Light Transport

CS434

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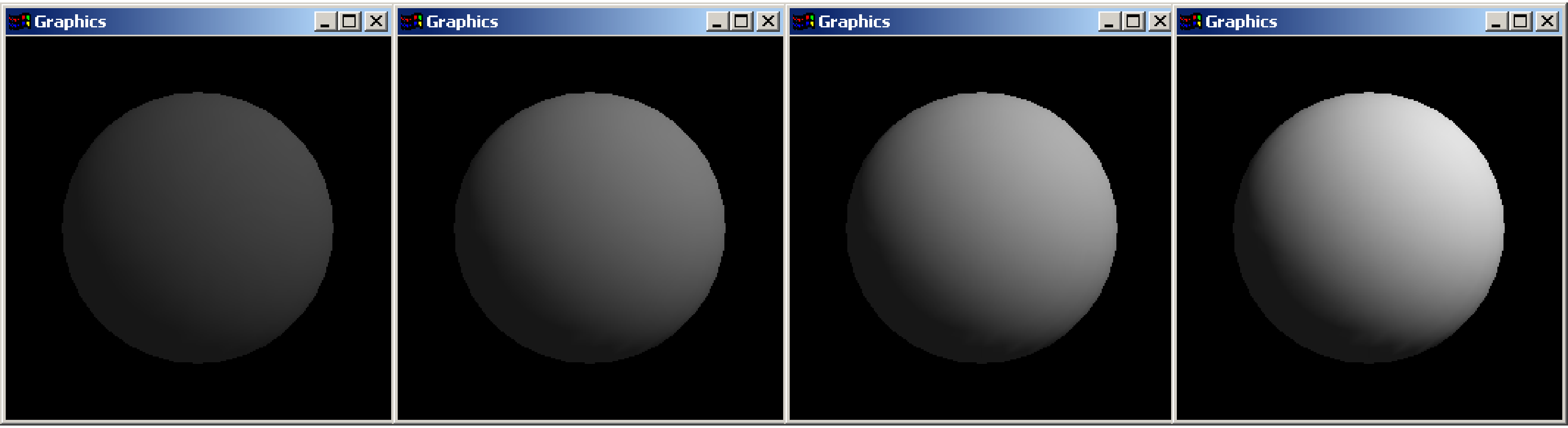
Topics

- 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

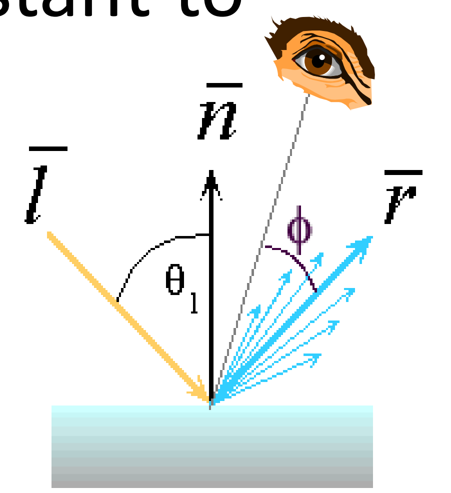


Specular Lighting

- The most common lighting model was suggested by Phong

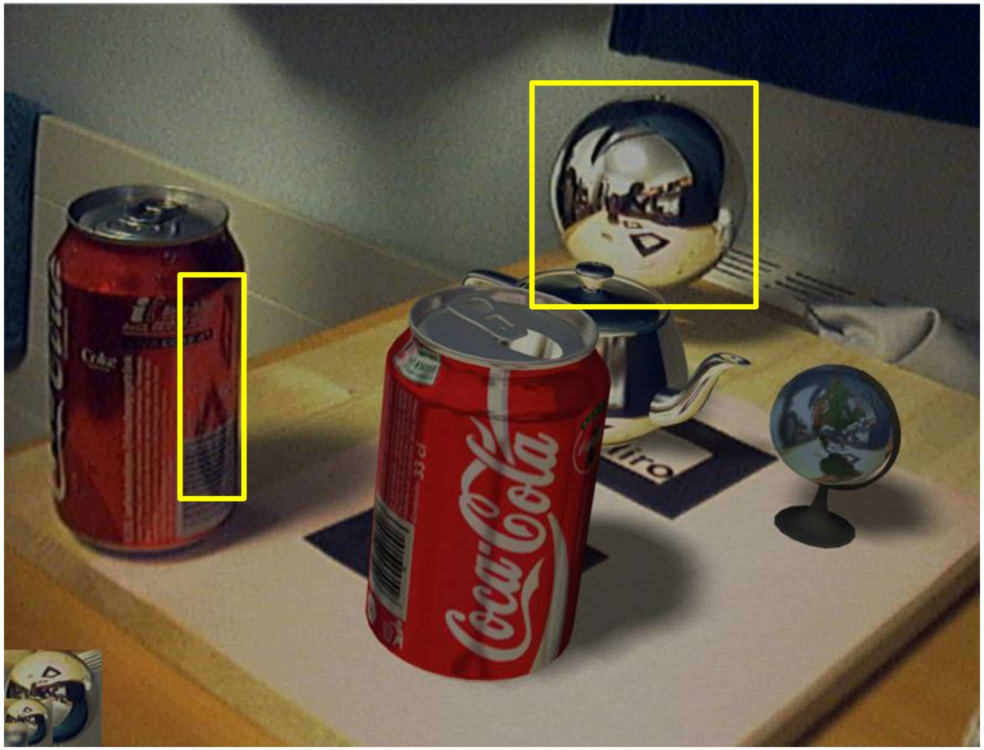
$$I_{spec} = \rho_{spec} I_{Light} (\cos\phi)^{n_{shiny}}$$

- The n_{shiny} term is an empirical constant to model the rate of falloff
- The model has no exact physical basis, but it "sort of works"



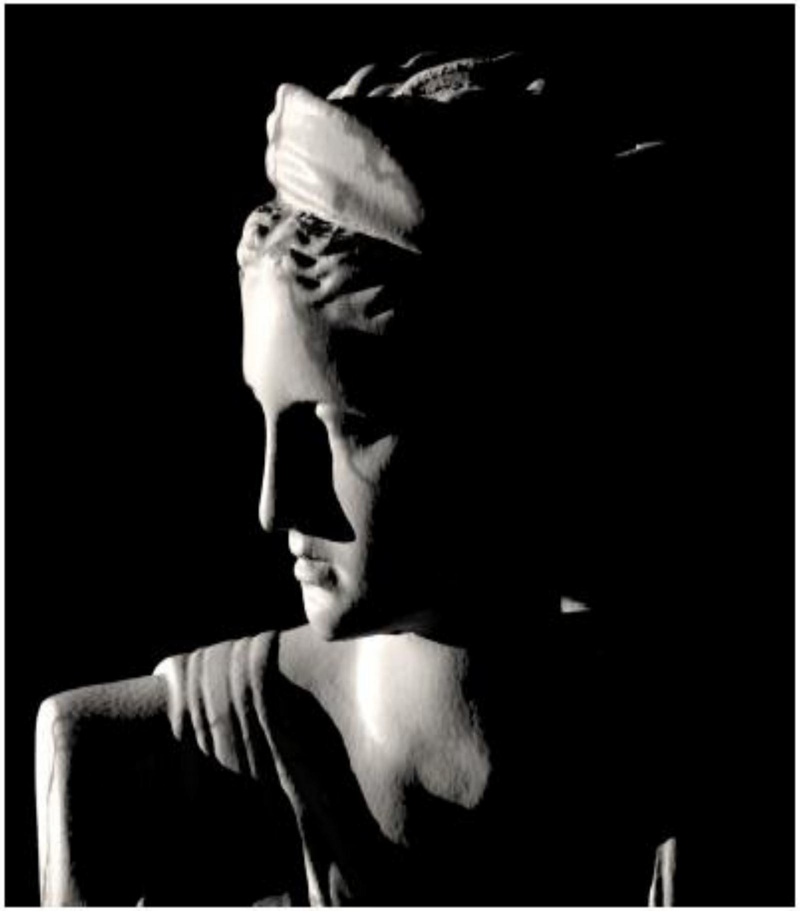
Example

Inter-reflections



Scattering

Scattering



Without (subsurface) scattering

With (subsurface) scattering

Scattering

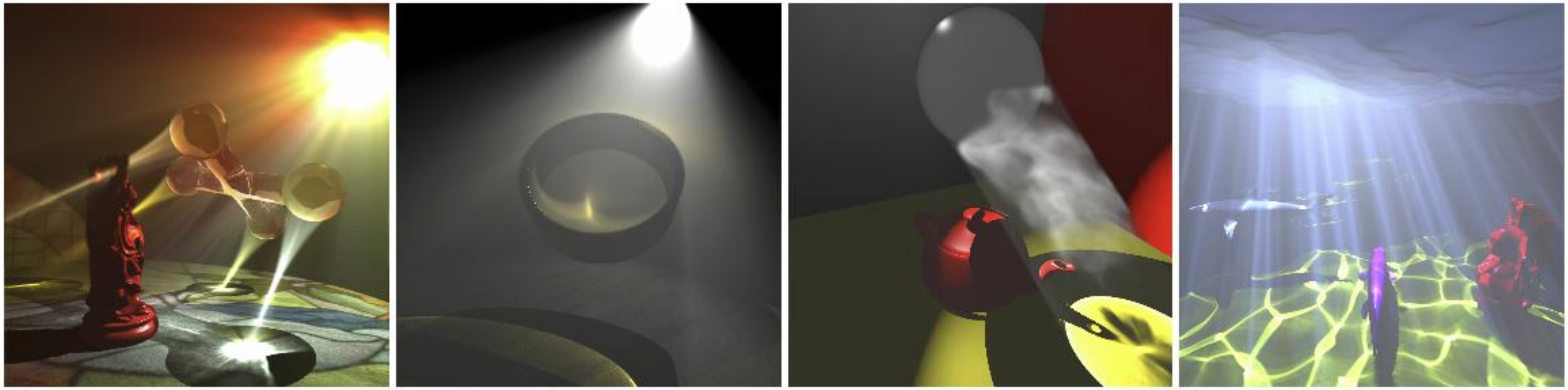
BRDF

Without (subsurface) scattering

BSSRDF

With (subsurface) scattering

Scattering



Hu et al. 2010

Scattering through participating media with volume caustics…

Rendering Equation
(also known as the light-transport equation)

- Illumination can be generalized to

$$L_r(x,\omega_r) = L_e(x,\omega_r) + \int_{\Omega} L_r(x',-\omega_i)\, f(x,\omega_i,\omega_r)\cos\theta_i\, d\omega_i$$

Reflected Light (Output Image)	Emission	Reflected Light	BRDF	Cosine of Incident angle

(note: equation is recursive)

…but it does not model all illumination effects!

