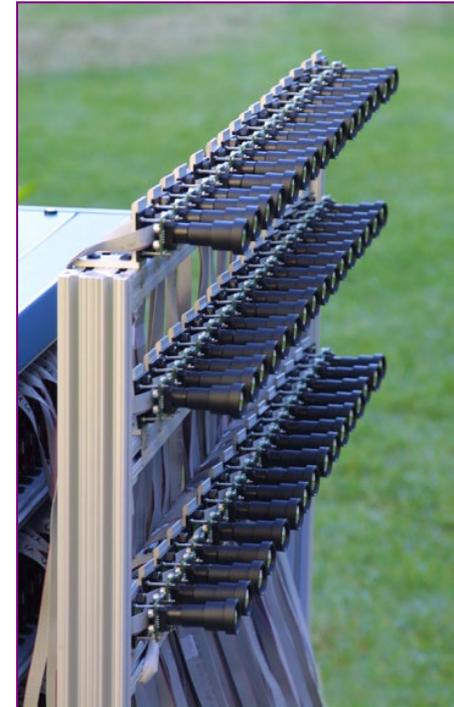
camera array
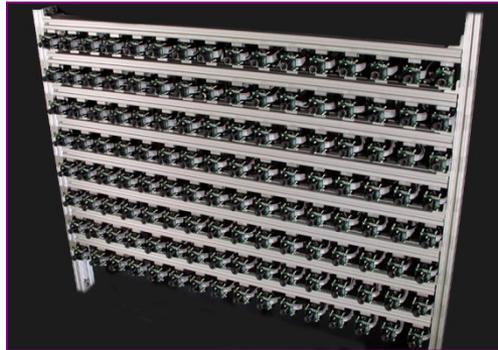
scene

$$pq \times mn \times uv$$

$$[C'] = [T^T][P']$$

$$pq \times 1 \qquad mn \times uv \times 1$$

- step 1: measure 6D transport matrix T
- step 2: capture a 4D light field
- step 3: relight scene using captured light field
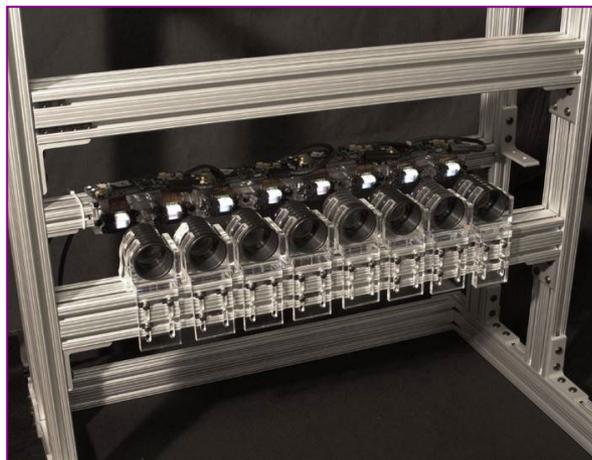
Running time

- the different rays within a projector can in fact be parallelized to some extent

- this parallelism can be discovered using a coarse-to-fine adaptive scan

- can measure a 6D transport matrix in 5 minutes
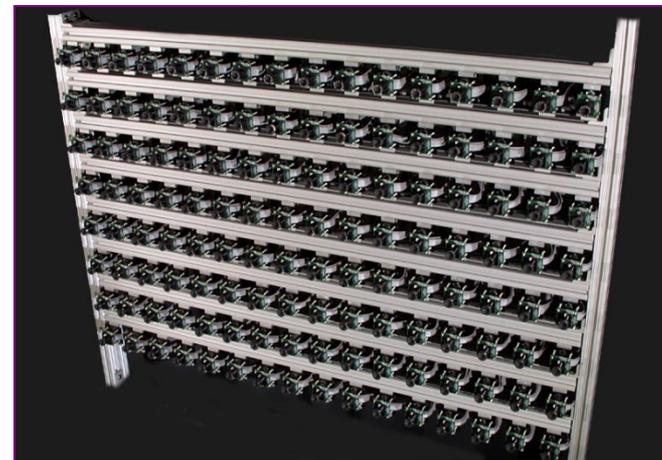
Can we measure an 8D transport matrix?

projector array

camera array

scene

Photon Cameras

- Seeing around corners
  - [How to see around corners](#)
  - Velten et al. (from MIT, Ramesh Raskar and more)
  - Uses Photon Cameras

- Here at Purdue…
  - Sotiris Nousias also does work using Photon Cameras

SPAD

- Single Photon Avalanche Diodes
  - Detect and count photons
- What is a photon?
  - "Photons are massless particles that can move no faster than the speed of light measured in vacuum. The photon belongs to the class of boson particles"
- https://www.dgp.toronto.edu/projects/ultra-wideband/

SPAD

- NLOS Imaging
  - https://www.youtube.com/watch?v=nVoEZuFFMzA

- And more using neural networks
  - https://www.youtube.com/watch?v=Jst-k6qfcM8