Coded Computational Imaging

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Mitsubishi Electric Research Labs (MERL)
Robotics Institute, CMU
MIT Media Lab

Course WebPage :
http://www.umiacs.umd.edu/~aagrawal/CVPR10Tutorial/index.html

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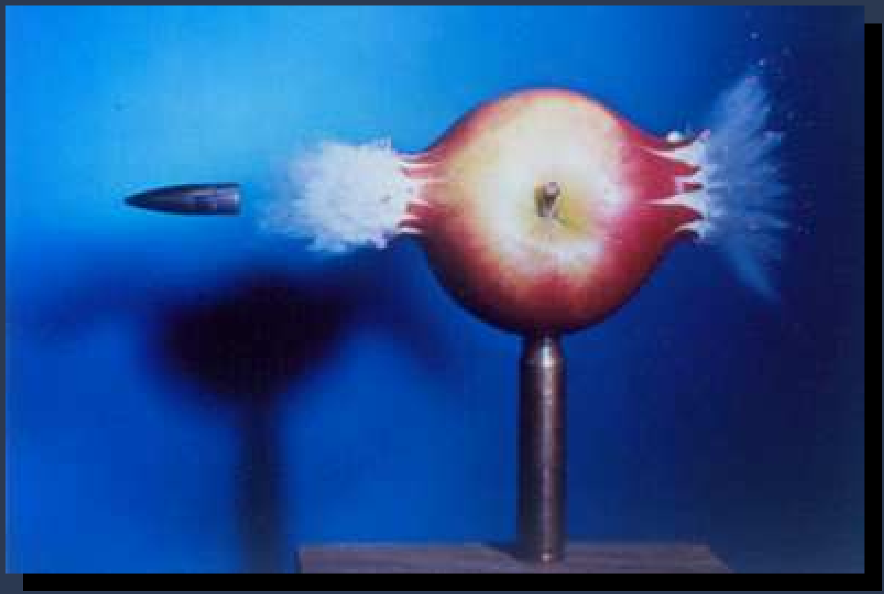
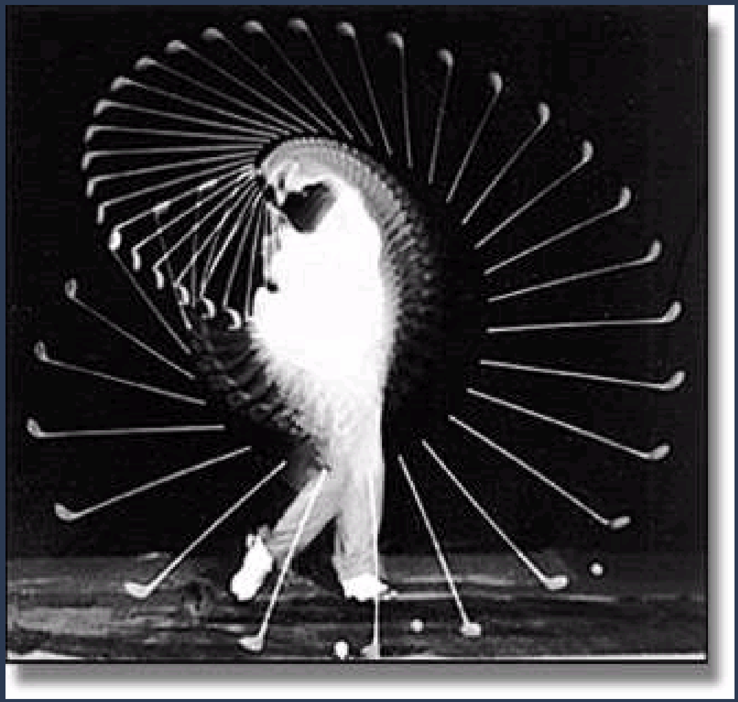
What parameters can we change ?

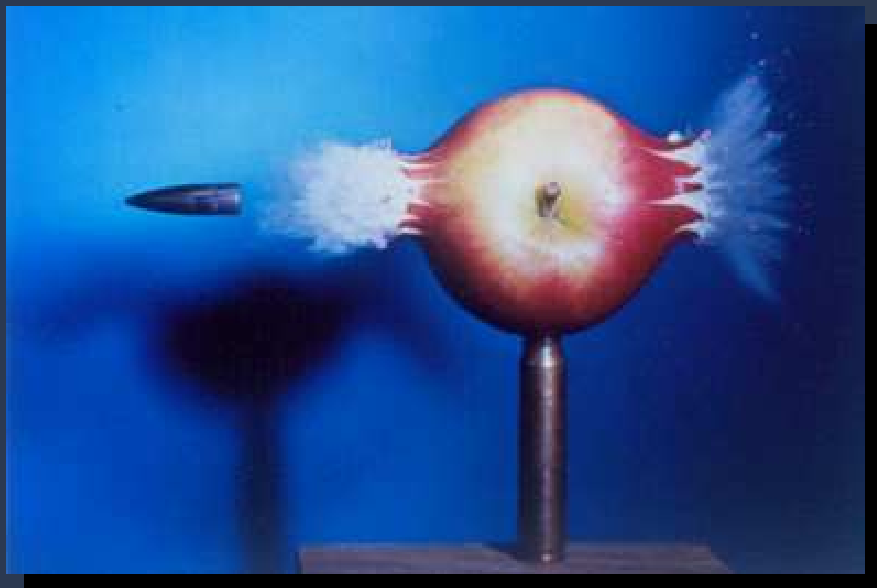
Edgerton 1930's

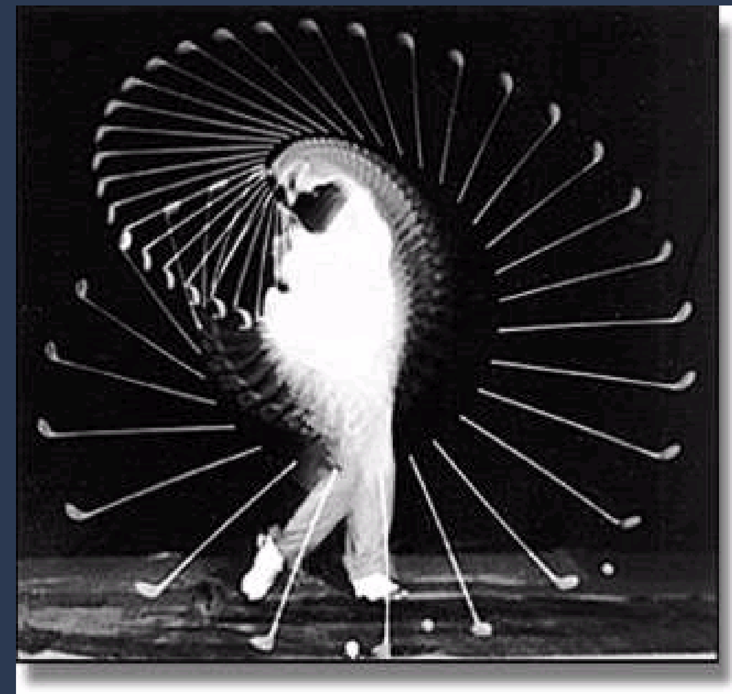




Not special cameras but special lighting

Edgerton 1930's



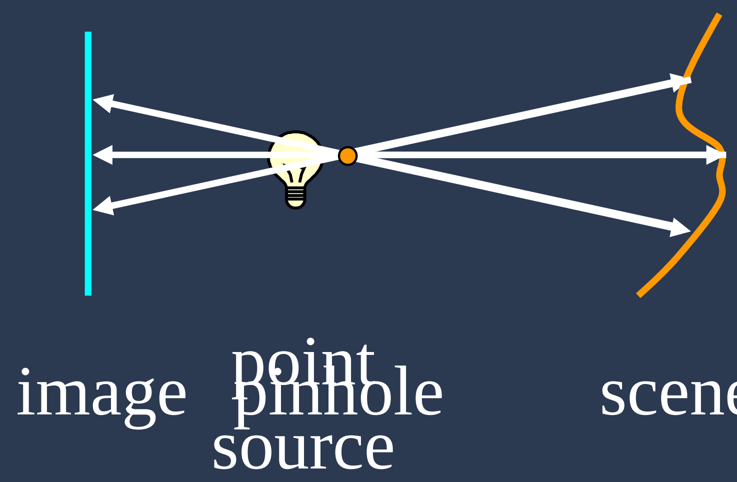


Stroboscope
(Electronic Flash)

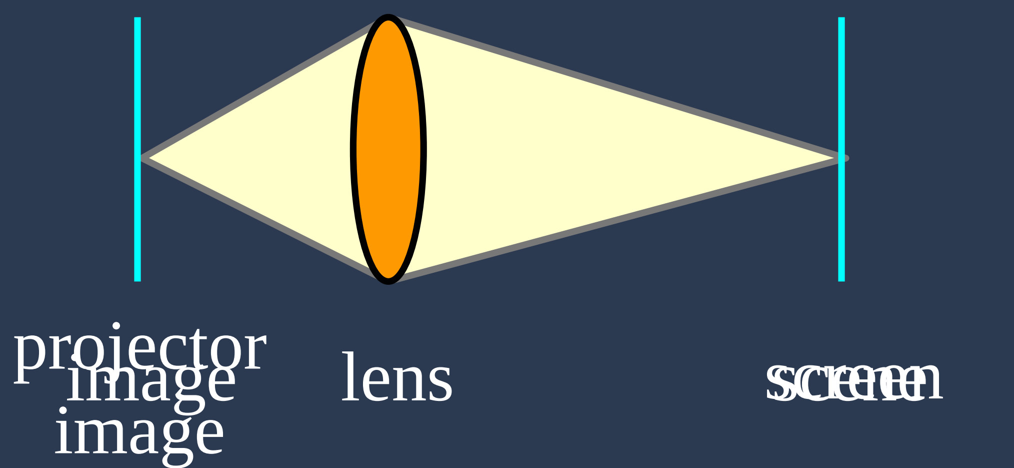
Multi-flash
Sequential Photography

Cameras and light sources are Optical duals

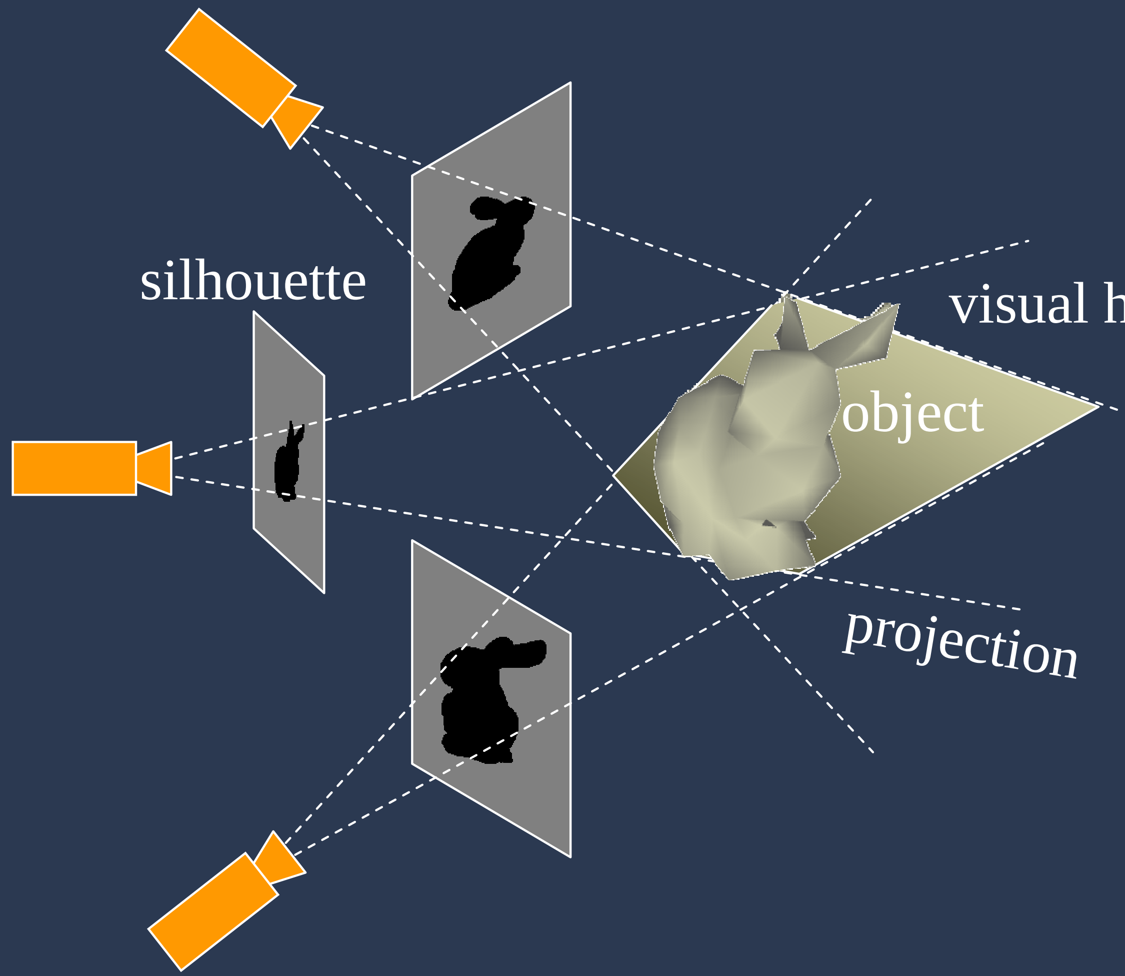
Point sources and Pinhole cameras



Projector-camera systems

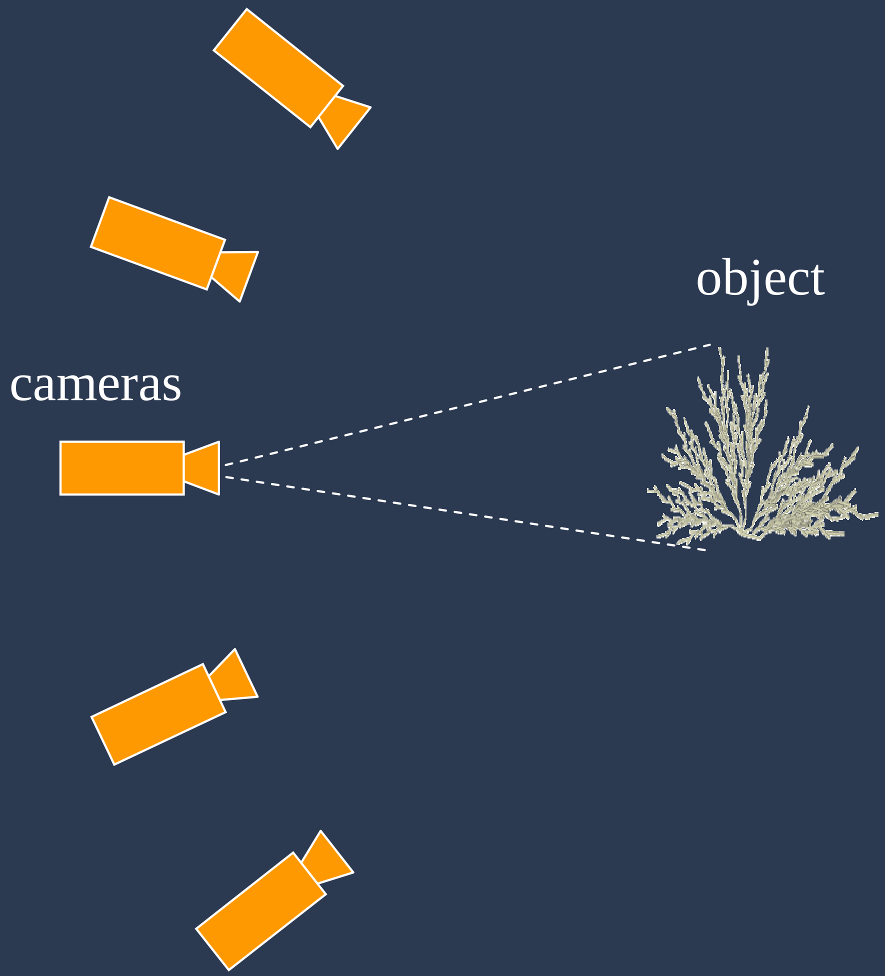


Shape from silhouettes



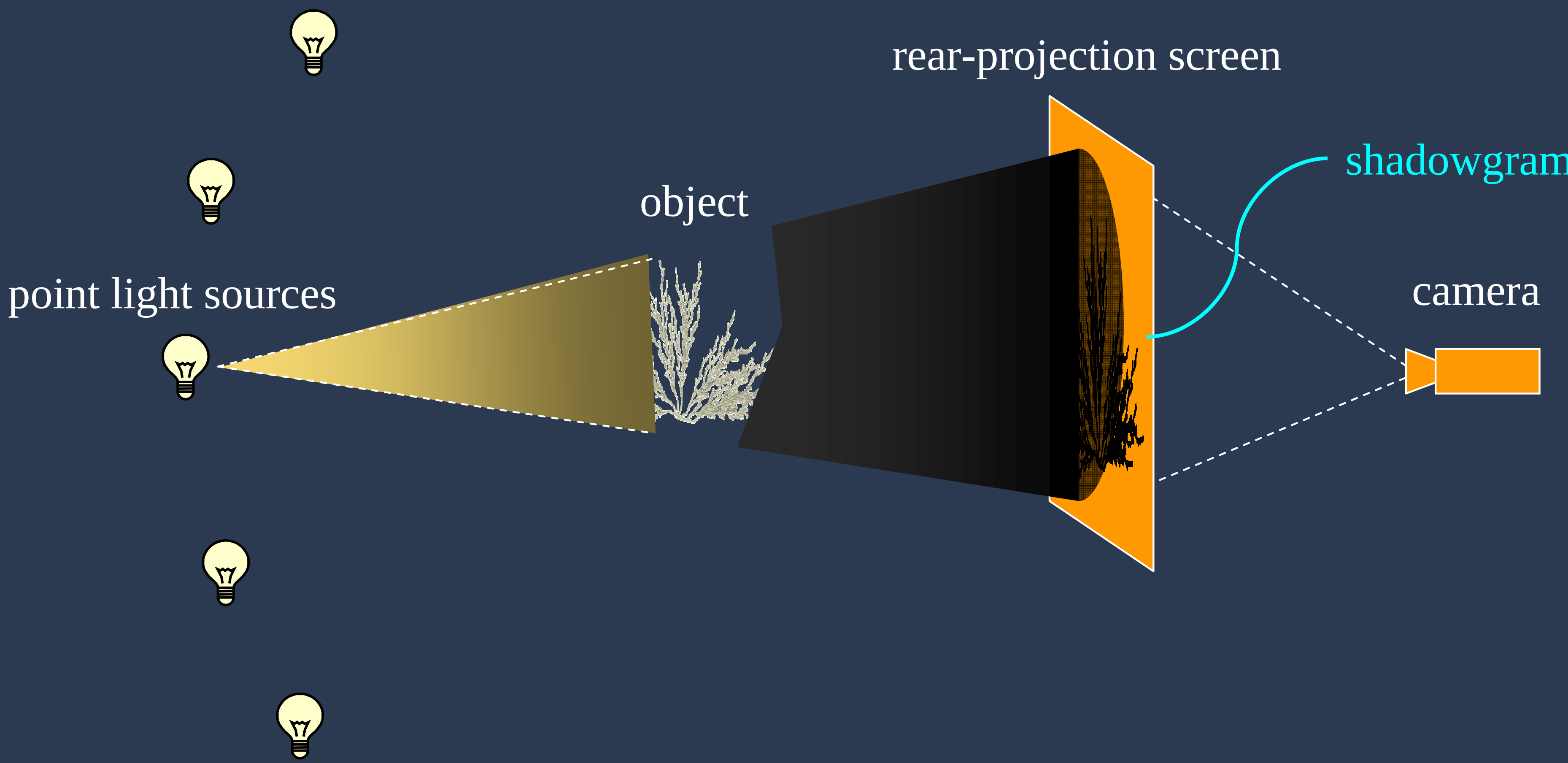
[Baumgart 74,Laurentini 94, Matusik et al 00]