Conclusion

- Modeling physical 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!

Recall the Linear Operator Equation…

$$L_r(x,\omega_r) = L_e(x,\omega_r) + \int_\Omega L_r(x',-\omega_i) f(x,\omega_i,\omega_r) \cos\theta_i d\omega_i$$

Reflected Light (Output Image)	Emission	Reflected Light	BRDF	Cosine of Incident angle

$$L = E + KL$$

where K can be thought of as the "light transport matrix"; i.e., it transports light from the previous surface (=light) to the next surface

Dual Photography

- Compute a light transport matrix T that "transports light" from an illumination vector P to a camera image vector C

- Thus rendering equation is now…

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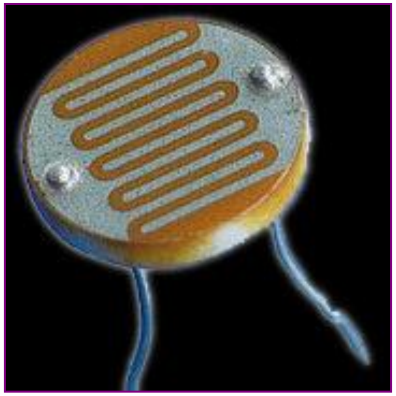
- Thus rendering equation is now…

$$C = TP$$

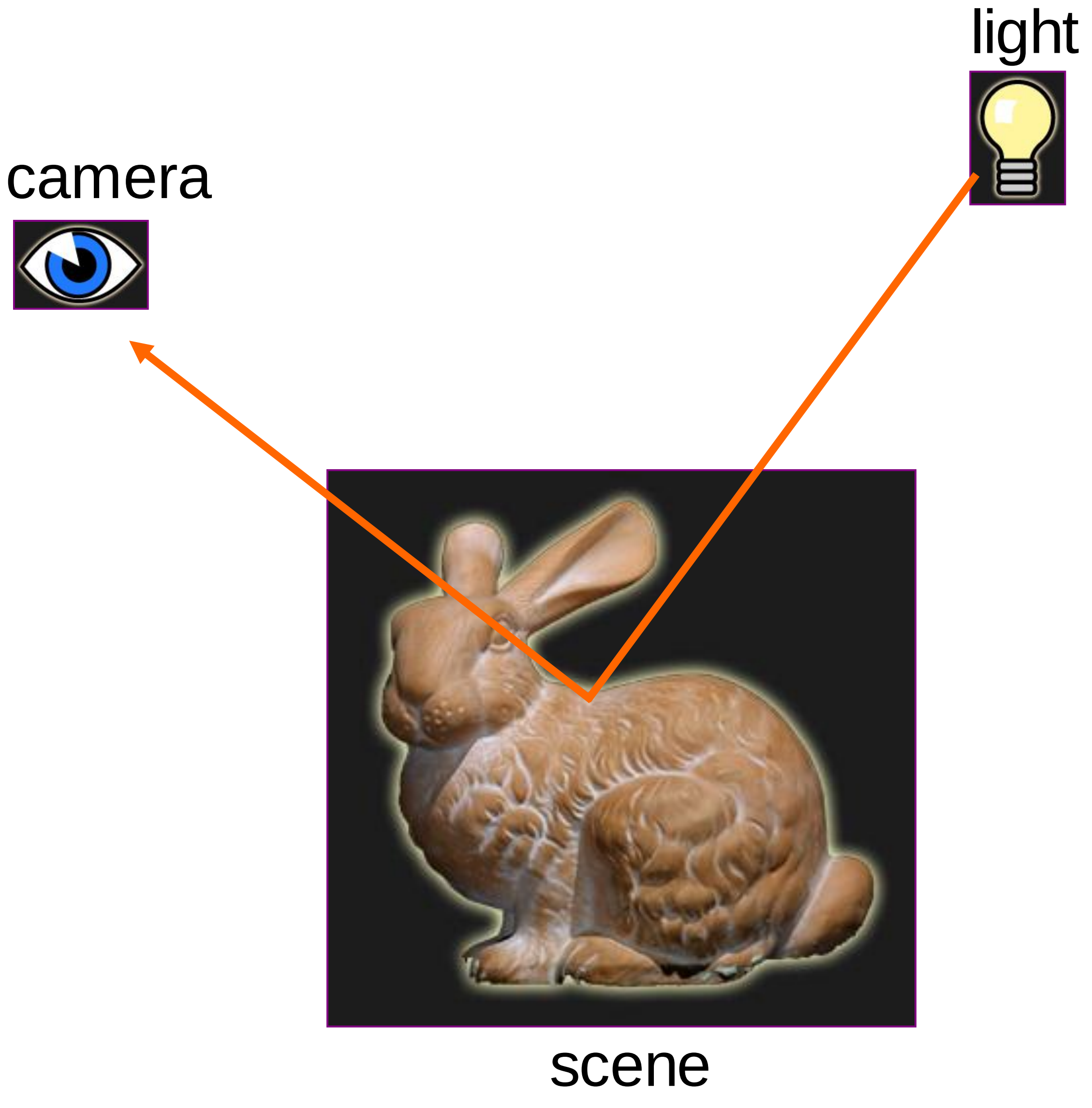
Dual Photography

- Compute a light transport matrix T that "transports light" from an illumination vector P to a camera image vector C

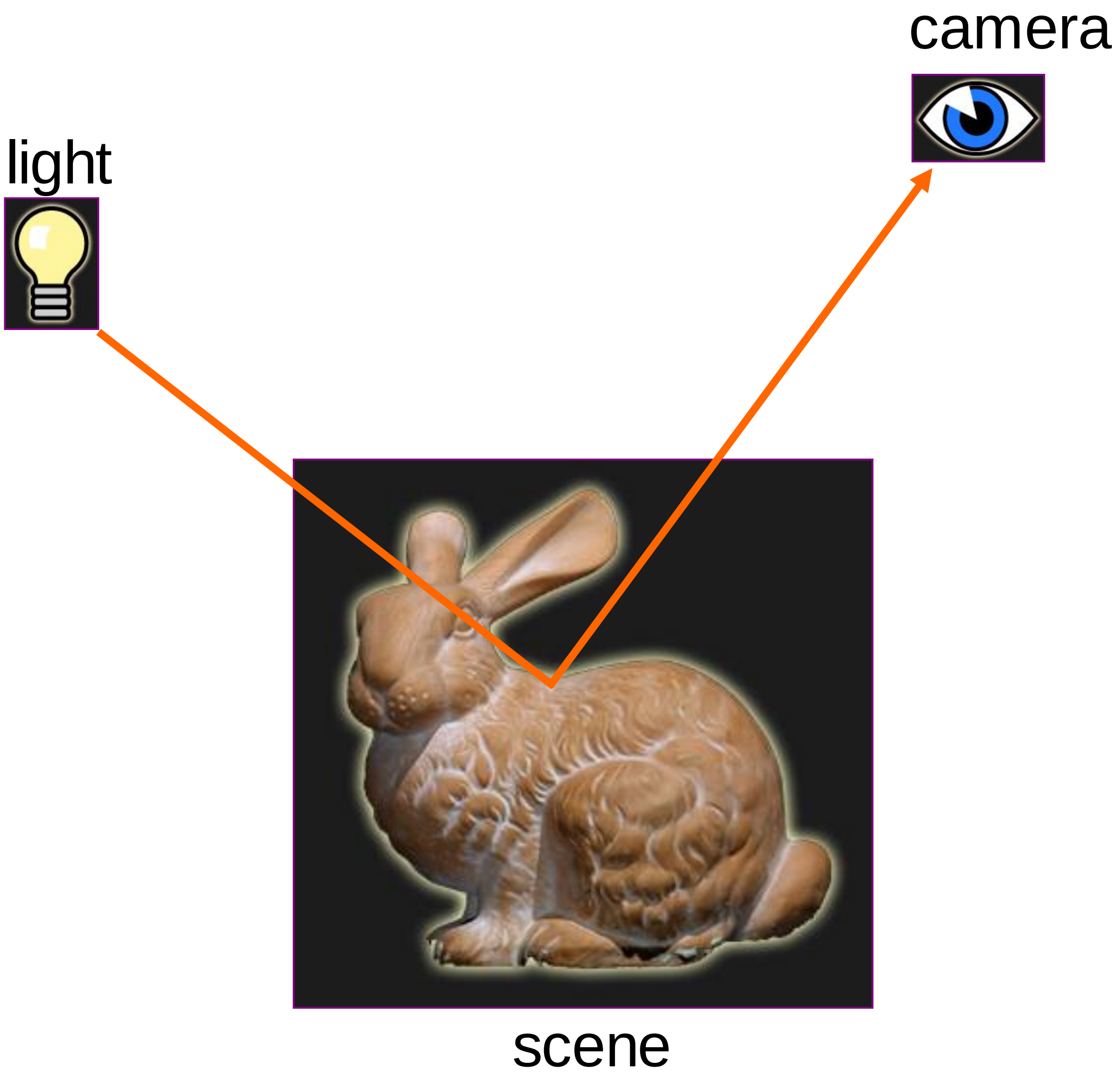


[Sen et al., SIGGRAPH 2005] (slides based on those from the paper)