Using light sources as cameras



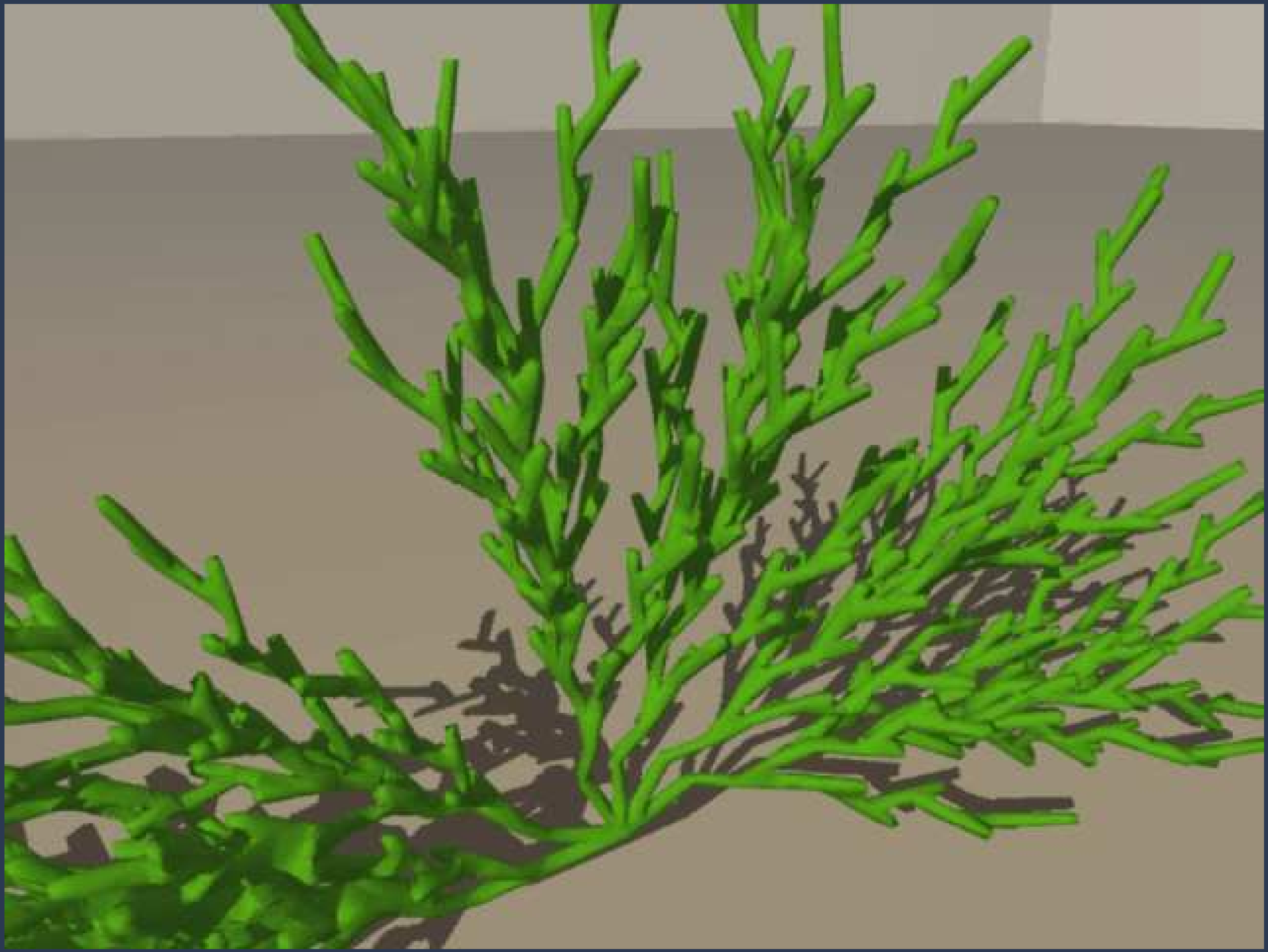
Number of parameters: $\left(\begin{array}{c} \text{camera rotation} \\ (3) \end{array} + \begin{array}{c} \text{camera translation} \\ (3) \end{array} \right) \times \begin{array}{c} \text{number of views} \\ (n) \end{array} = 6n$

Coplanar shadowgram imaging

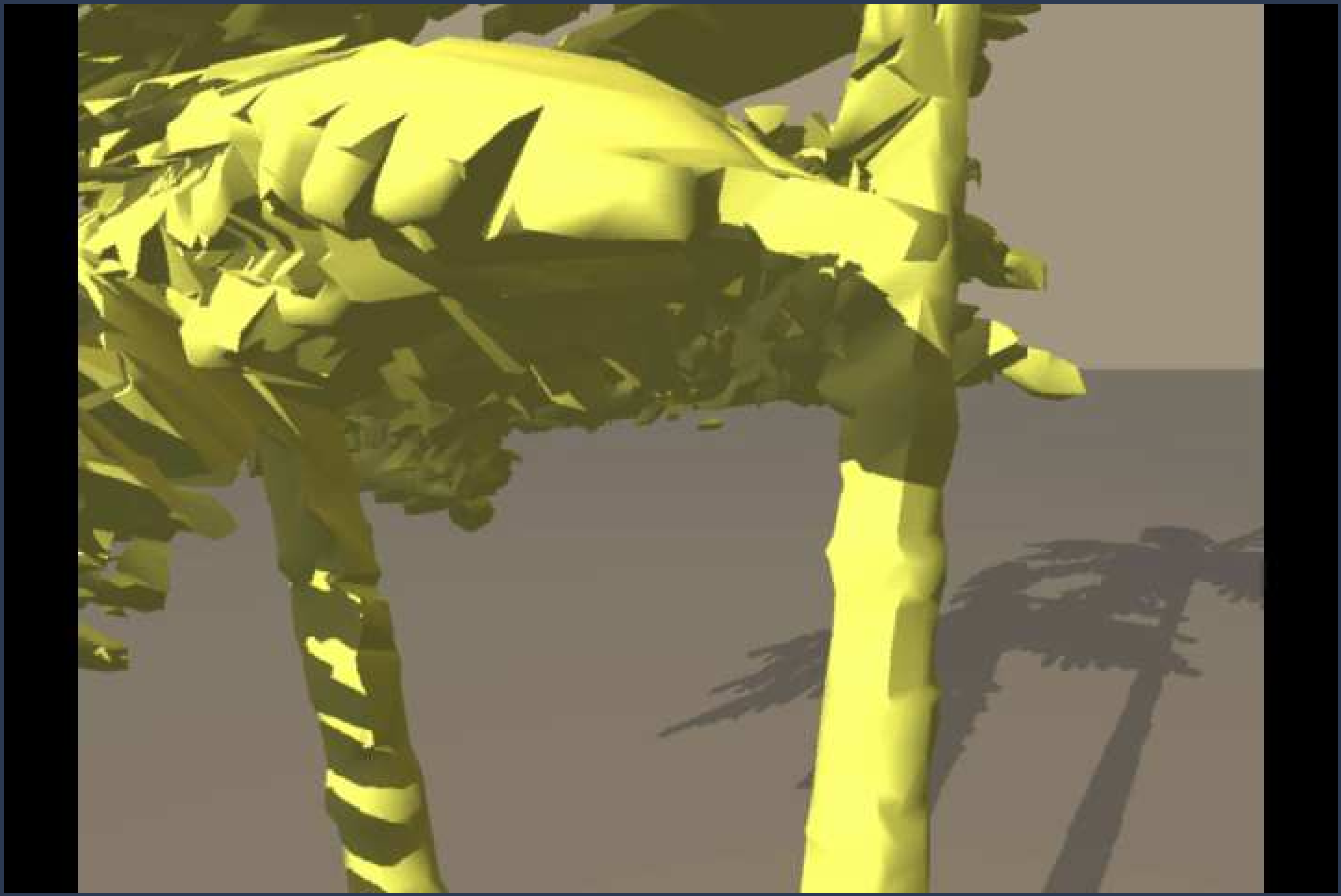


Number of parameters = light source translation (3) X number of views (n) = $3n$

50 views



70 views



90 views

125 views

Shape reconstruction

30 (of 50) silhouettes

Ground truth visual hull

Reconstructed visual hull
(initial calibration)

Shape reconstruction

30 (of 50) silhouettes

Ground truth visual hull

Reconstructed visual hull
(Epipolar geometry)

Shape reconstruction

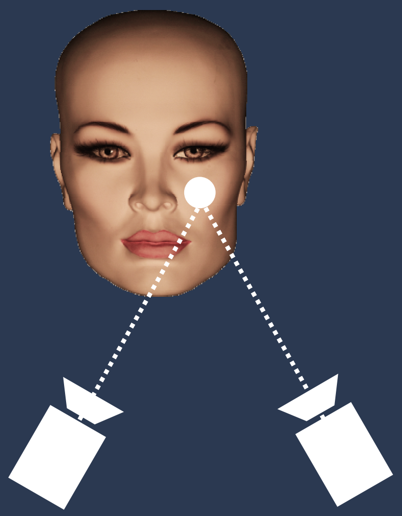
30 (of 50) silhouettes

Ground truth visual hull

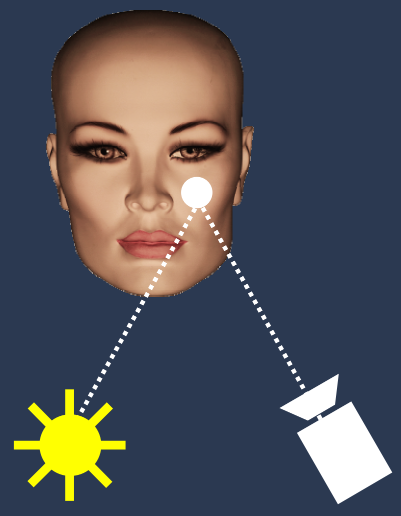
Reconstructed visual hull
(silhouette consistency)

Stereo vs. Helmholtz Stereo

STEREO



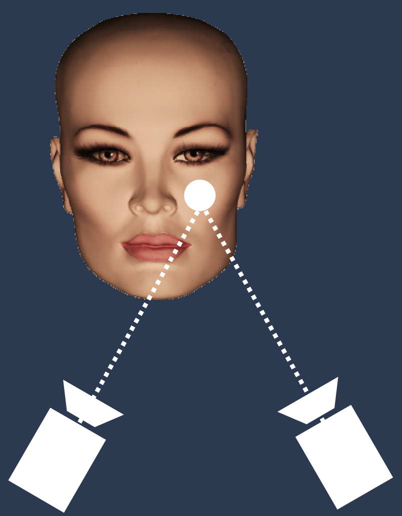
HELMHOLTZ STEREO



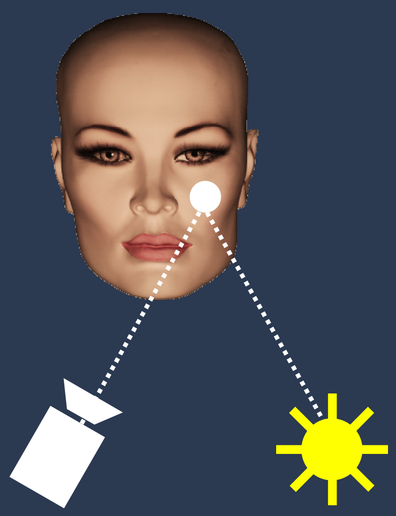
[Zickler et al., ECCV 2002]

Stereo vs. Helmholtz Stereo

STEREO



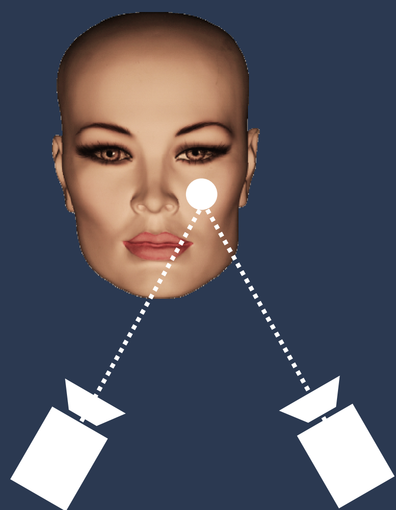
HELMHOLTZ STEREO



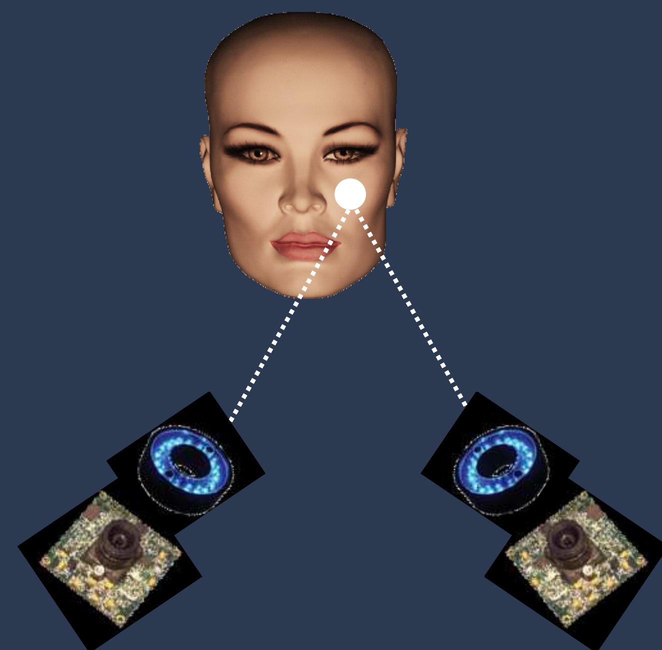
[Zickler et al., ECCV 2002]

Stereo vs. Helmholtz Stereo

STEREO

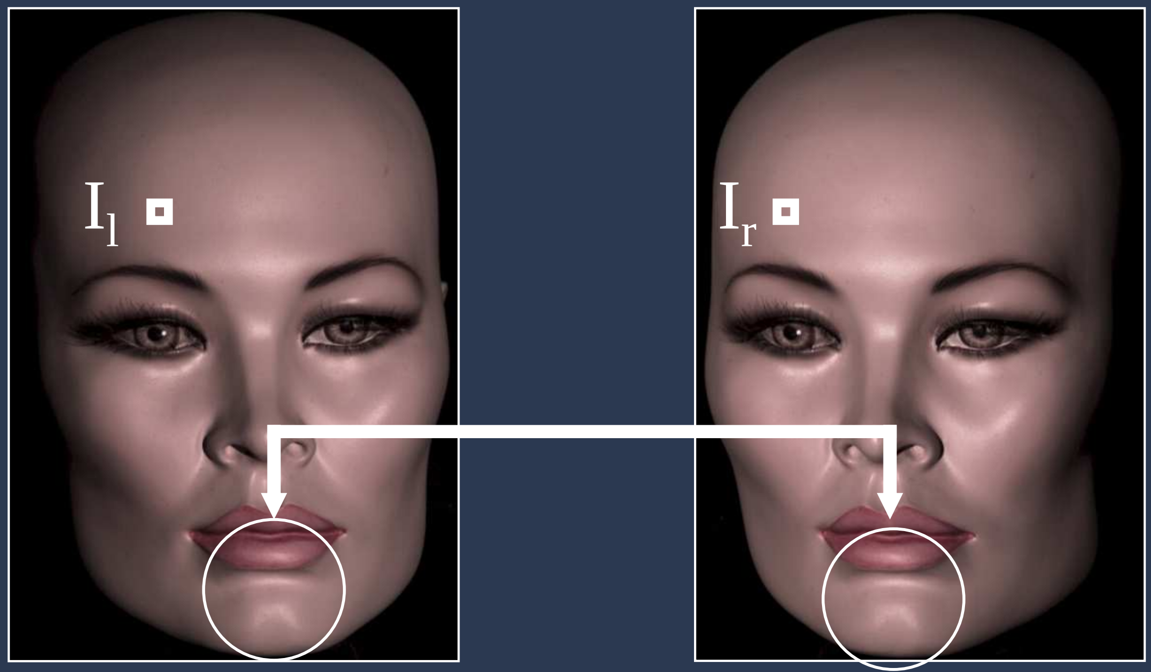


HELMHOLTZ STEREO



[Zickler et al., ECCV 2002]