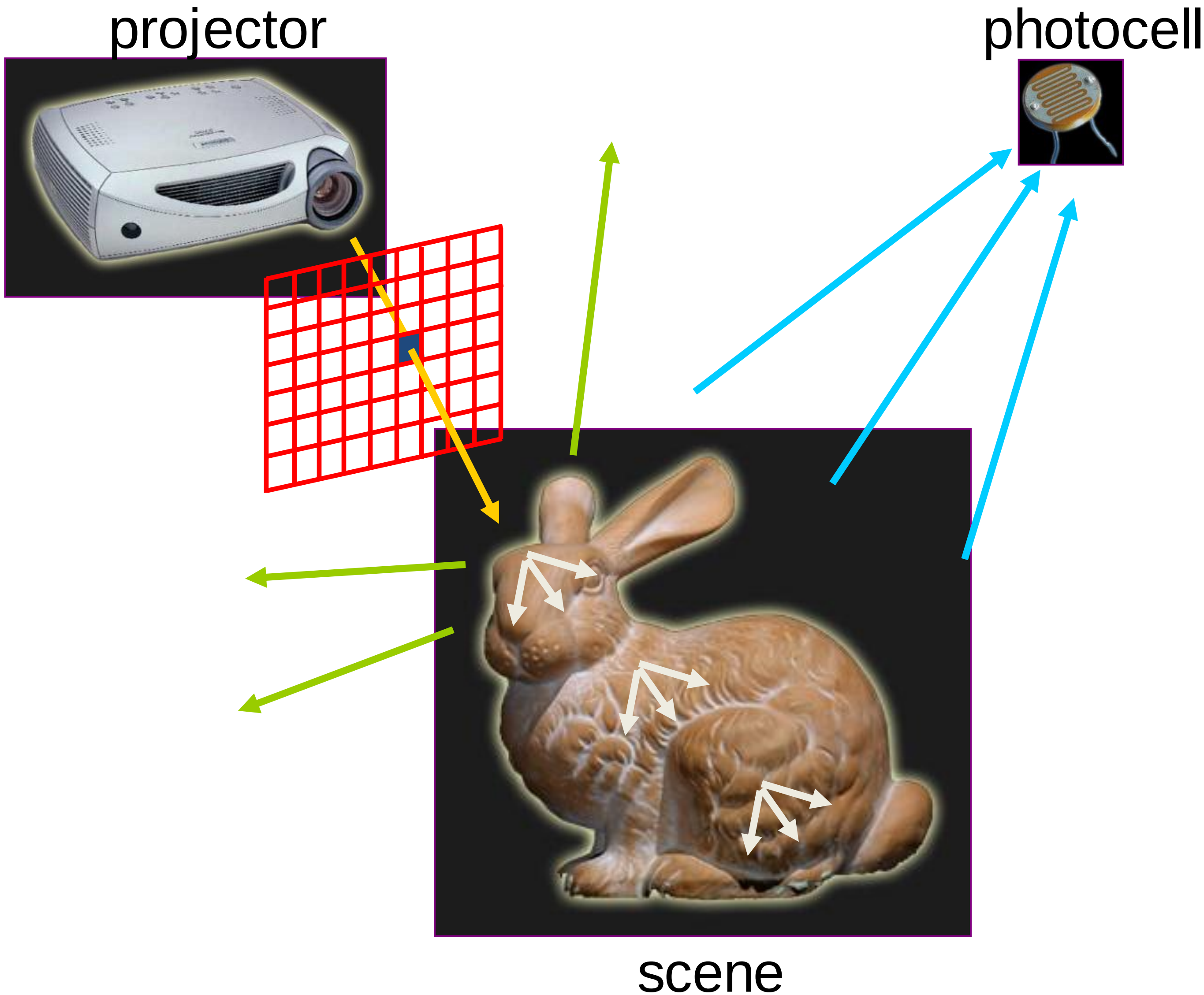
Helmholtz Reciprocity



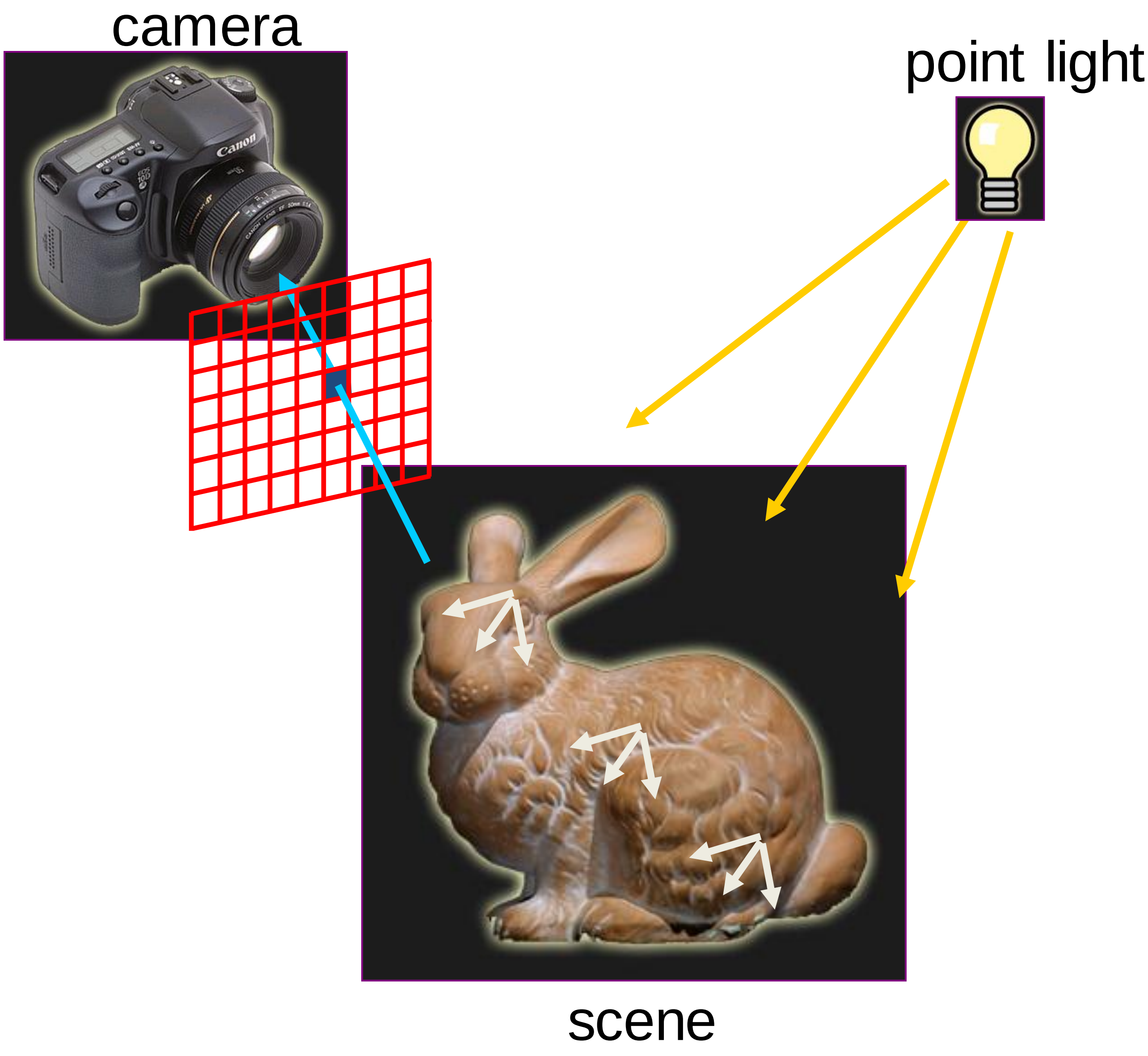
Helmholtz Reciprocity



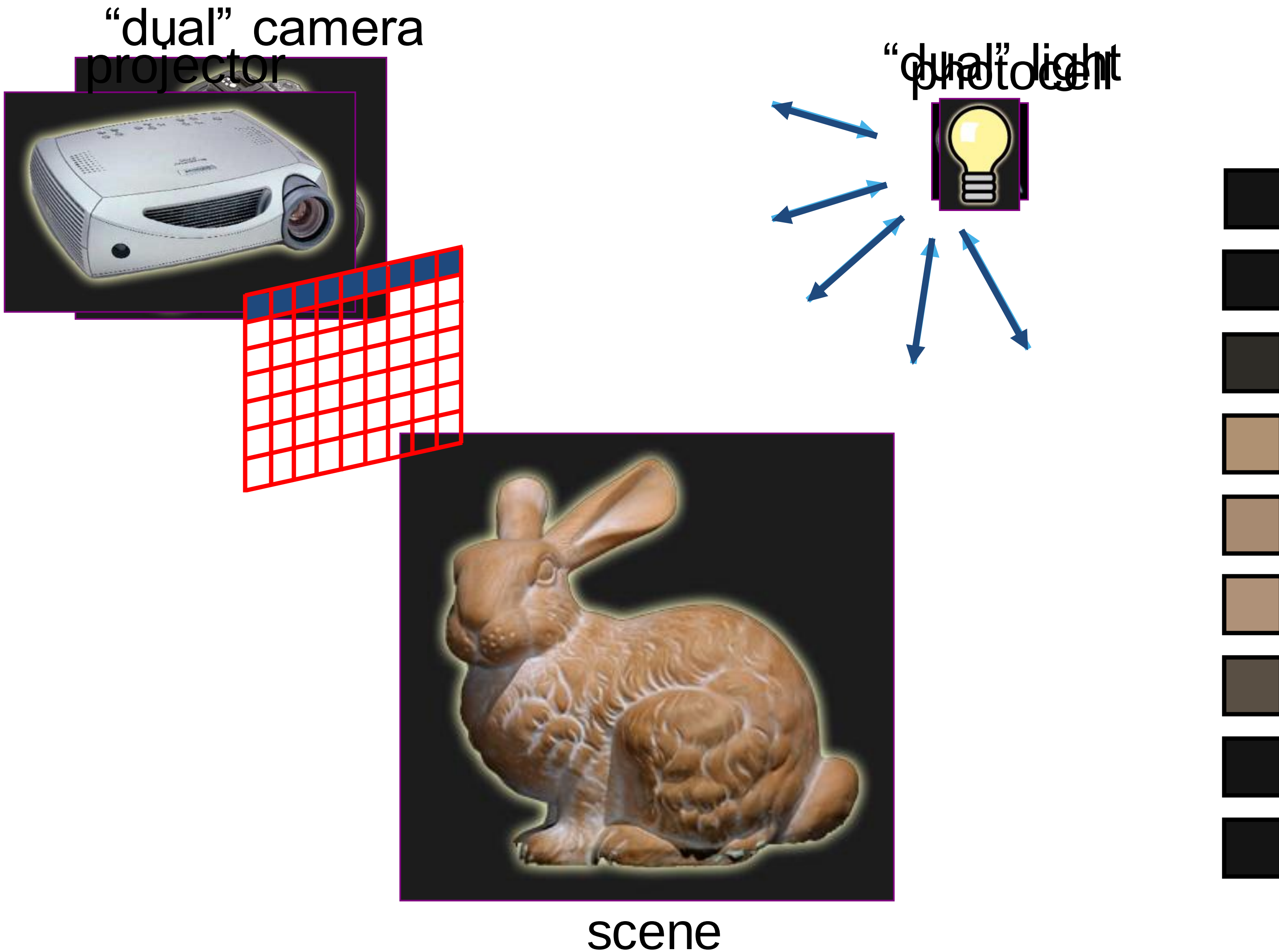
Measuring transport along a set of paths



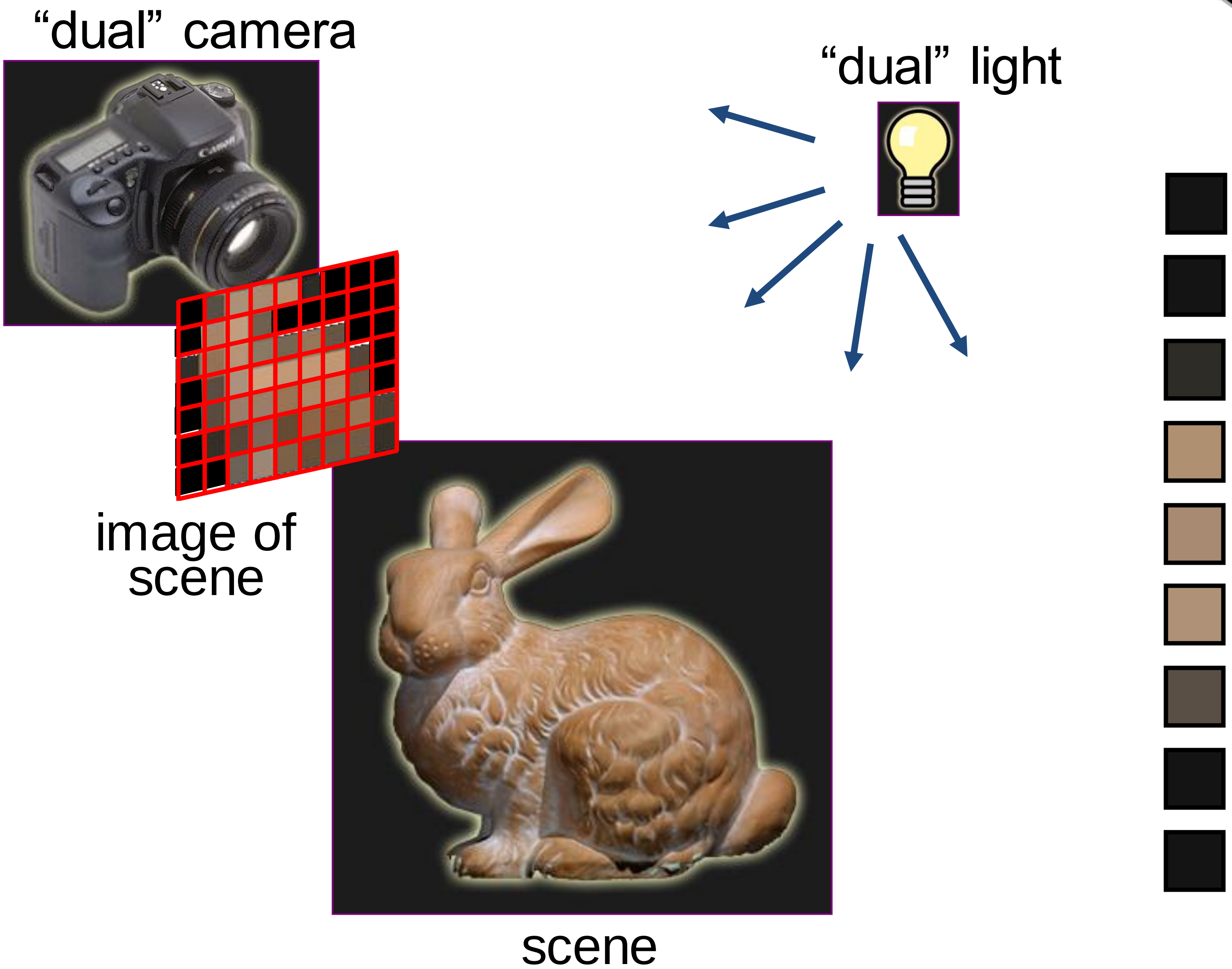
Reversing the paths



Forming a dual photograph