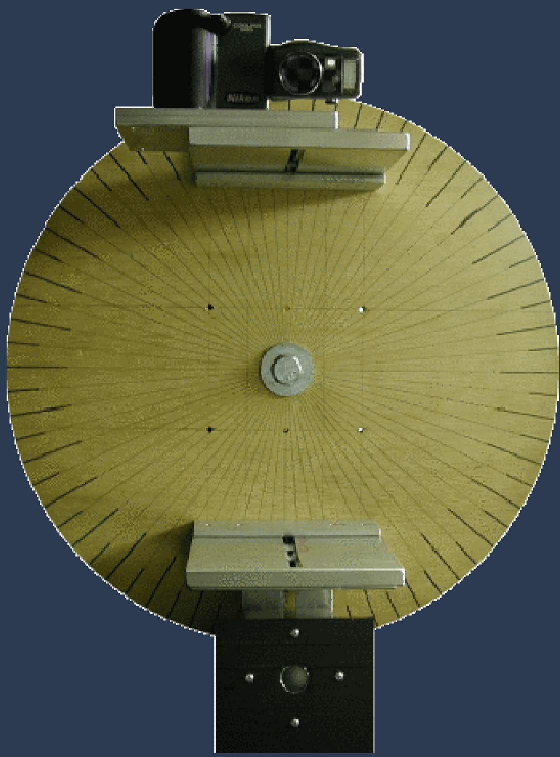
Reciprocal Images



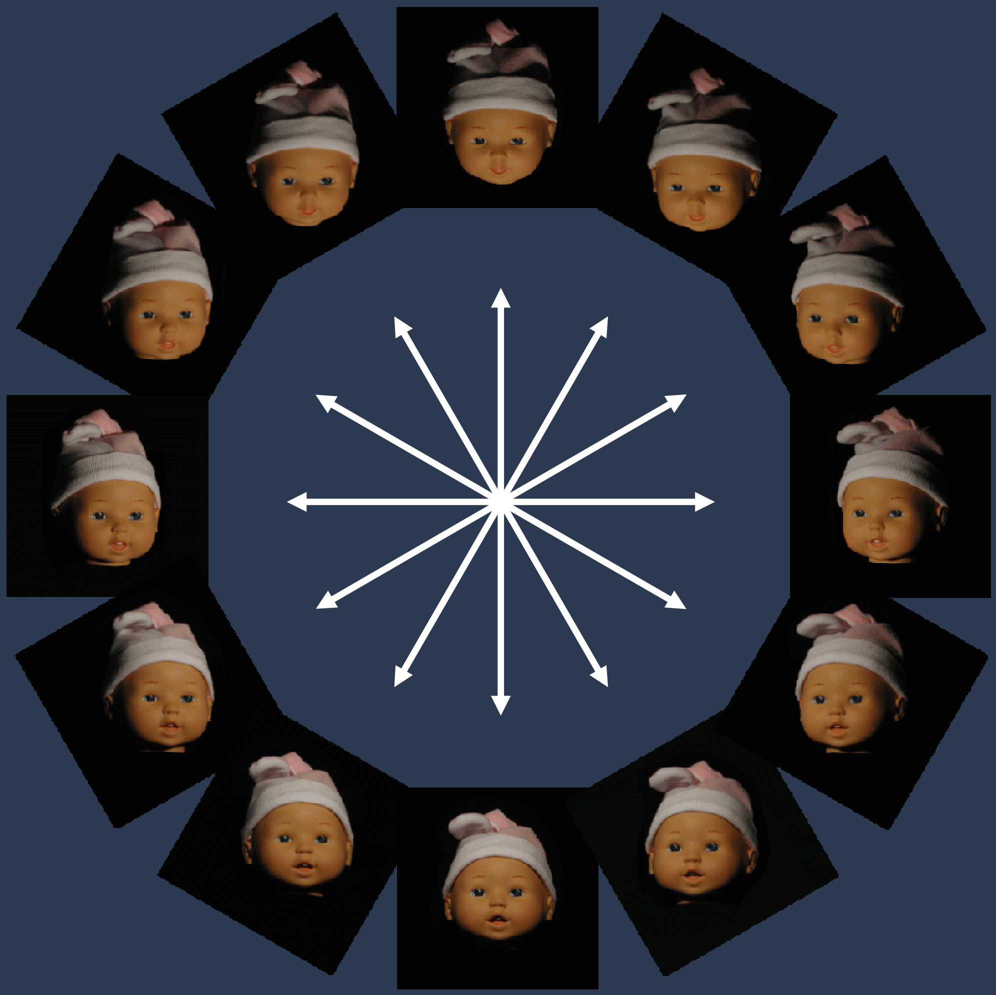
- Specularities “fixed” to surface
- Relation between I_l and I_r independent of BRDF

Reciprocal Acquisition

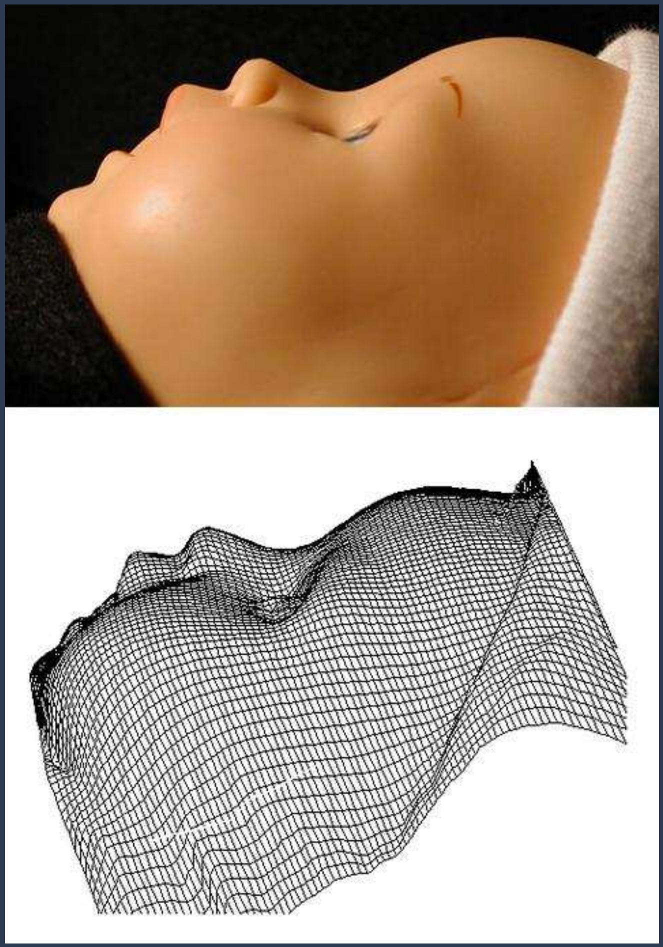
CAMERA

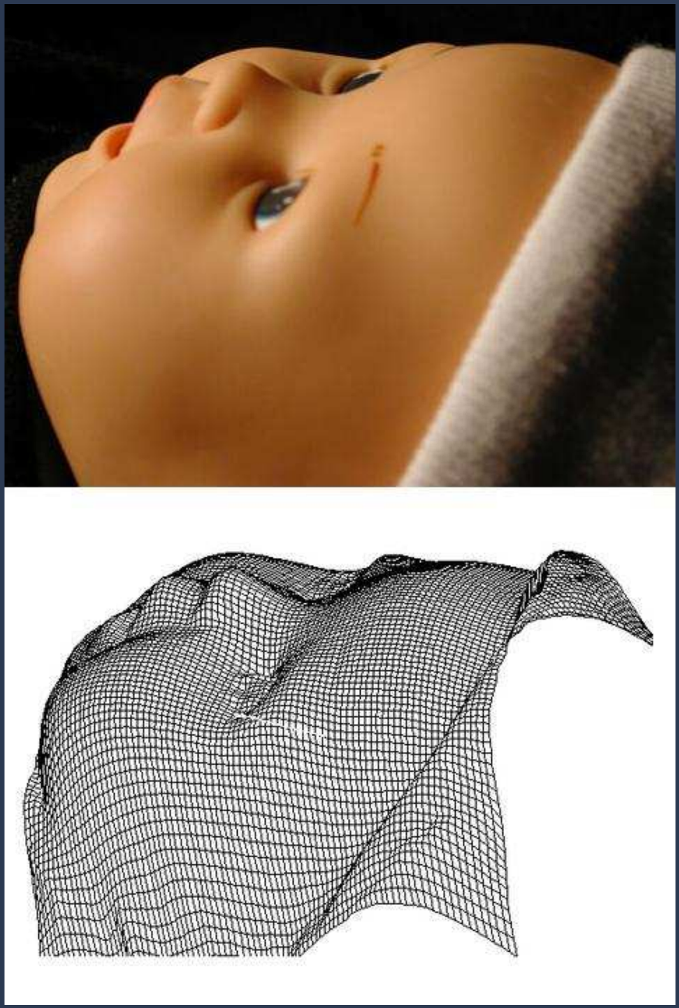


LIGHT SOURCE



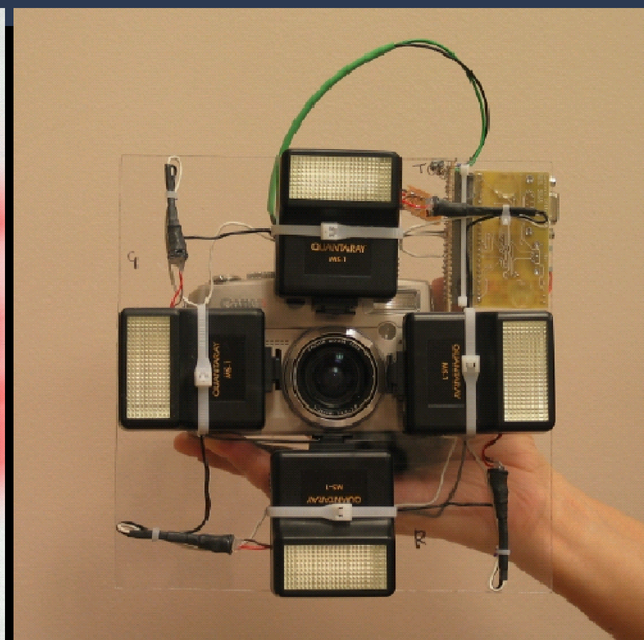
Recovered Surface



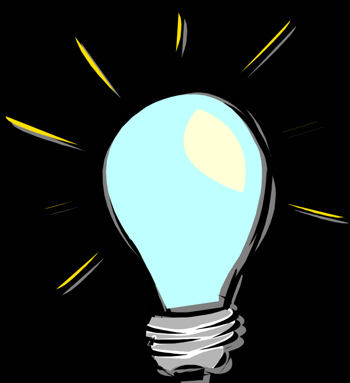


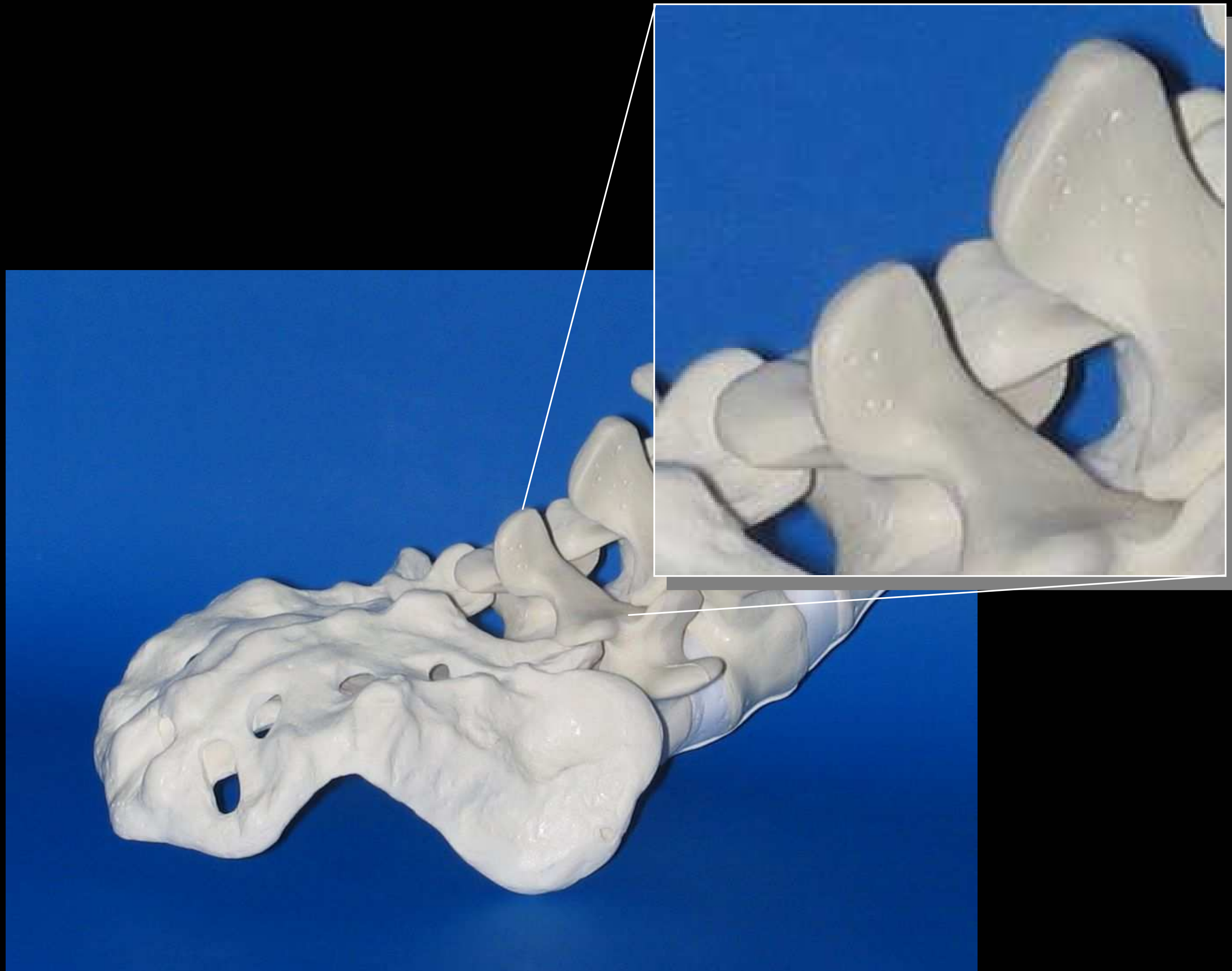
[Zickler et al., ECCV 2002]

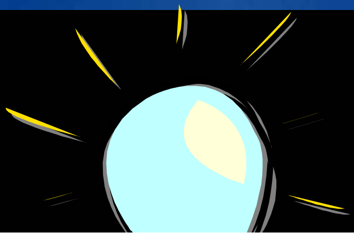
Depth Edge Detection using Multi-Flash Imaging



Raskar et al 2005



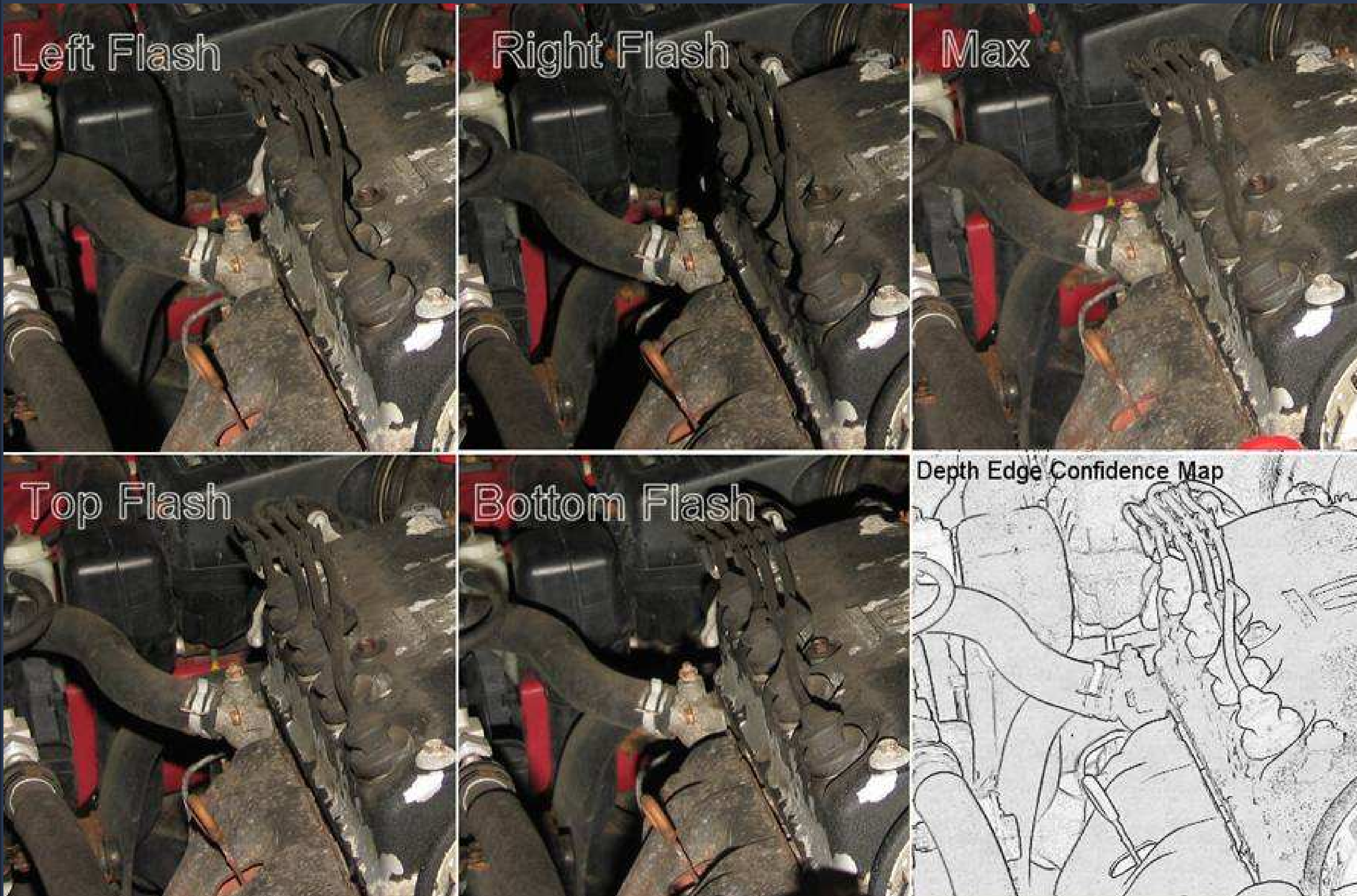




Depth Discontinuities

Internal and external

Shape boundaries, Occluding contour, Silhouettes


Left Flash
Right Flash
Max
Top Flash
Bottom Flash
Depth Edge Confidence Map

Denoising dark images

Available light:

+ nice lighting

- noise/blurriness
- color

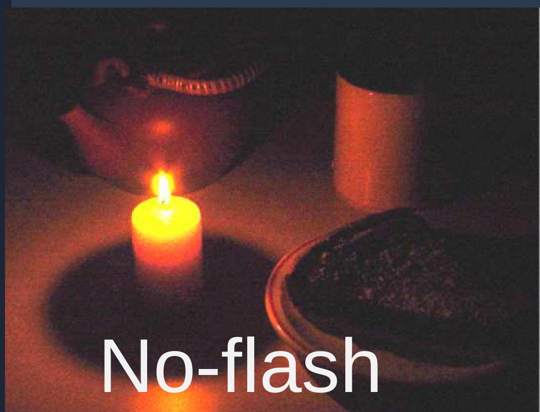
Exploiting Flash

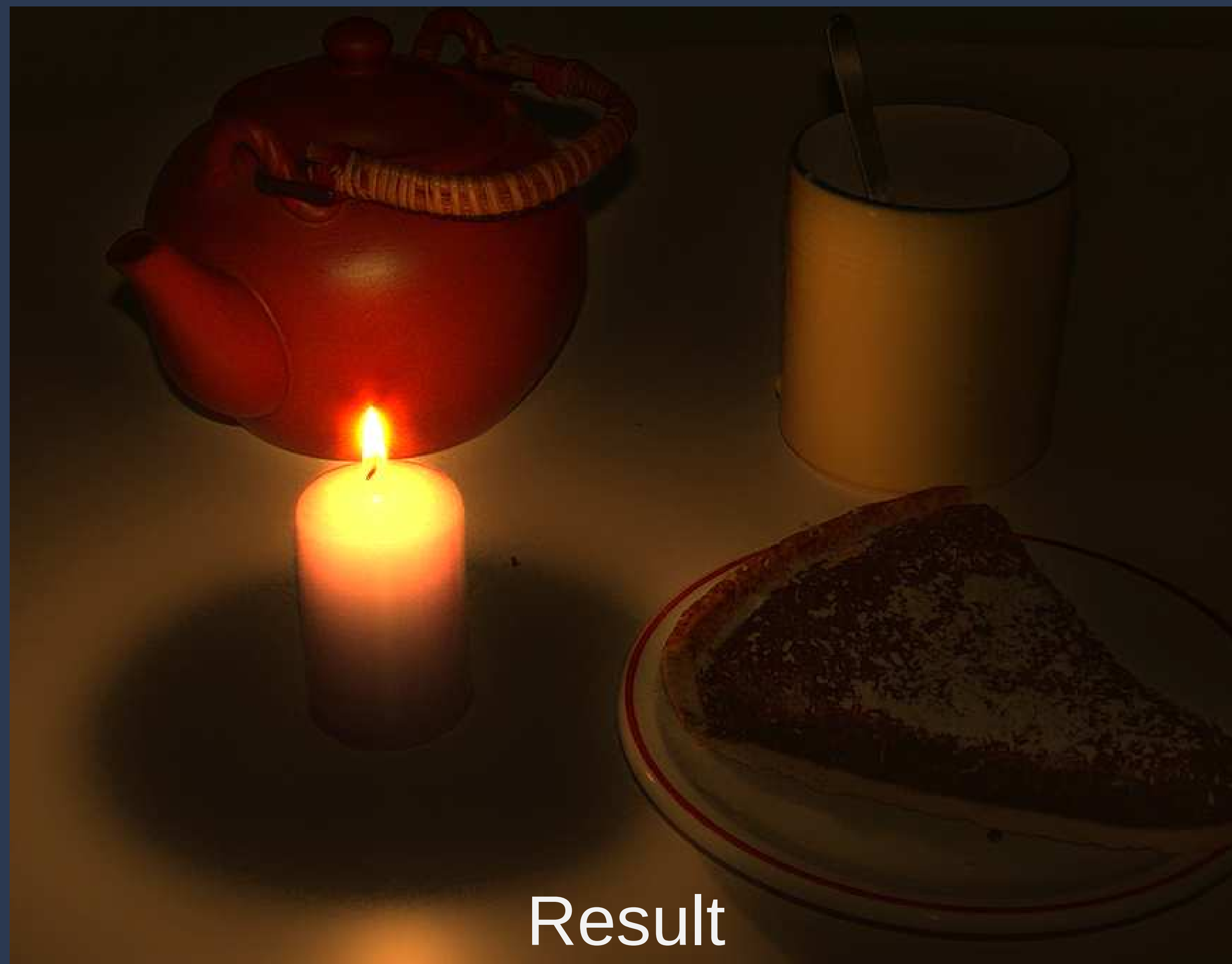
Flash:

+ details
+ color

- flat/artificial

Denoise no-flash image using flash image





[Petschnigg at al, Eisemann and Durand]

Detail from flash image to no-flash image

+ original lighting
+ details/sharpness
+ color

Debevec et al. 2002: Light Stage 3

Image-Based Re-lighting

Film the background in Milan

Film the actress in LA

Matched LA and Milan lighting

Matte the background

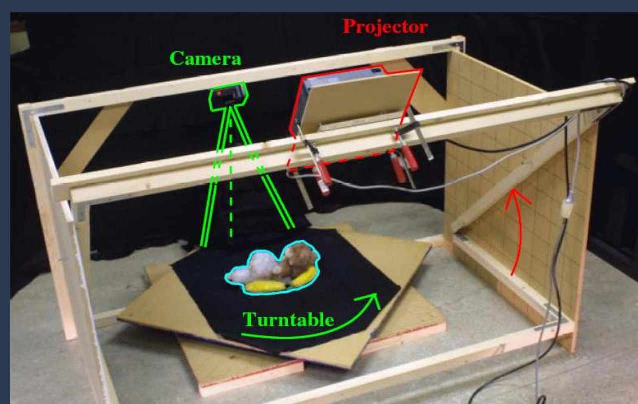
A 4-D Light Source


[Debevec et al. 2000]

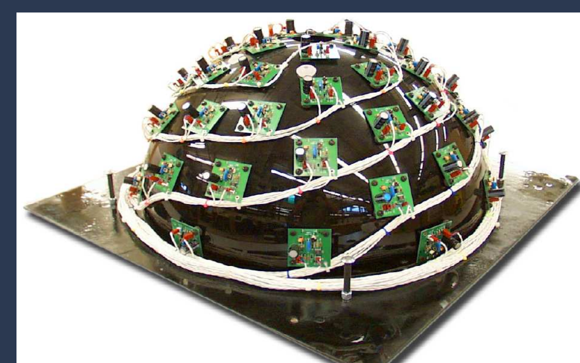

[Masselus et al. 2002]


[Matusik et al. 2002]

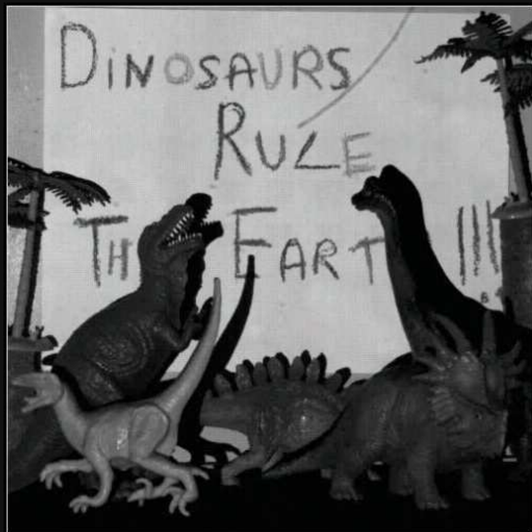

[Debevec et al. 2002]



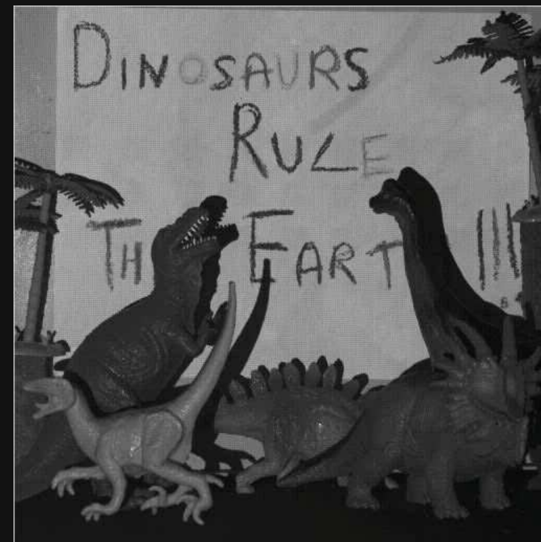
[Masselus et al. 2003]


[Malzbender et al. 2002]

Illumination from DLP projectors



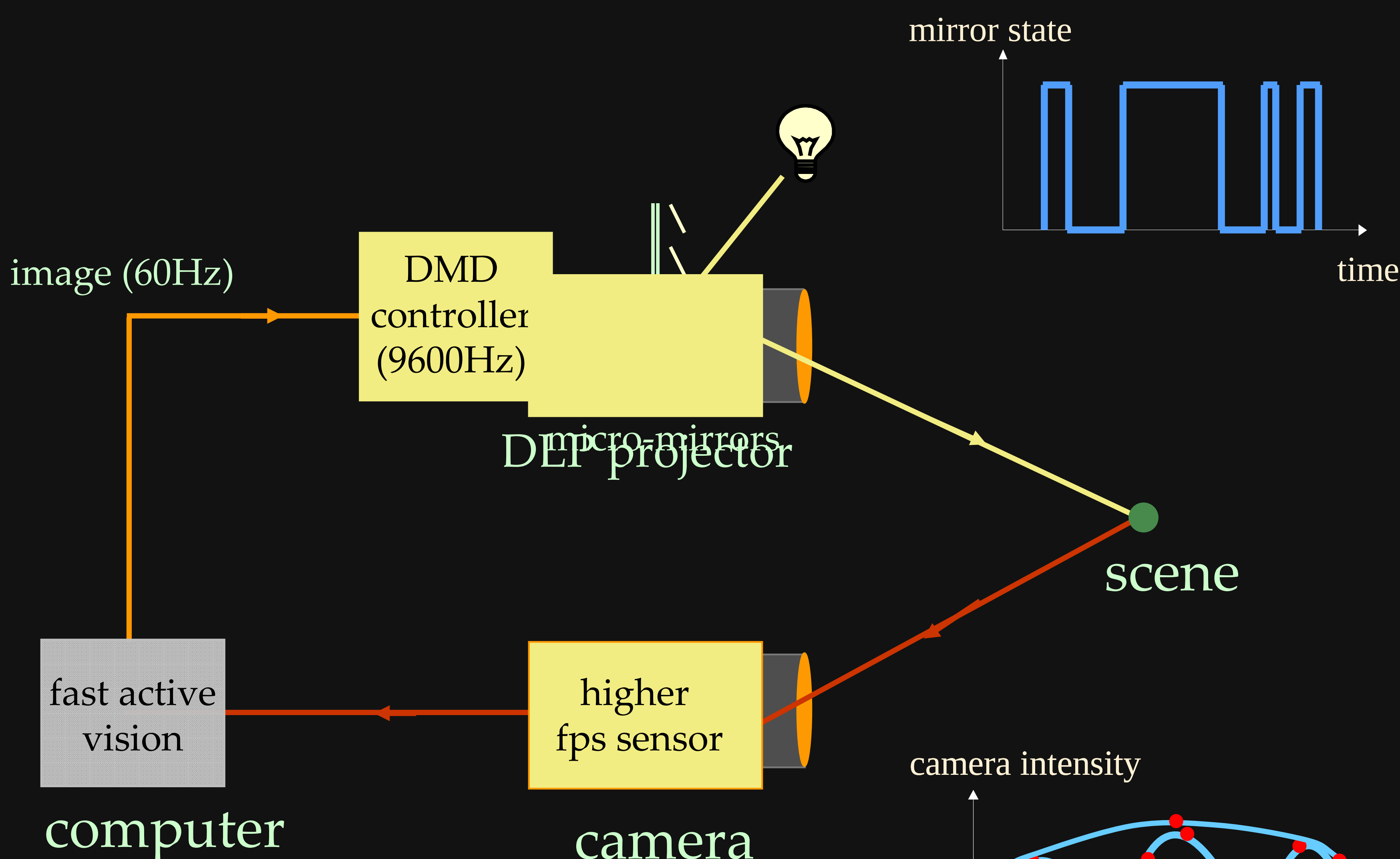
Video acquired at 60Hz

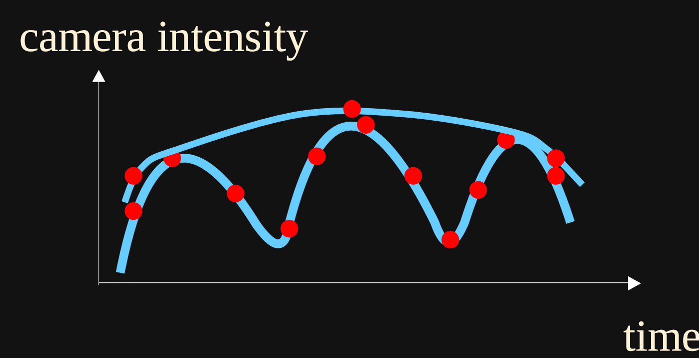


Video acquired at 1000Hz

Fast way of encoding scene illumination

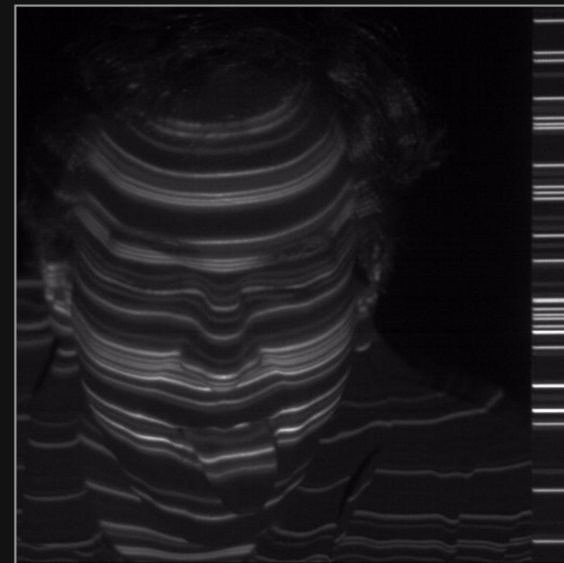
High-speed Illumination Dithering



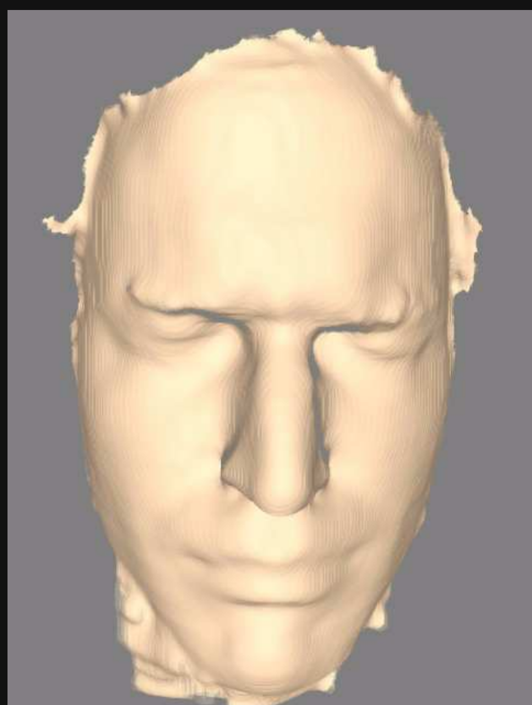


Pulse-Width Modulation (PWM) Coding

Captured video (30Hz)