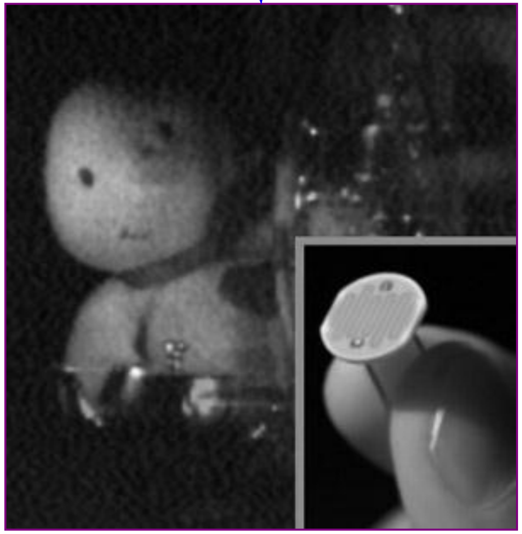
Forming a dual photograph



Physical demonstration

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

conventional photograph,
with light coming from right

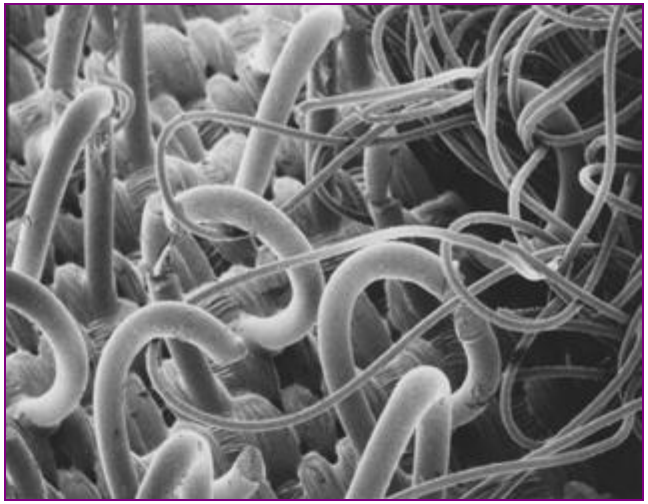


dual photograph,
as seen from projector's position
and as illuminated from photocell's position

Related imaging methods

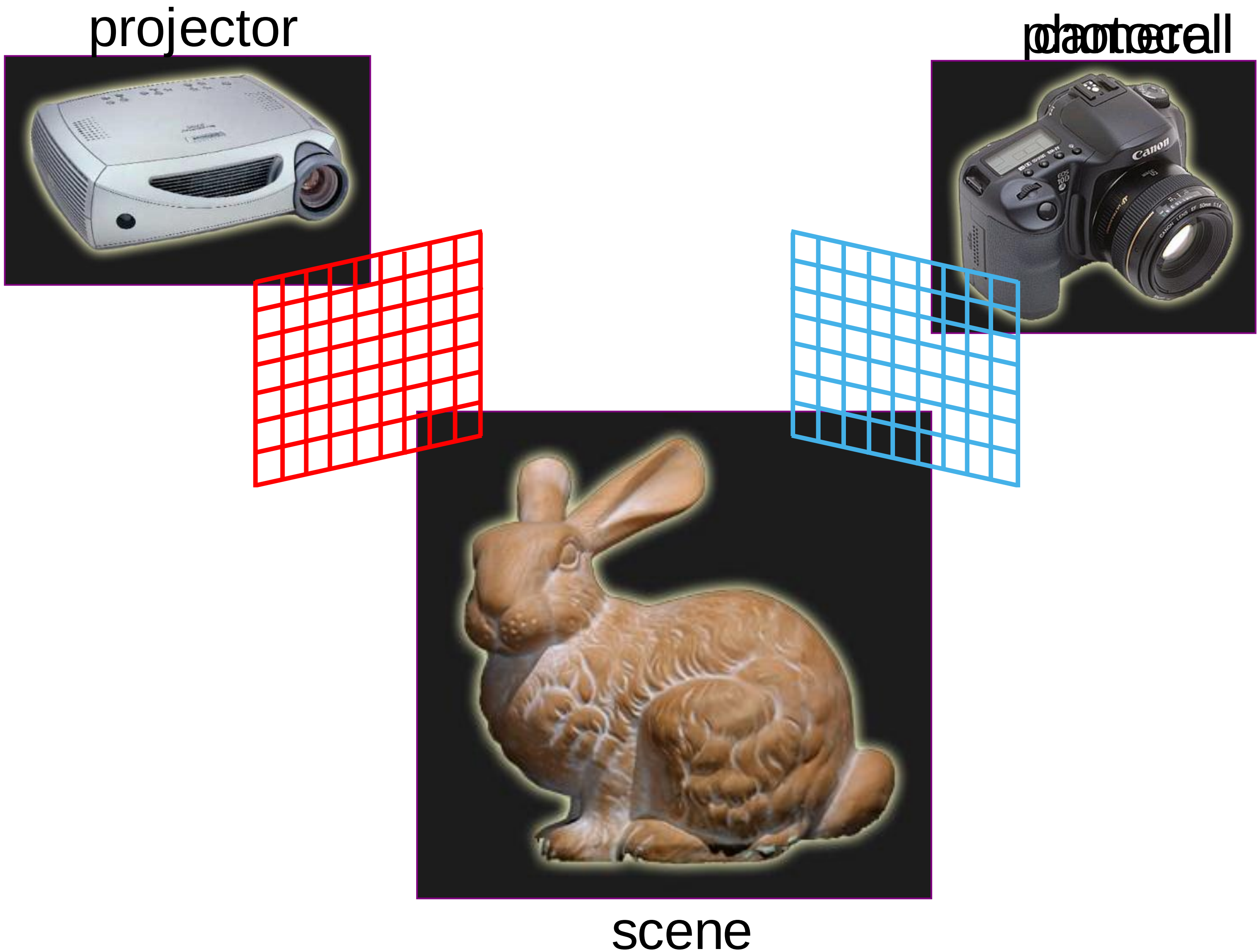
- time-of-flight scanner
  - if they return reflectance as well as range
  - but their light source and sensor are typically coaxial

- scanning electron microscope

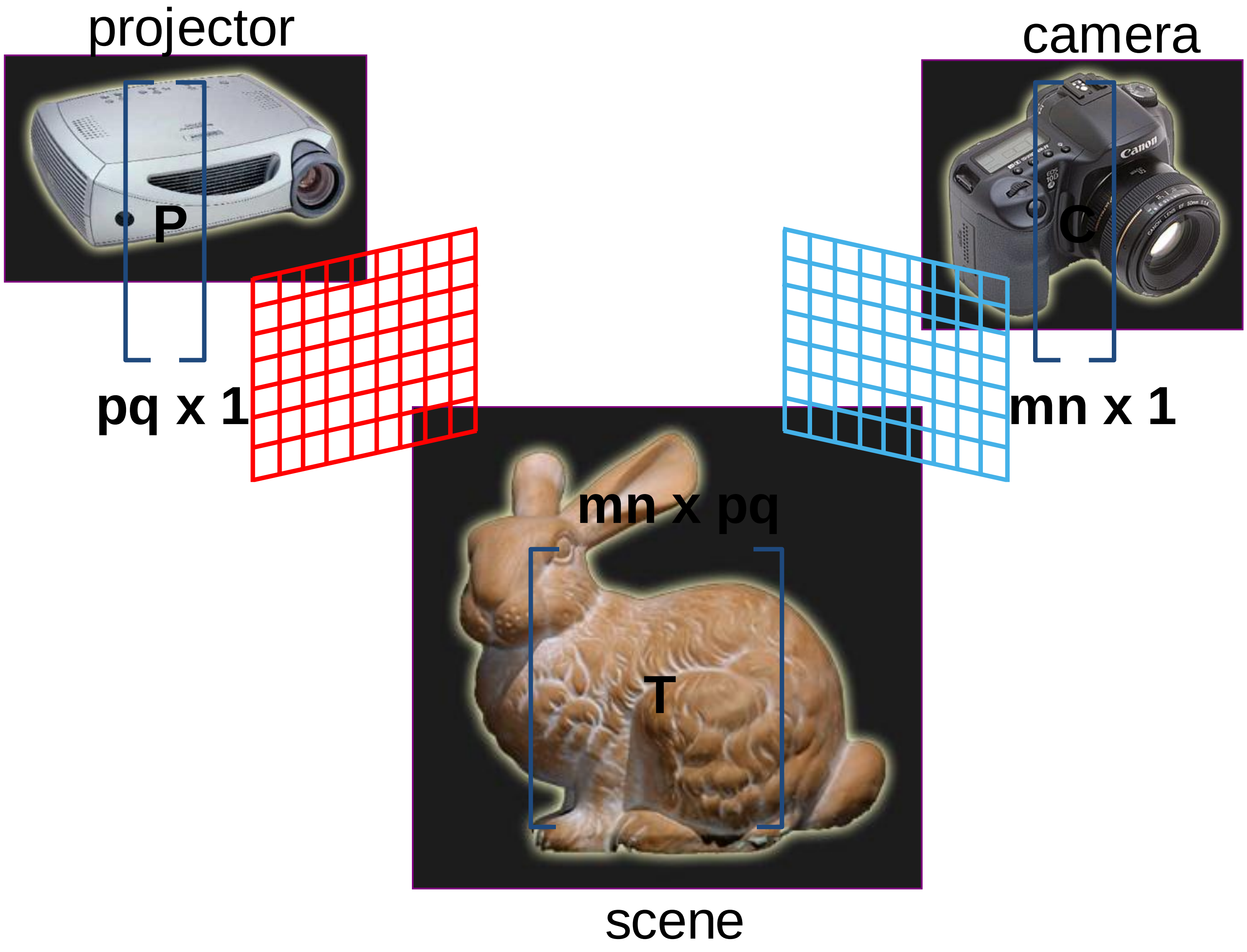


Velcro® at 35x magnification,
Museum of Science, Boston

The 4D transport matrix



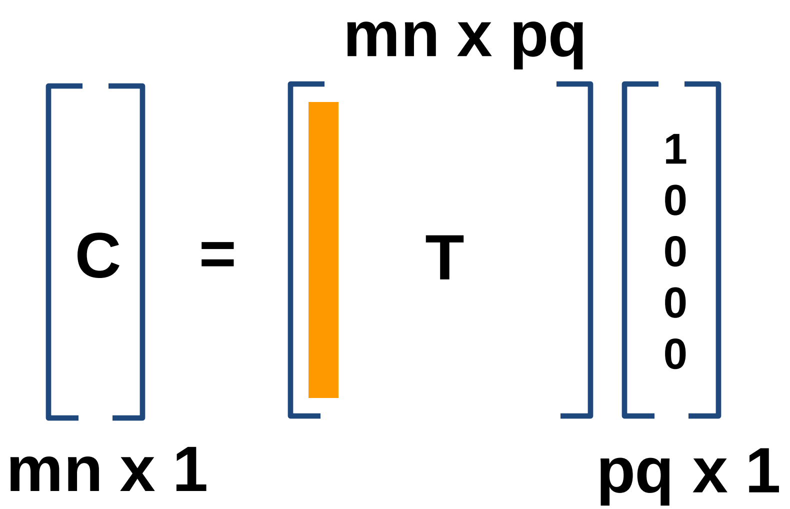
The 4D transport matrix



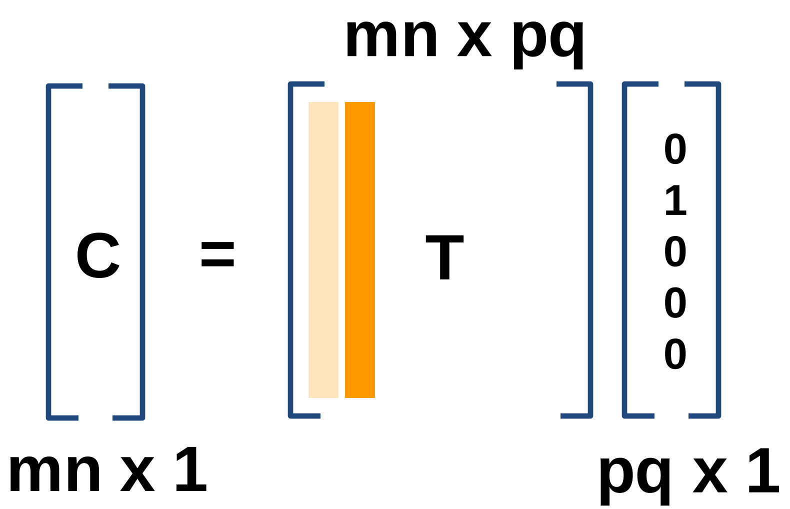
The 4D transport matrix

$$\underbrace{\begin{bmatrix} C \end{bmatrix}}_{mn \times 1} = \overbrace{\begin{bmatrix} & T & \end{bmatrix}}^{mn \times pq} \underbrace{\begin{bmatrix} P \end{bmatrix}}_{pq \times 1}$$