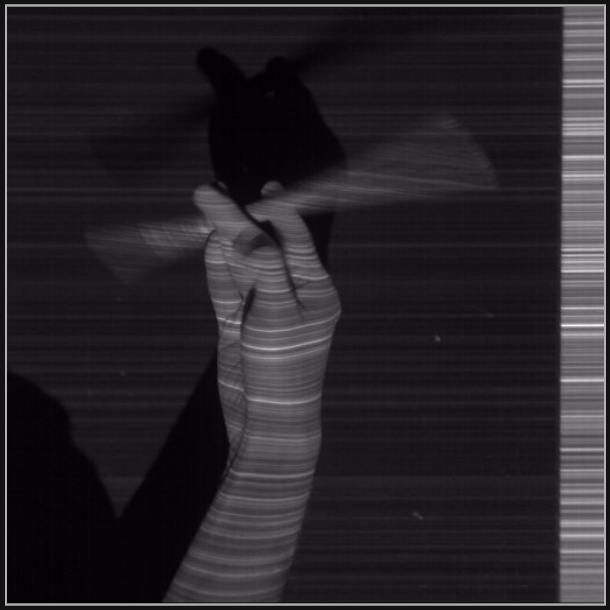
Captured video (3000Hz)



Reconstruction (30Hz)

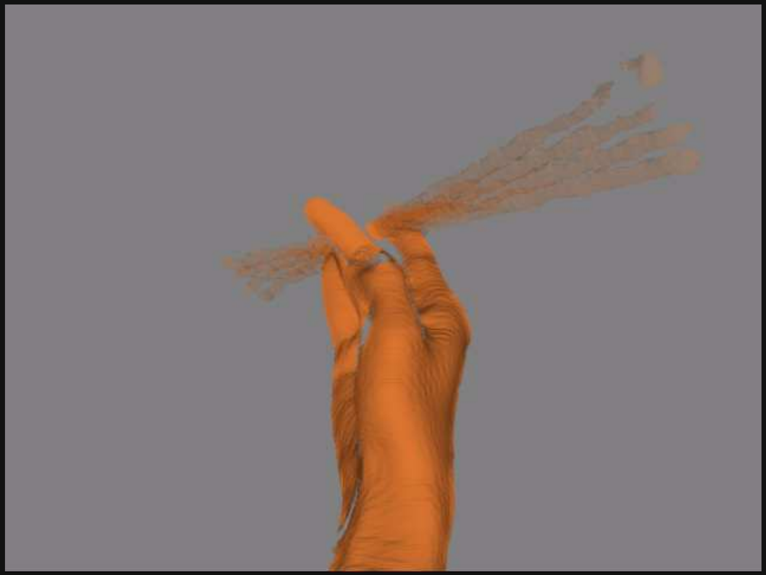
Reconstruction – different view (120Hz)

Reconstruction (120Hz)

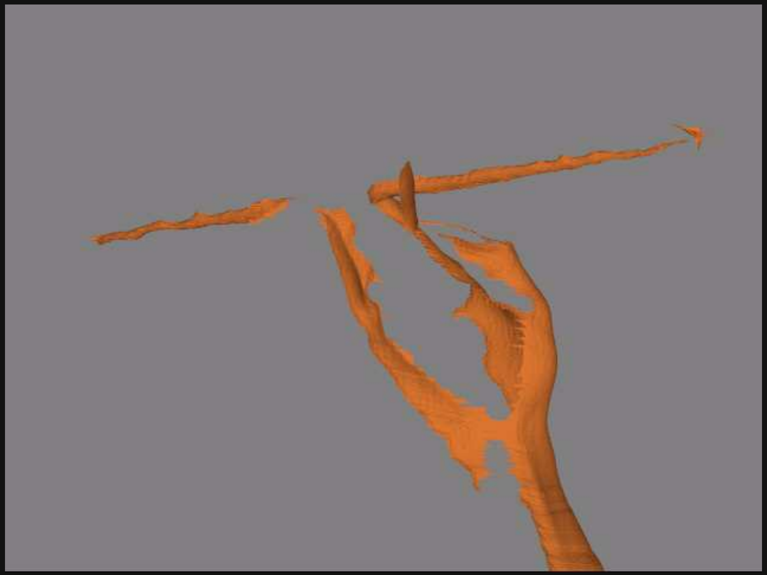


Captured video (30Hz)

Captured video (3000Hz)



Reconstruction (30Hz)



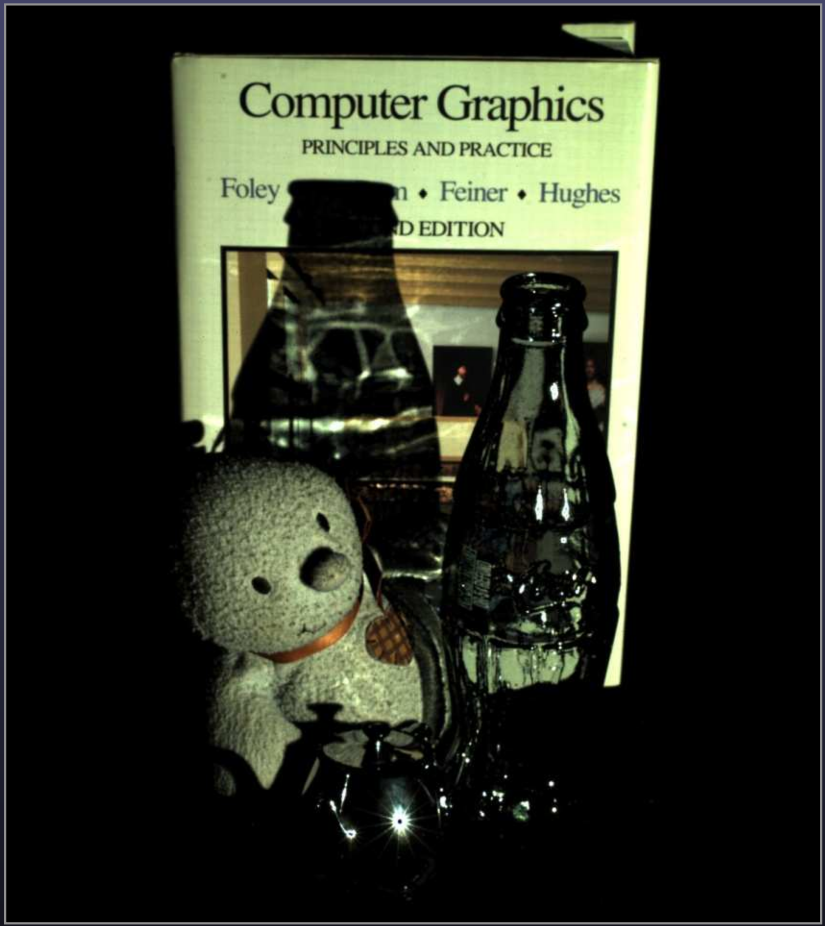
Reconstruction – different view (120Hz)

Reconstruction (120Hz)

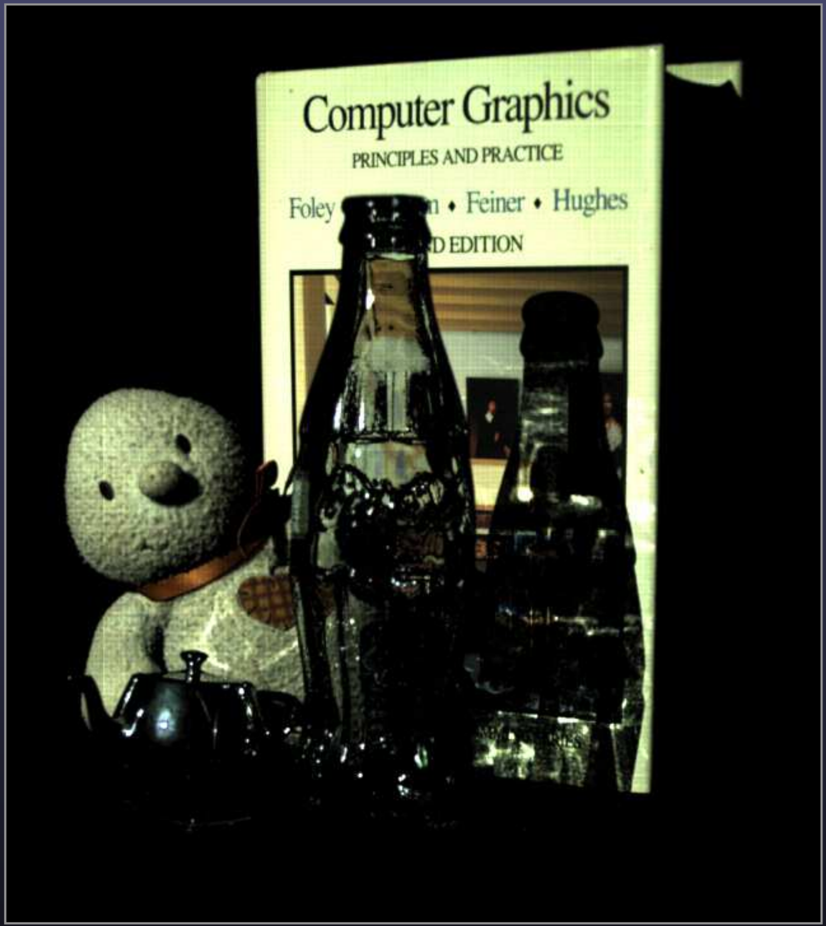
Dual Photography

Pradeep Sen, Billy Chen, Gaurav Garg, Steve Marschner,
Mark Horowitz, Marc Levoy, Hendrik Lensch

Dual Photographs

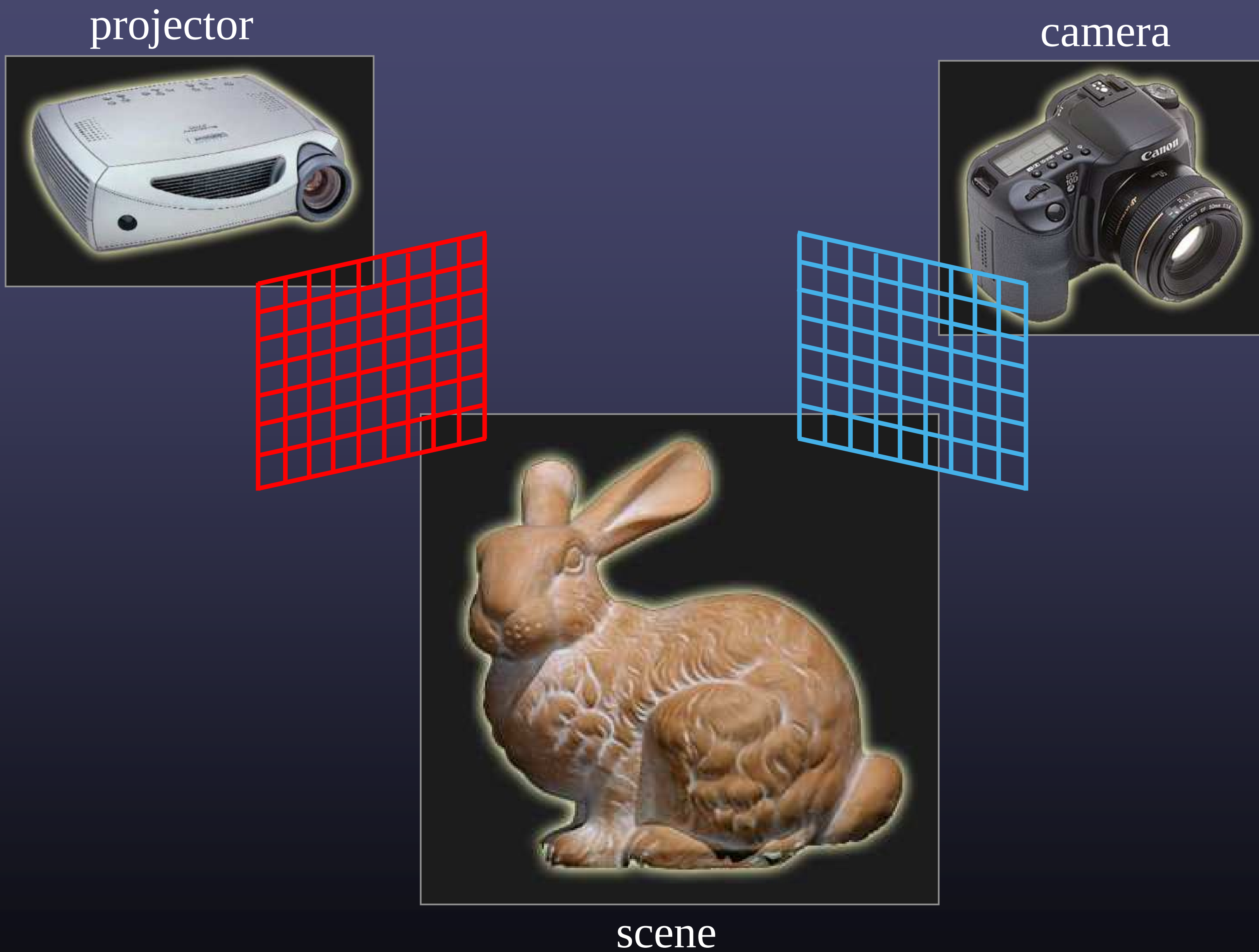


conventional photograph
with light coming from right

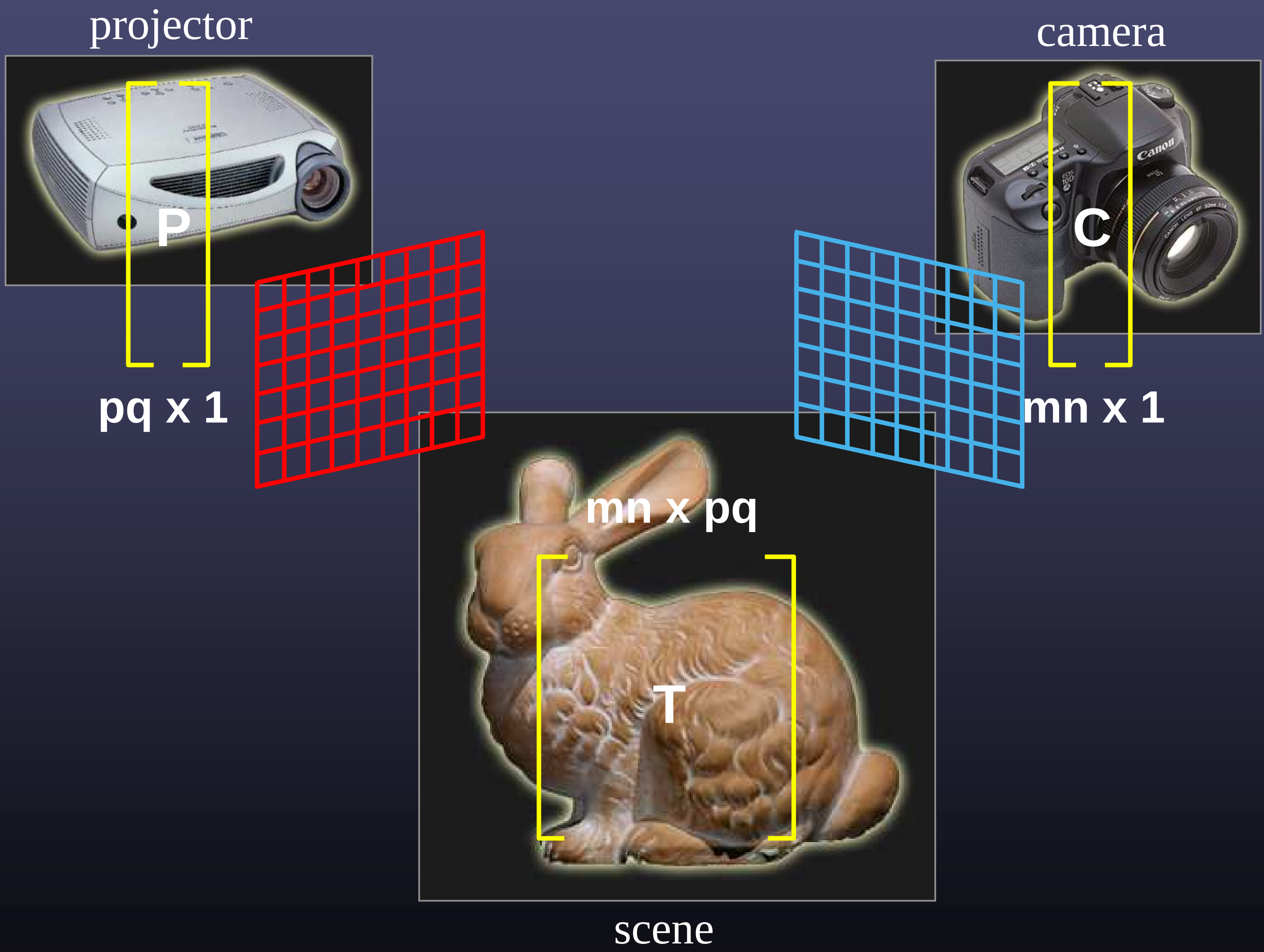


dual photograph
as seen from projector’s position

The 4D transport matrix



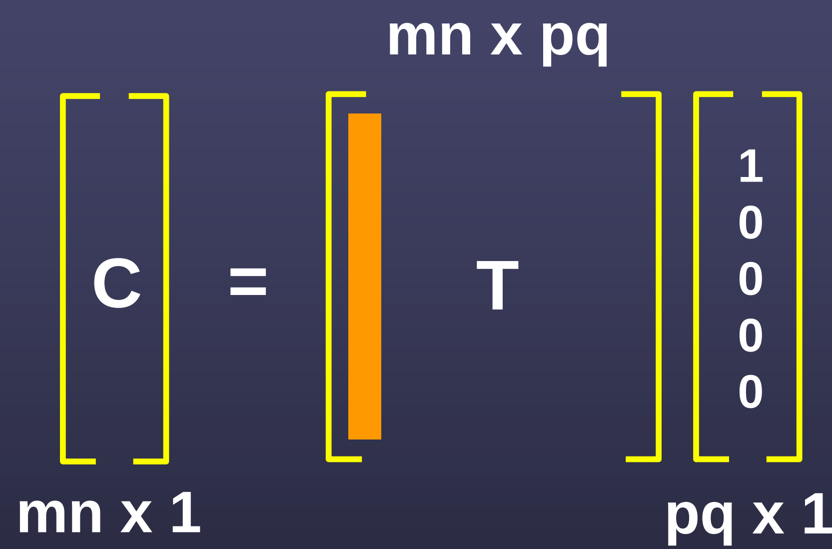
The 4D transport matrix



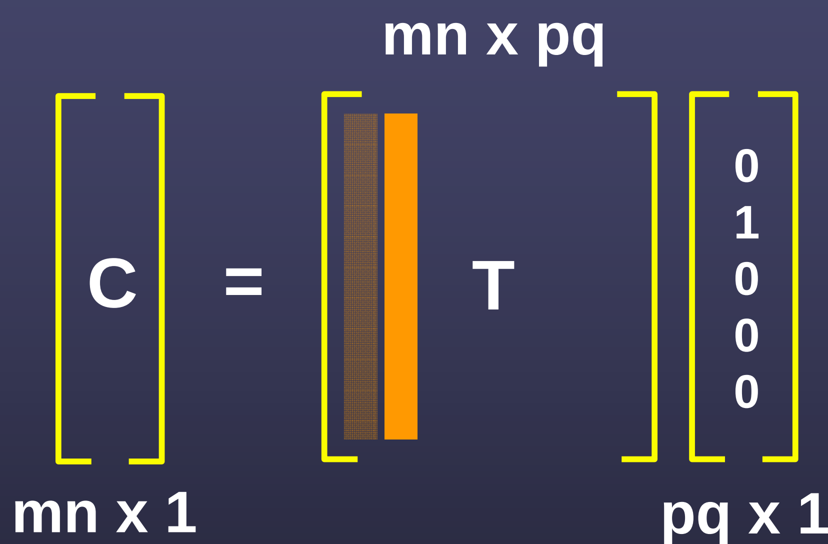
The 4D transport matrix

$$\underset{mn \times 1}{\left[\, C \,\right]} = \overset{mn \times pq}{\left[\quad T \quad\right]} \underset{pq \times 1}{\left[\, P \,\right]}$$

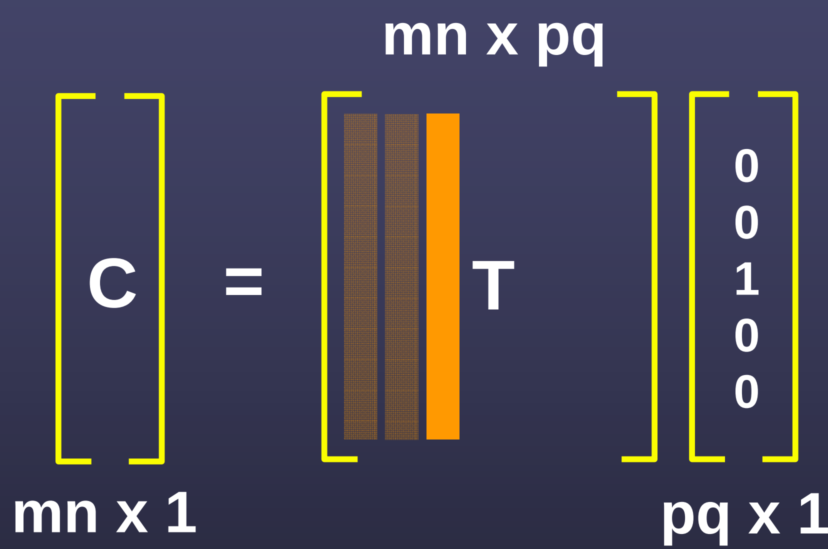
The 4D transport matrix



The 4D transport matrix



The 4D transport matrix



The 4D transport matrix

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

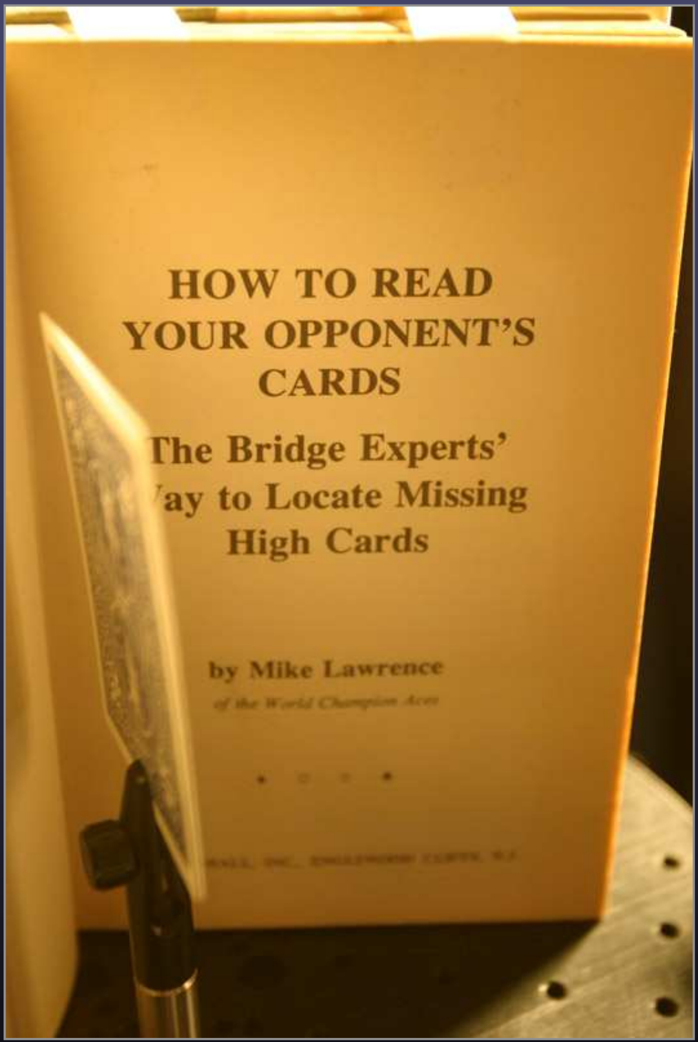
The 4D transport matrix

$$\underset{mn \times 1}{[\,C\,]} = \overset{mn \times pq}{[\quad T \quad]} \underset{pq \times 1}{[\,P\,]}$$

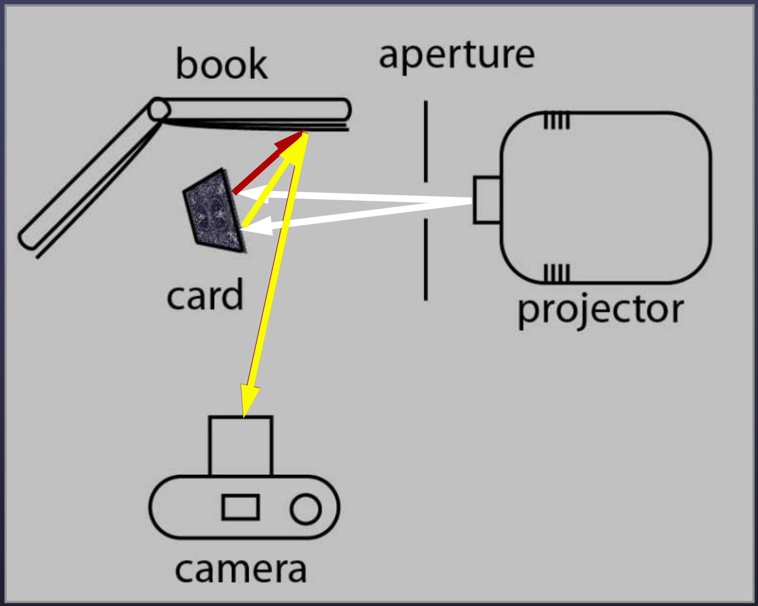
applying Helmholtz reciprocity...

$$\underset{pq \times 1}{[\,C'\,]} = \overset{pq \times mn}{[\quad T^T \quad]} \underset{mn \times 1}{[\,P'\,]}$$

Dual photography from diffuse reflections



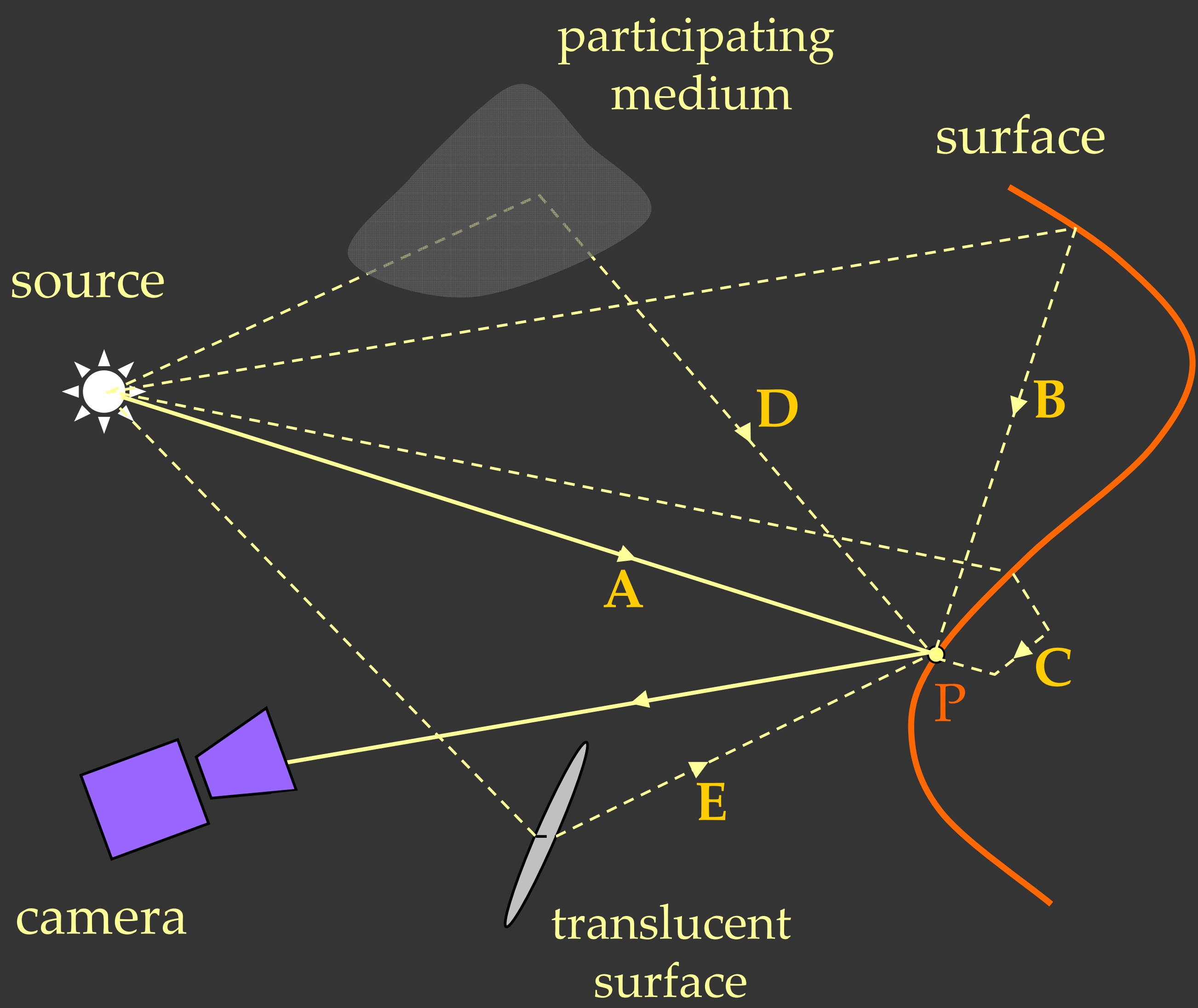
the camera's view

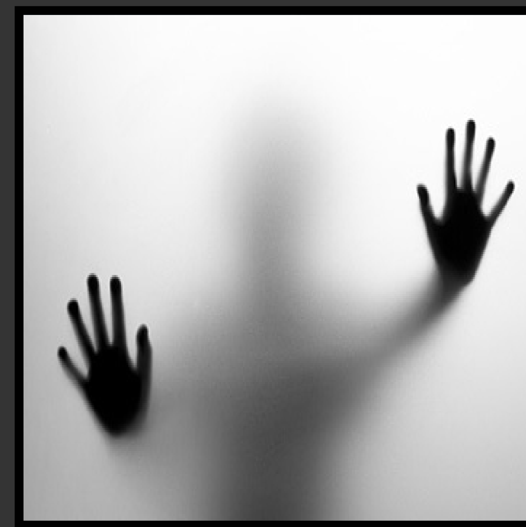


The advantage of dual photography

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

Direct and Global Illumination





A : Direct

B : Interrelection

C : Subsurface

D : Volumetric

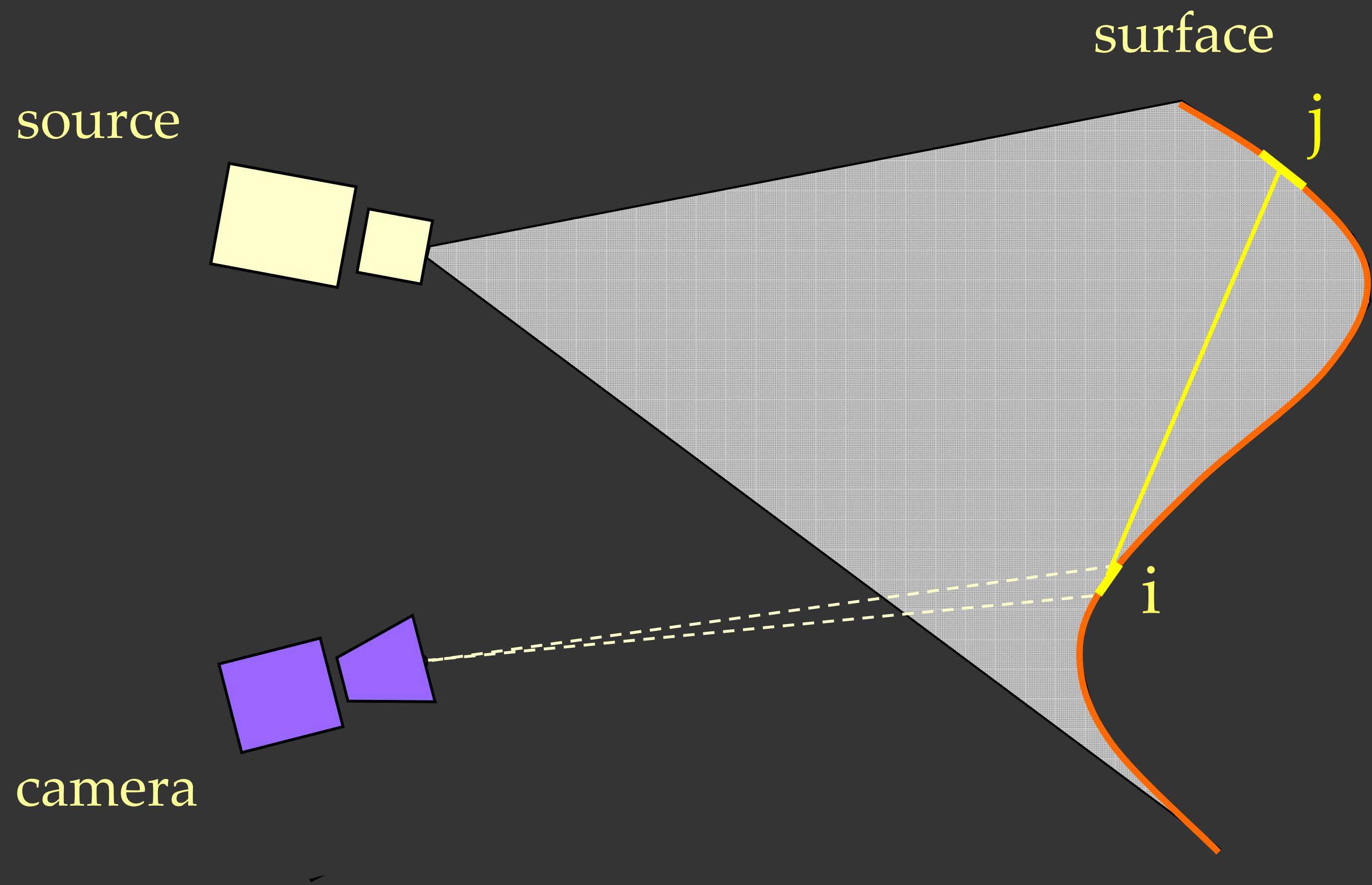
E : Diffusion

[Nayar et al, Siggraph 2006]

Fast Separation of Direct and Global Images

- Create Novel Images of the Scene
- Enhance Brightness Based Vision Methods
- New Insights into Material Properties