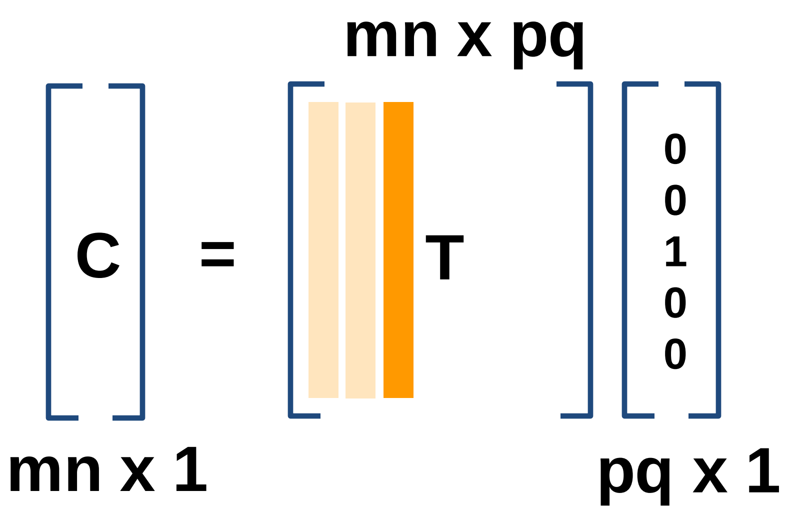
The 4D transport matrix



The 4D transport matrix



The 4D transport matrix



The 4D transport matrix

mn x pq

$$\begin{bmatrix} C \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} P \end{bmatrix}$$

mn x 1 | pq x 1

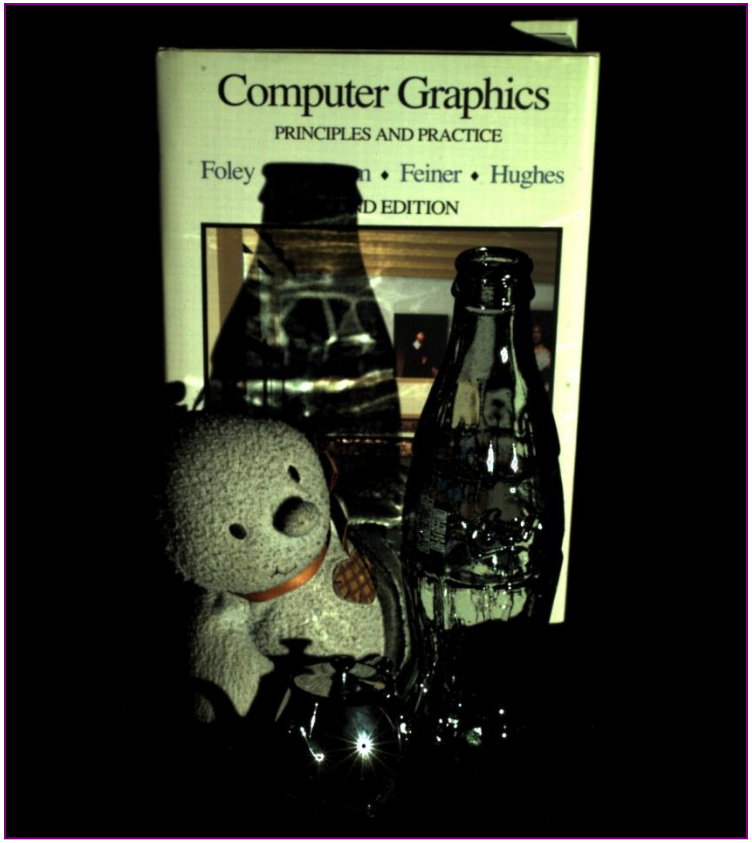
The 4D transport matrix

$$\underbrace{\begin{bmatrix} C \end{bmatrix}}_{mn \times 1} = \overbrace{\begin{bmatrix} \quad T \quad \end{bmatrix}}^{mn \times pq} \underbrace{\begin{bmatrix} P \end{bmatrix}}_{pq \times 1}$$

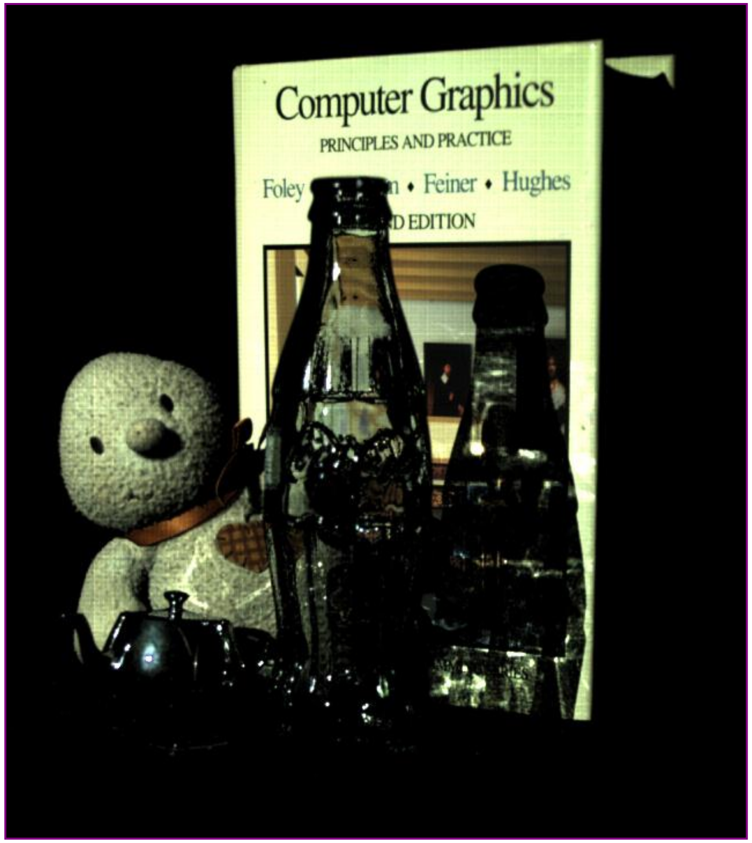
applying Helmholtz reciprocity...

$$\underbrace{\begin{bmatrix} C' \end{bmatrix}}_{pq \times 1} = \overbrace{\begin{bmatrix} \quad T^T \quad \end{bmatrix}}^{pq \times mn} \underbrace{\begin{bmatrix} P' \end{bmatrix}}_{mn \times 1}$$

Example



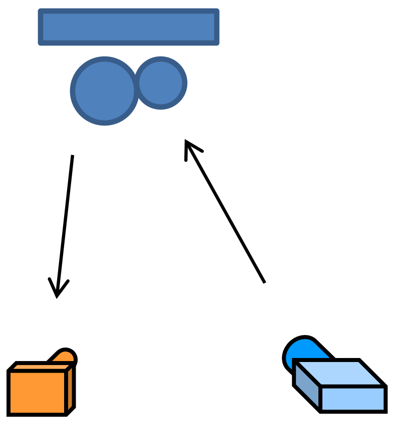
conventional photograph
with light coming from right



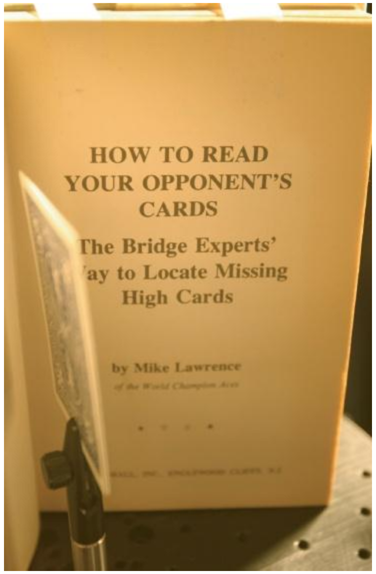
dual photograph
as seen from projector's position