Direct and Global Components: Interreflections



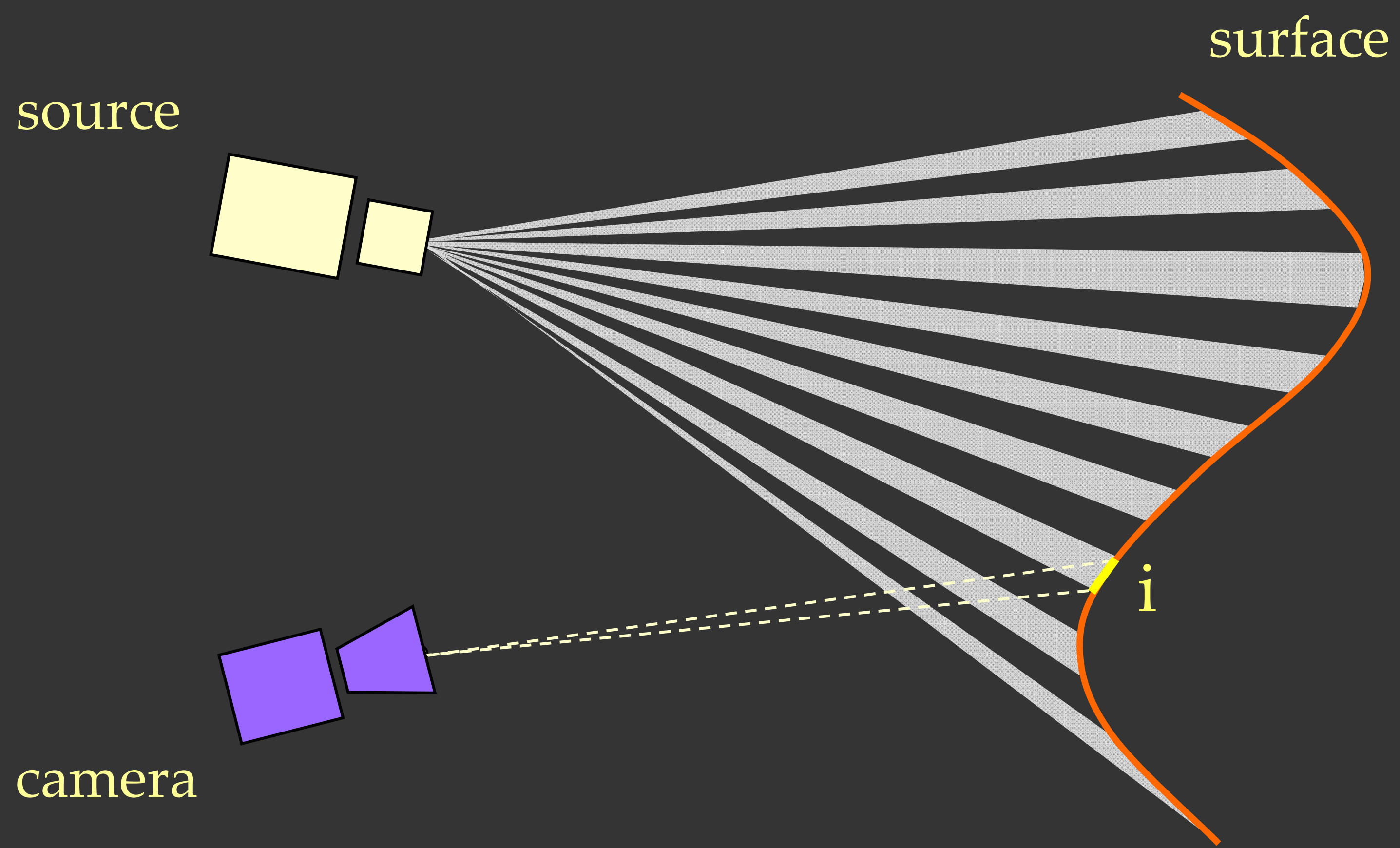
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct global

$$L_g[c,i] = \sum_P A[i,j]\, L[i,j]$$

BRDF and geometry

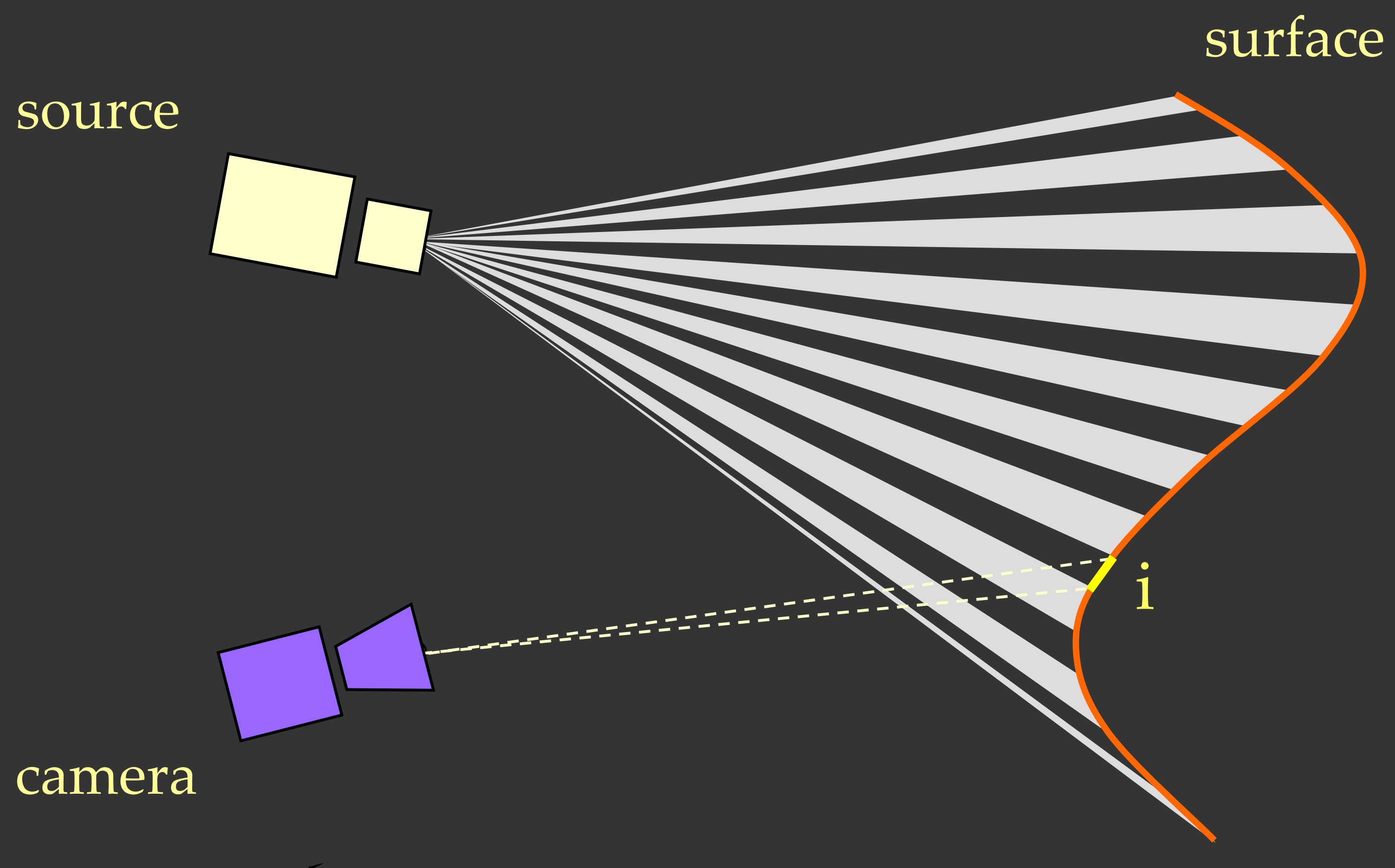
High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

fraction of activated source elements

High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

$$L^{-}[c,i] = (1-\alpha) L_g[c,i]$$

fraction of activated source elements

Separation from Two Images

$$\alpha = \frac{1}{2}: \quad L_d = L_{max} - L_{min}, \quad L_g = 2L_{min}$$

direct (L_d) global (L_g)

Diffuse Interreflections

Specular Interreflections

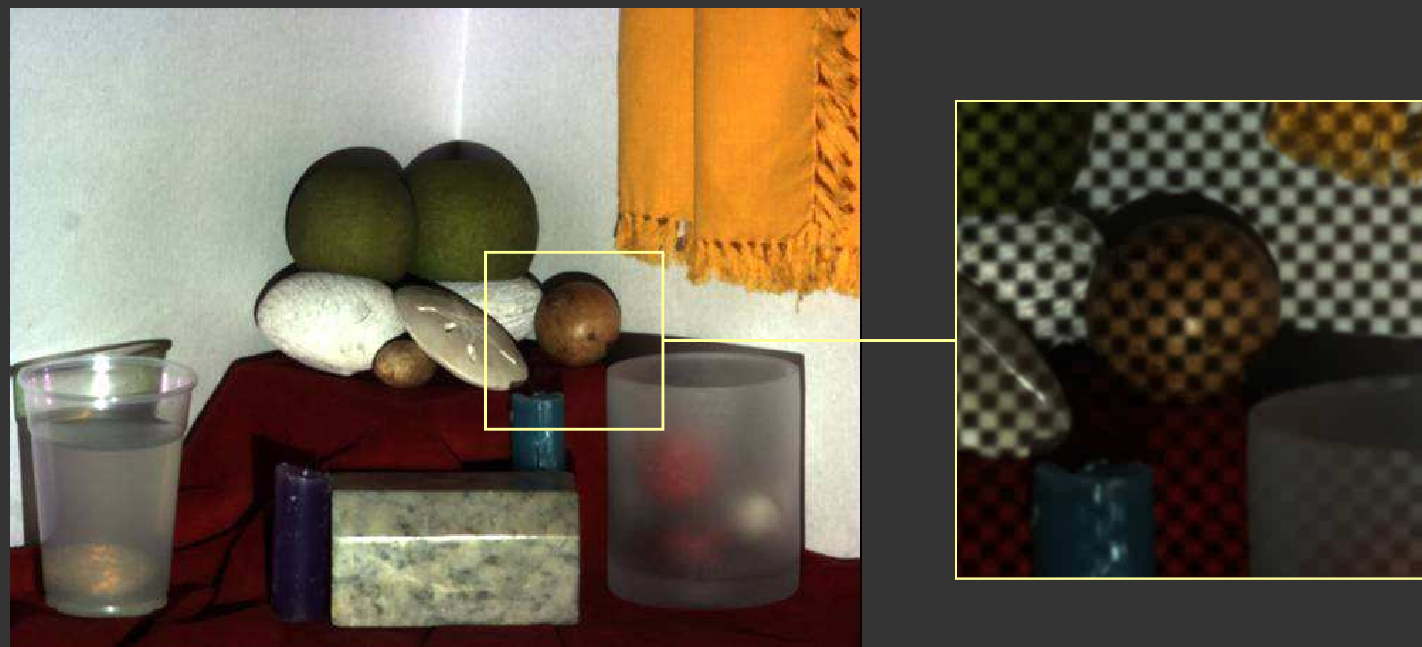
Diffusion

Volumetric Scattering

Subsurface Scattering

Scene

Scene



Direct

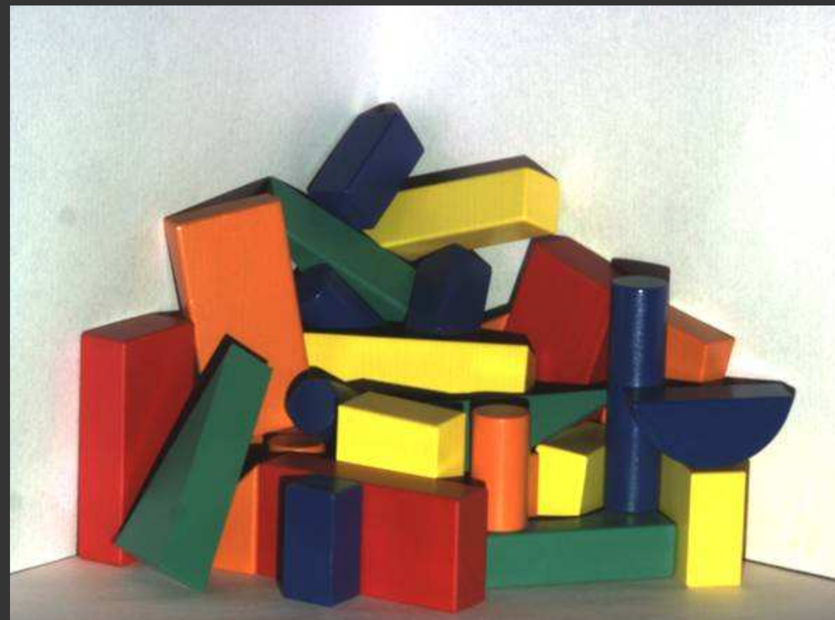
Global

Eggs: Diffuse Interreflections

Direct

Global

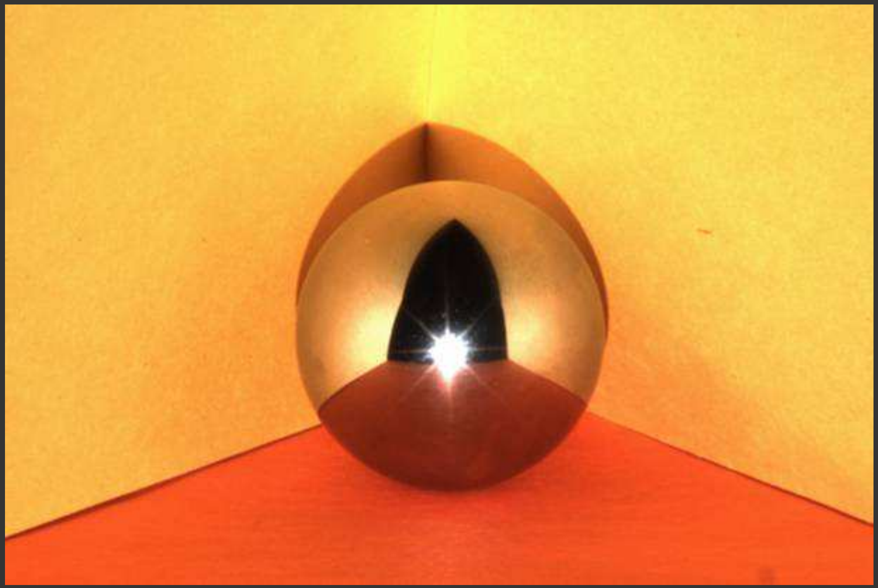
Wooden Blocks: Specular Interreflections