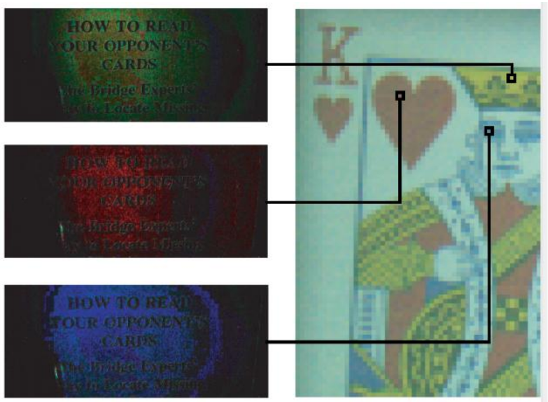
Example

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



Camera c Projector p





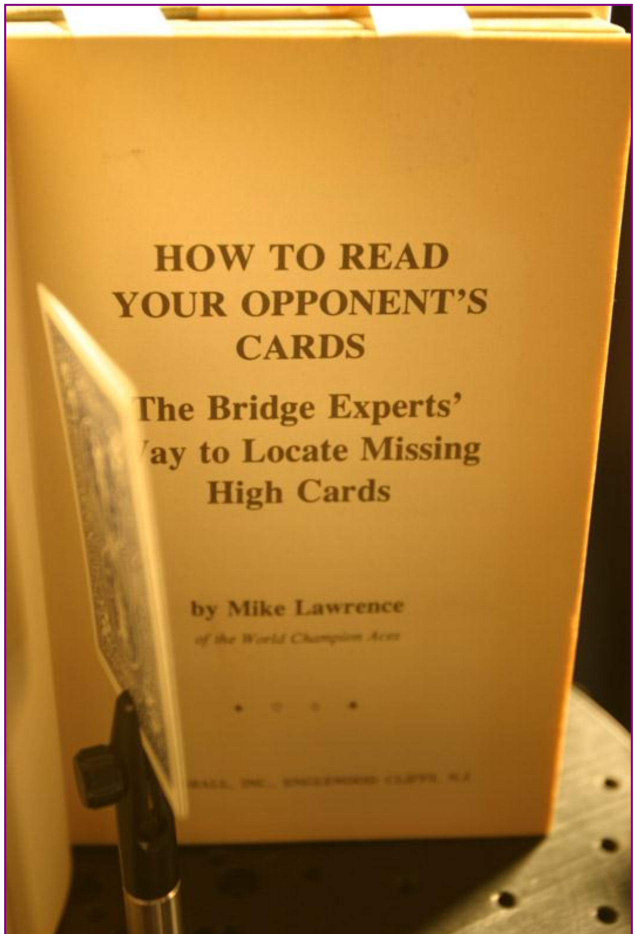
$$\begin{bmatrix} c \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} p \end{bmatrix}$$

As seen from camera…

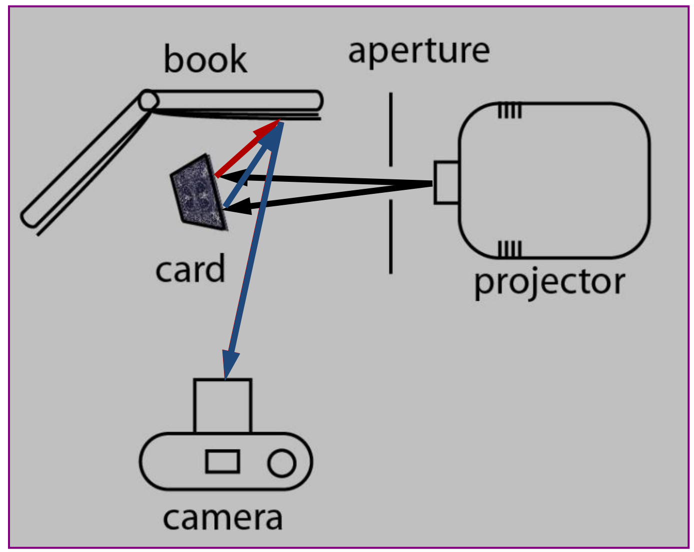
$$\begin{bmatrix} p \end{bmatrix} = \begin{bmatrix} T^t \end{bmatrix} \begin{bmatrix} c \end{bmatrix}$$

As seen from projector!!!

Dual photography from diffuse reflections



the camera's view



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?

Relighting

Paul Debevec's
Light Stage 3

- subject captured under multiple lights
- one light at a time, so subject must hold still
- point lights are used, so can't relight with cast shadows

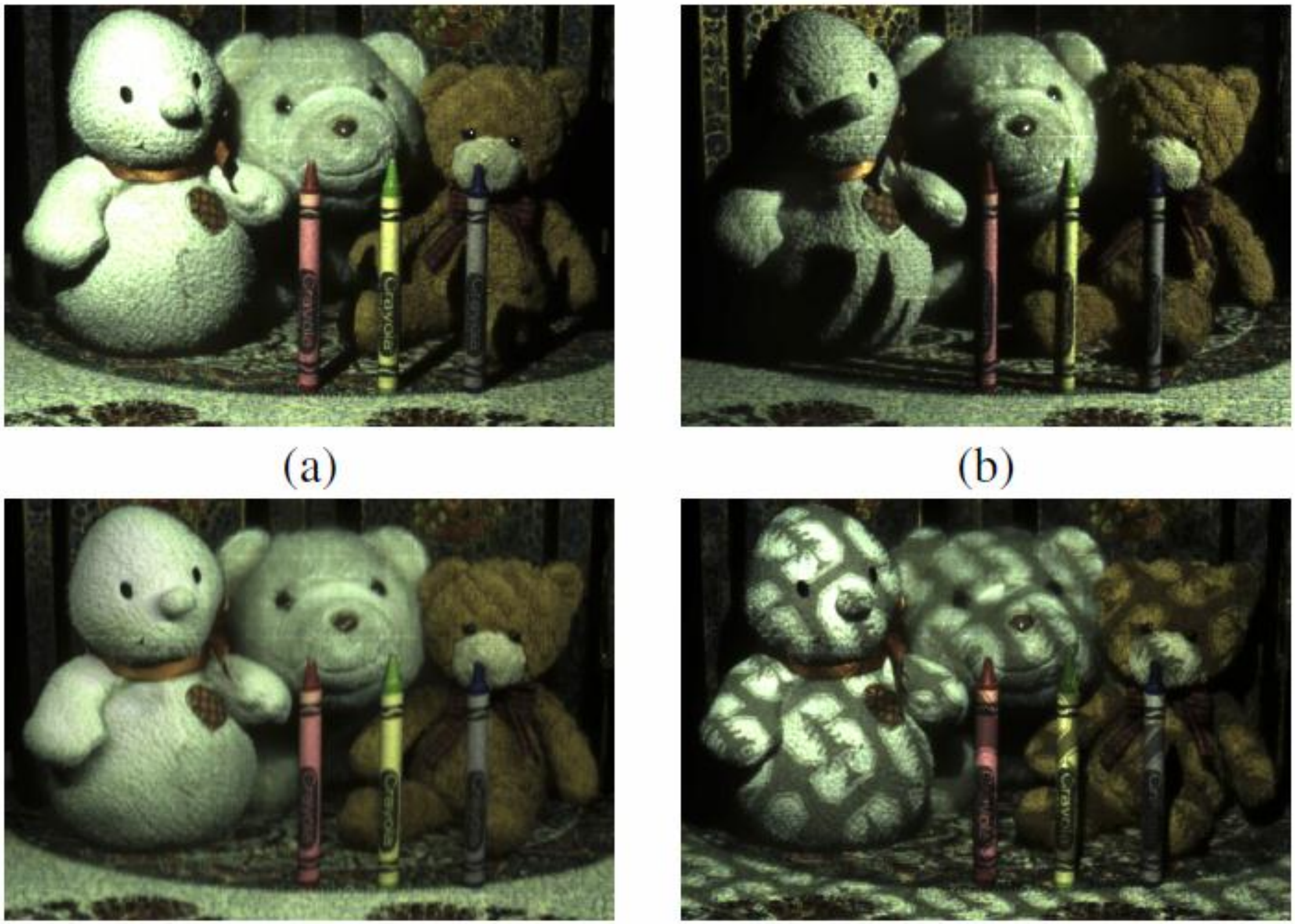
Relighting

With Dual Photography…

Relighting

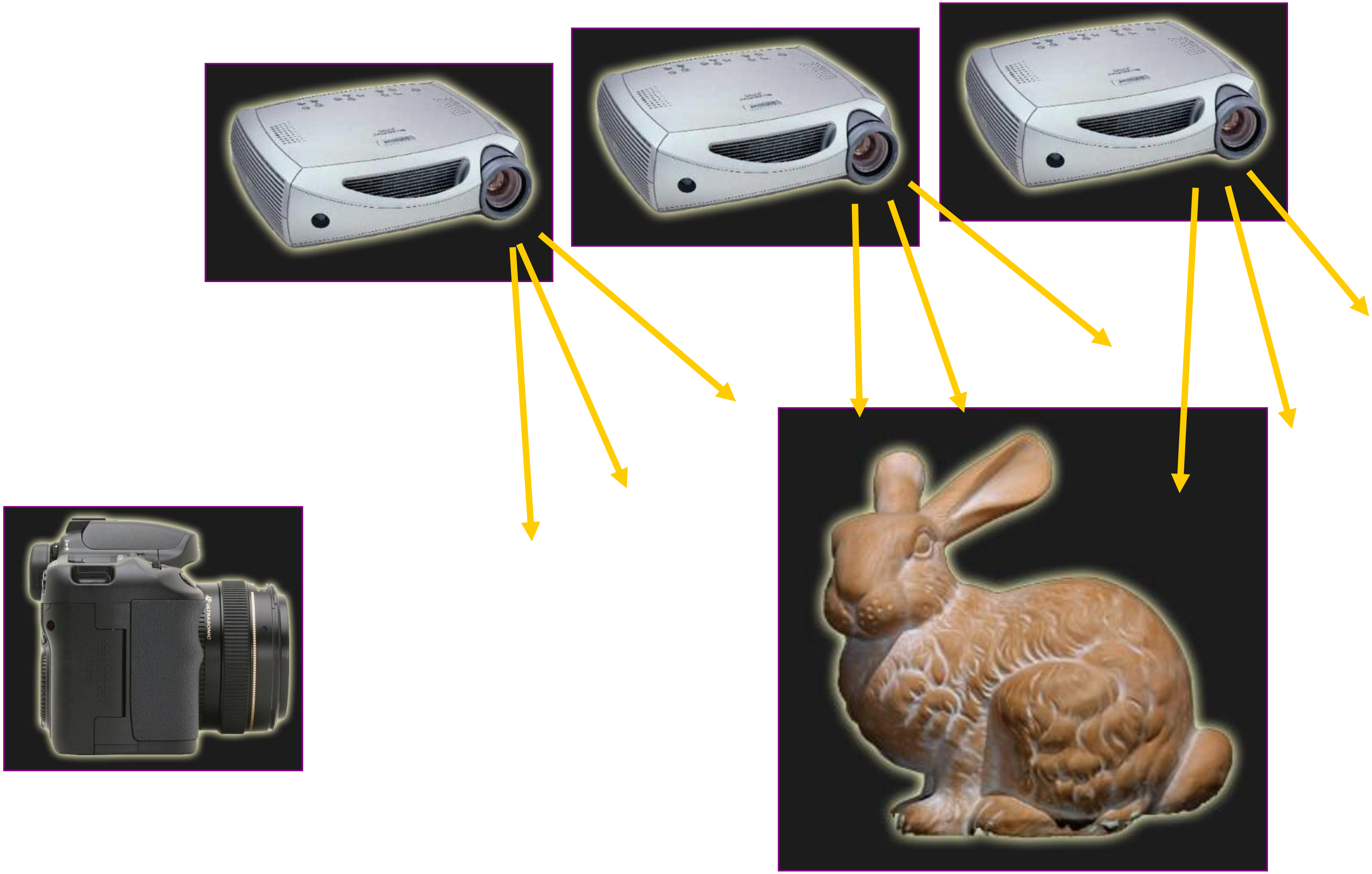
With Dual Photography…

Relighting

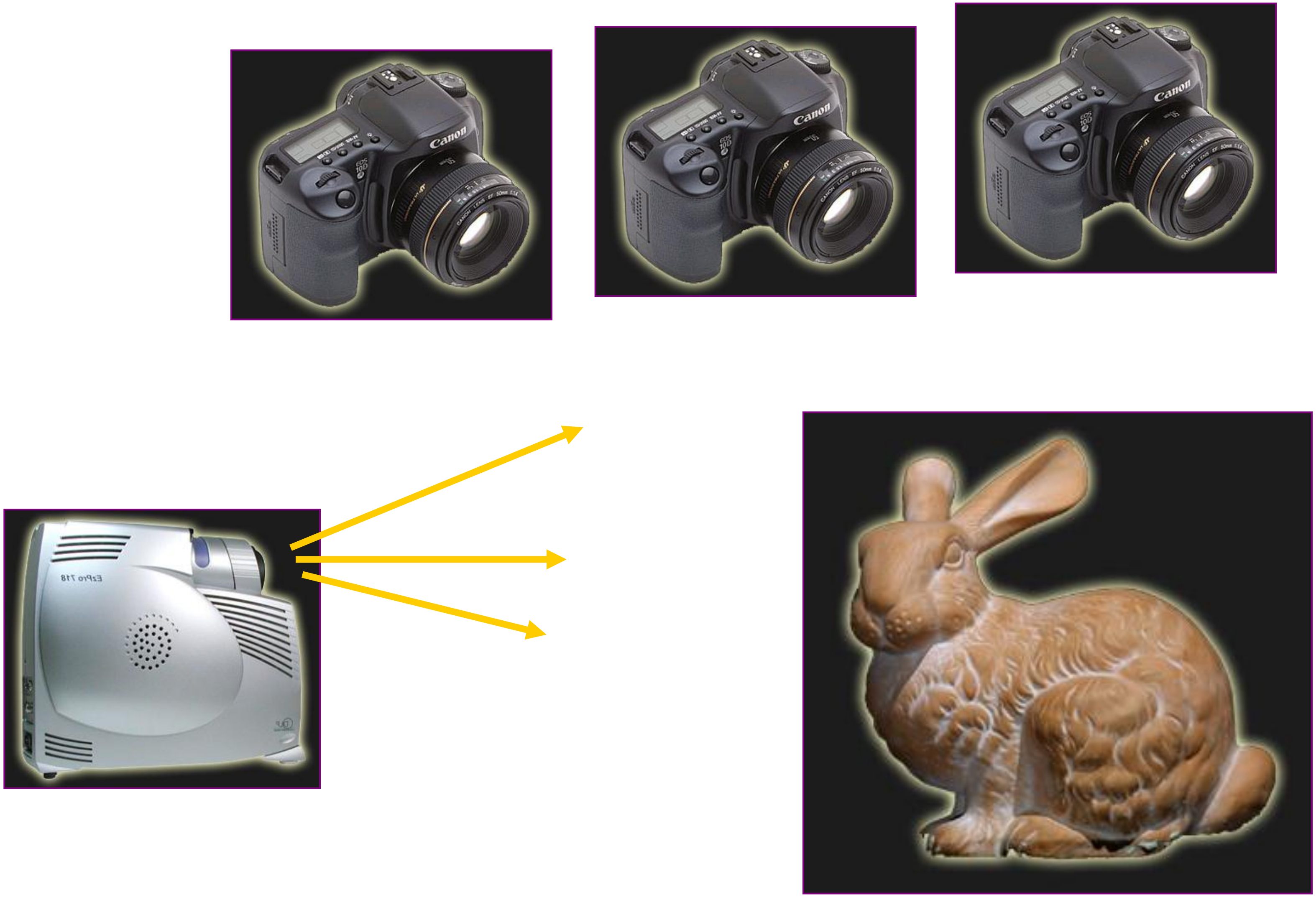


With Dual Photography…

The 6D transport matrix



The 6D transport matrix



The advantage of dual photography

- capture of a scene as illuminated by different lights cannot be parallelized

- capture of a scene as viewed by different cameras <u>can</u> be parallelized

Measuring the 6D transport matrix

projector

camera

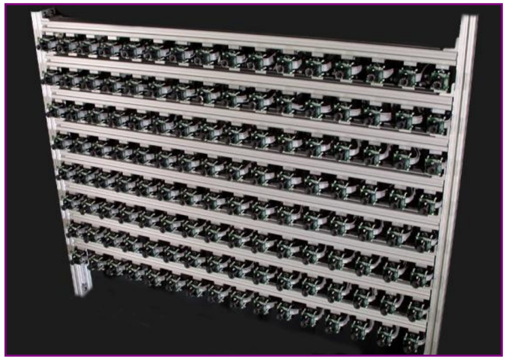
camera array

scene

Relighting with complex illumination

projector

camera array



scene

pq x mn x uv

$$\begin{bmatrix} C' \end{bmatrix} = \begin{bmatrix} T^T \end{bmatrix} \begin{bmatrix} P' \end{bmatrix}$$

pq x 1 mn x uv x 1

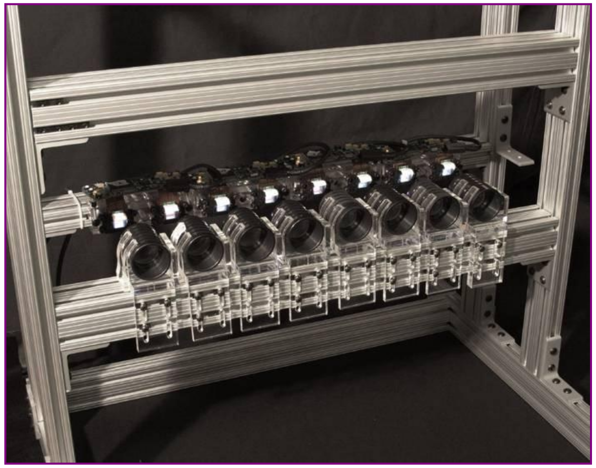
- step 1: measure 6D transport matrix T
- step 2: capture a 4D light field
- step 3: relight scene using captured light field

Running time

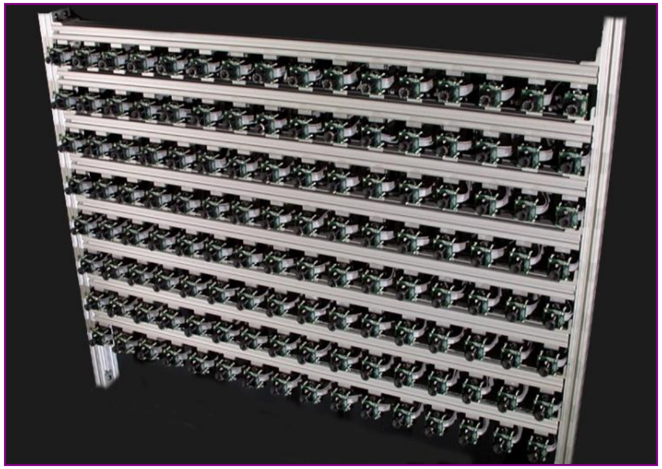
- the different rays within a projector can in fact be parallelized to some extent
- this parallelism can be discovered using a coarse-to-fine adaptive scan
- can measure a 6D transport matrix in 5 minutes

Can we measure an 8D transport matrix?

projector array



camera array



scene

Demos

- Metropolis Light Transport
  - http://www.youtube.com/watch?v=3Xo0qVT3nxg
  - http://www.youtube.com/watch?v=GMDfy_B0rvQ

- Faster acquisition:
  - http://www.youtube.com/watch?v=fVBICVBEGVU&playnext=1&list=PL361744591665D18D&feature=results_video