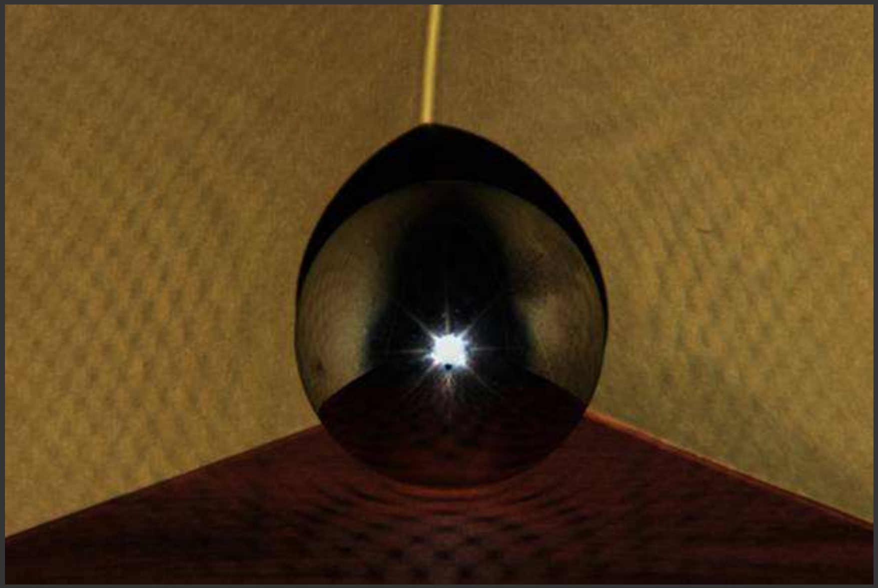


Direct

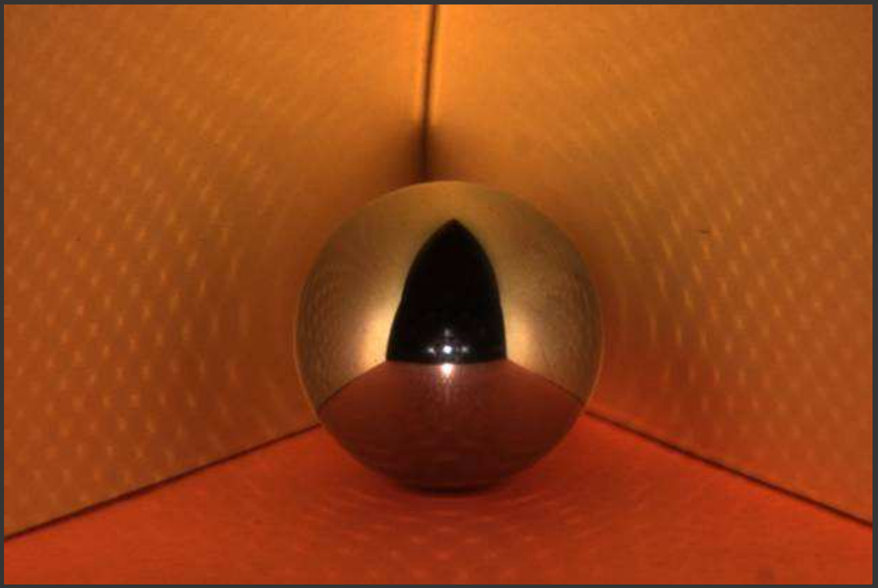
Global

Mirror Ball: Failure Case





Direct



Global

Kitchen Sink: Volumetric Scattering

Volumetric Scattering:
Chandrasekar 50, Ishimaru 78

Direct

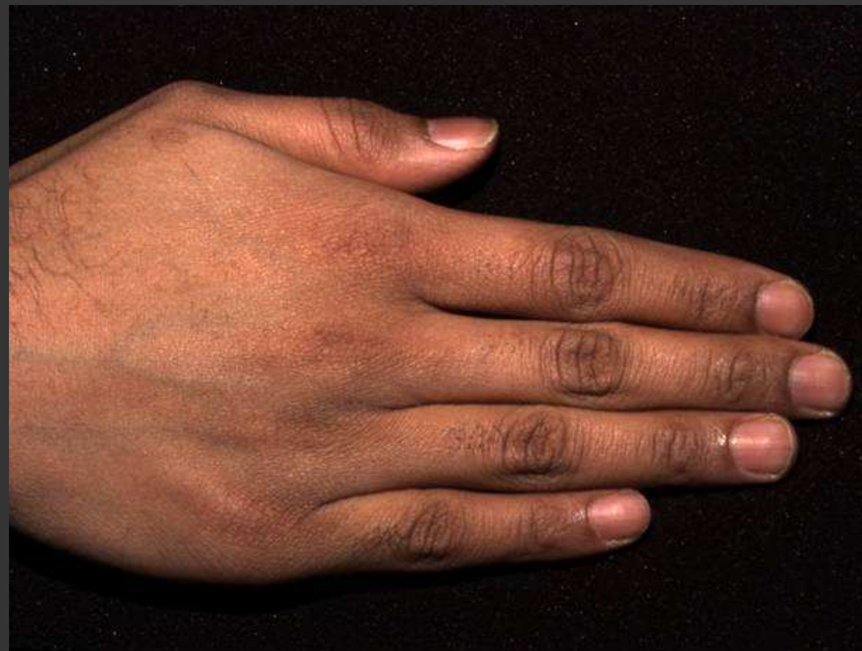
Global

Peppers: Subsurface Scattering

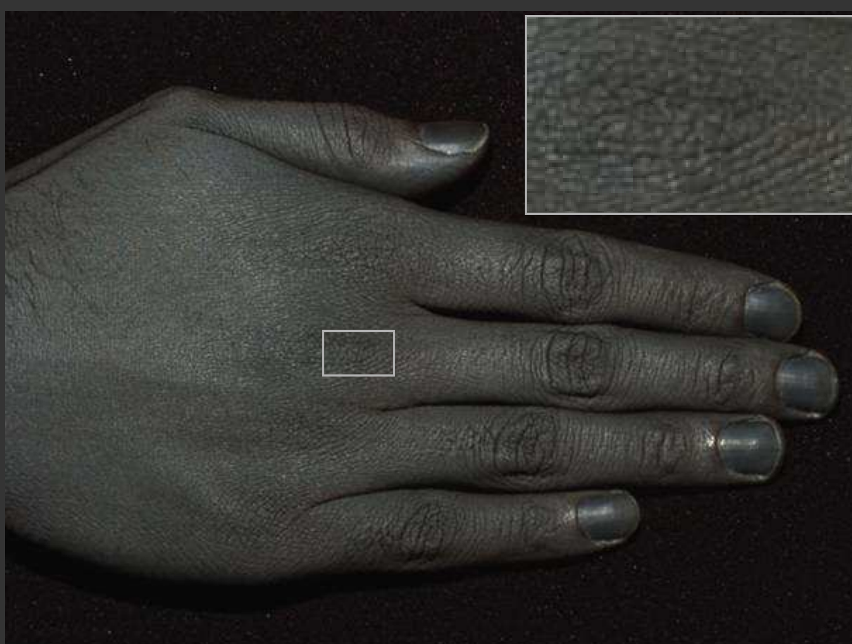
Direct

Global

Hand



Skin: Hanrahan and Krueger 93, Uchida 96, Haro 01, Jensen et al. 01, Cula and Dana 02, Igarashi et al. 05, Weyrich et al. 05



Direct

Global

Face: Without and With Makeup

Without Makeup

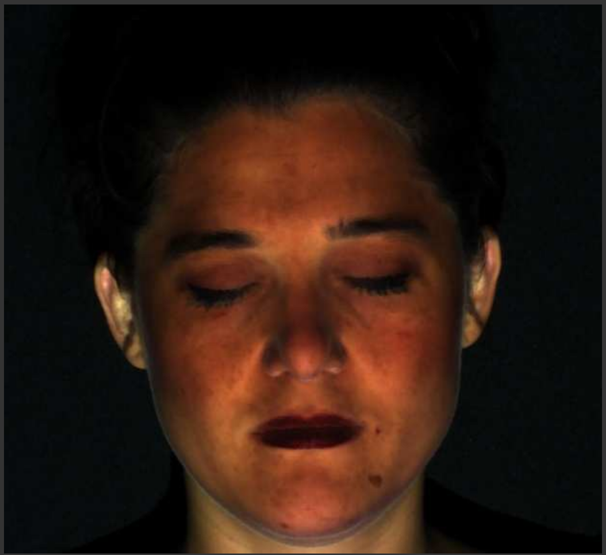
Direct

Global

With Makeup

Direct

Global



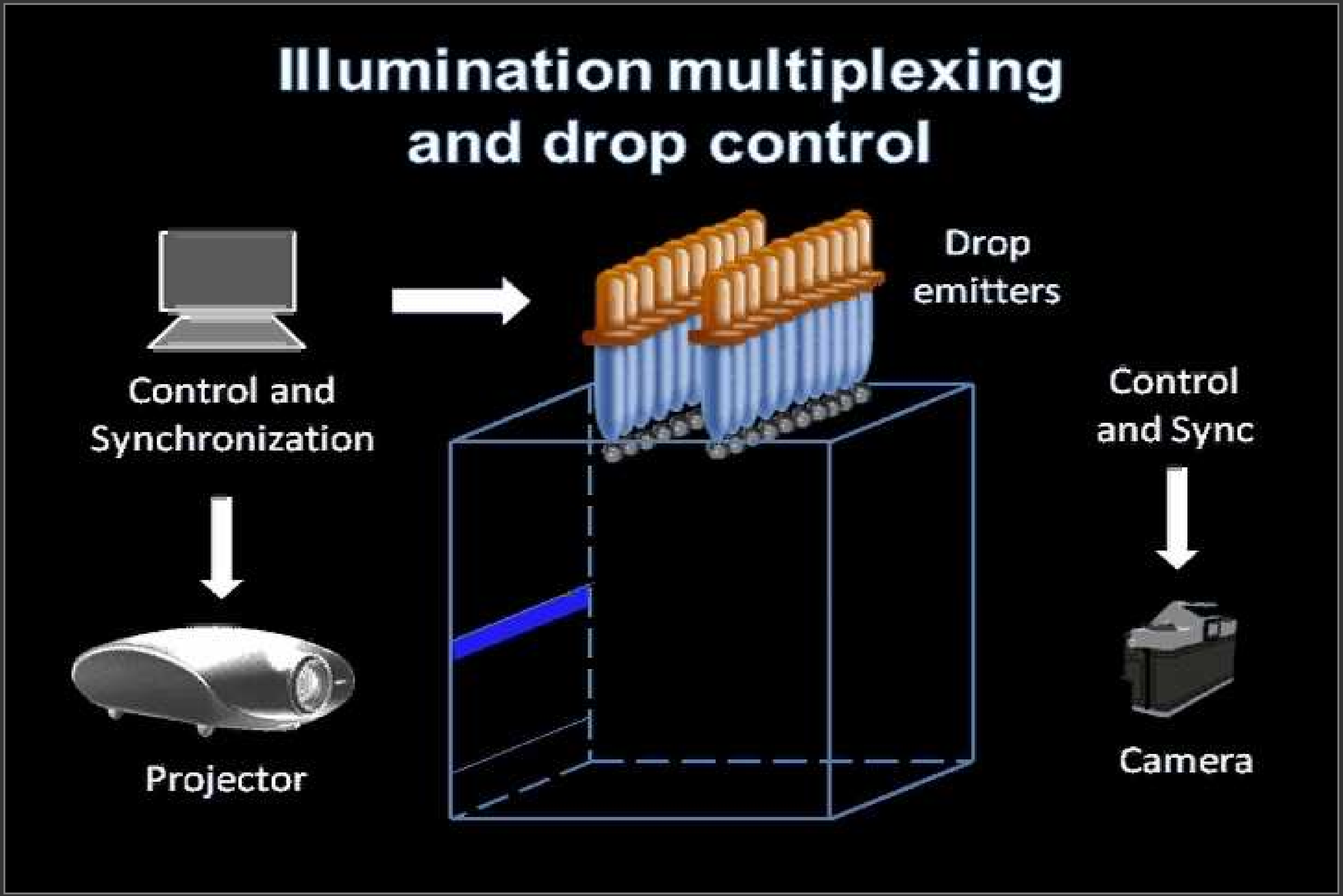
Blonde Hair

Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03

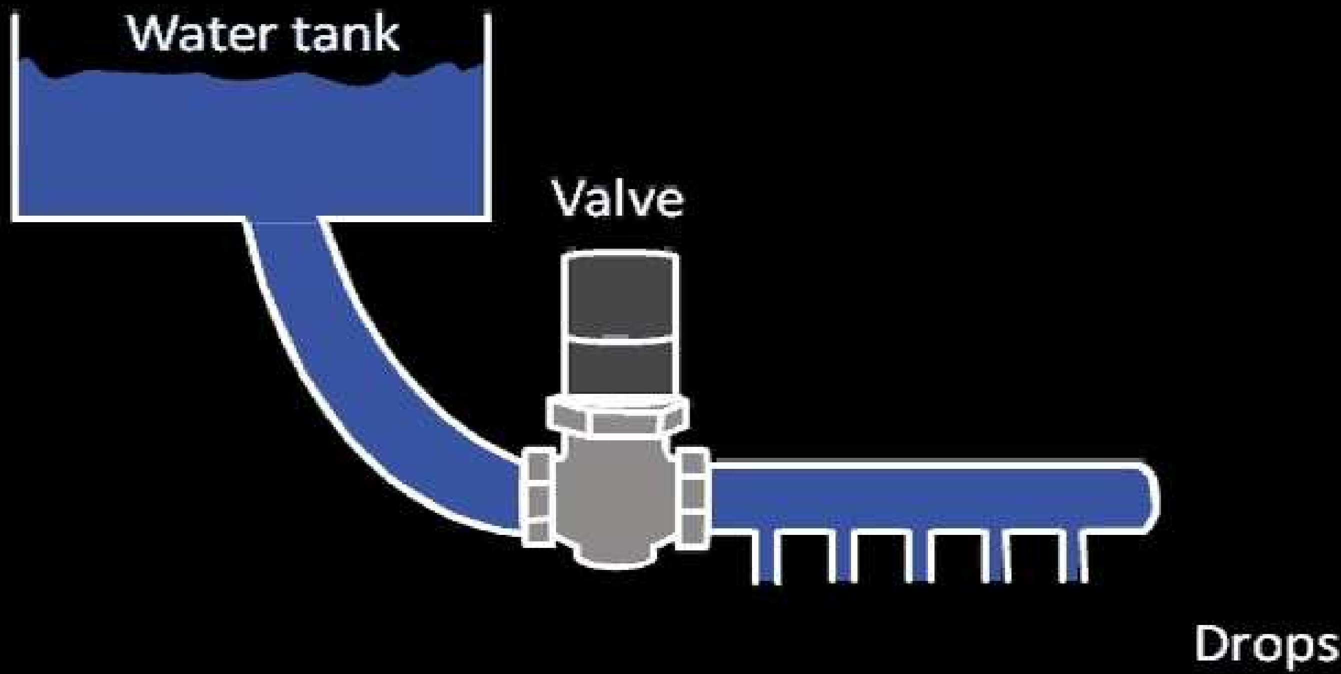
Direct

Global

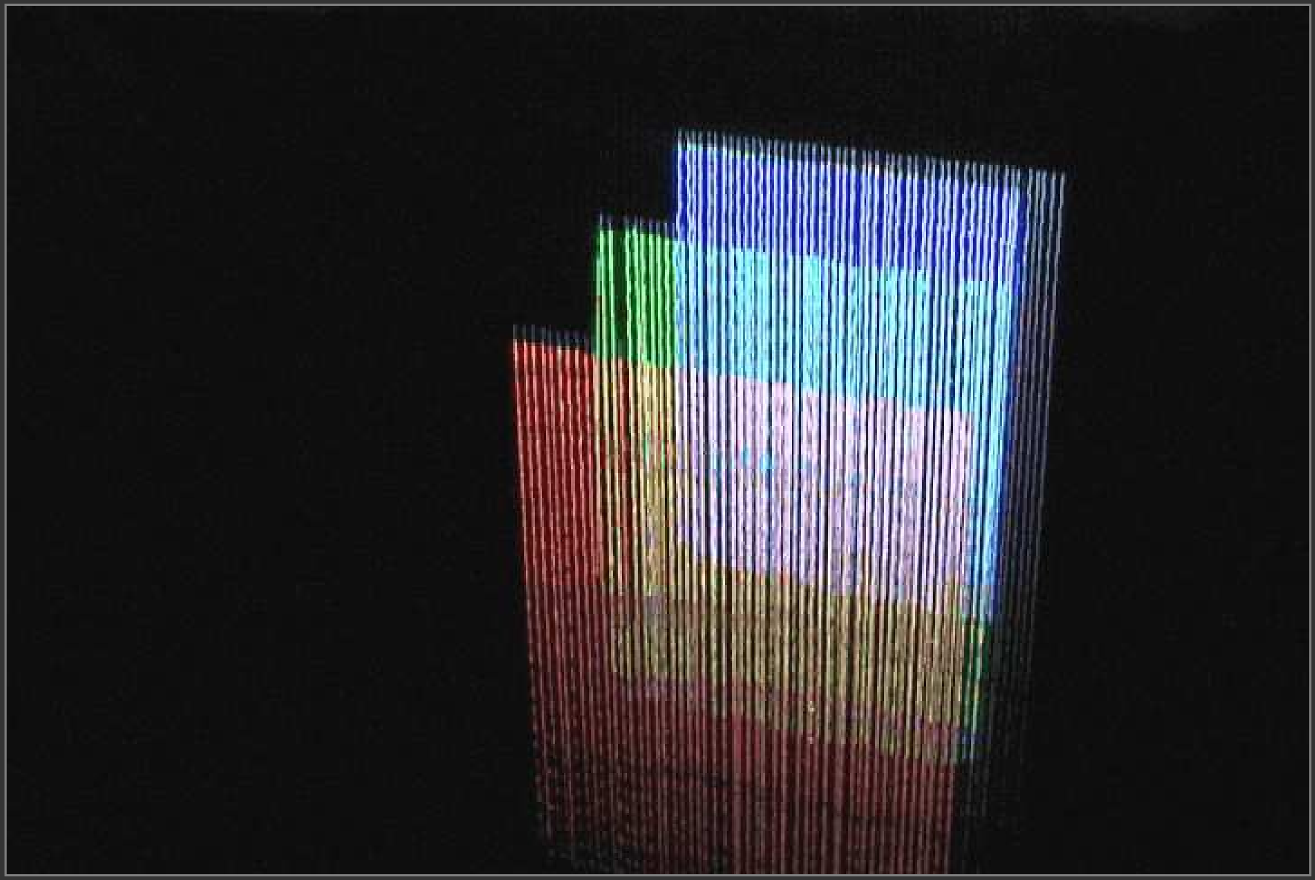
A Multi-layered Display with Water Drops



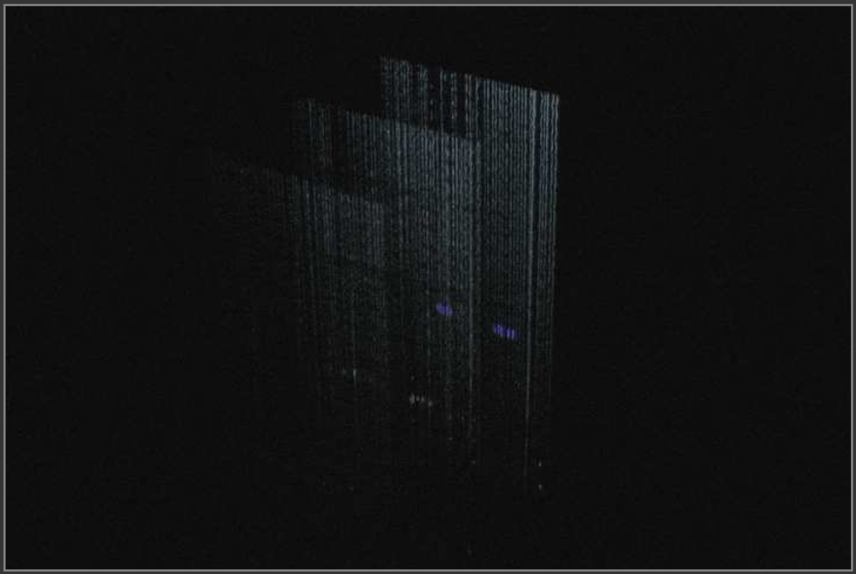
Drop on demand

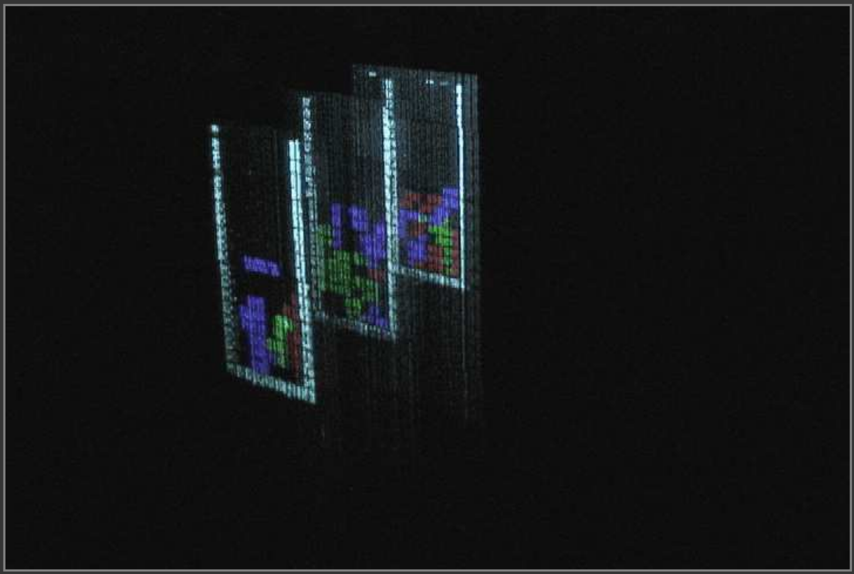


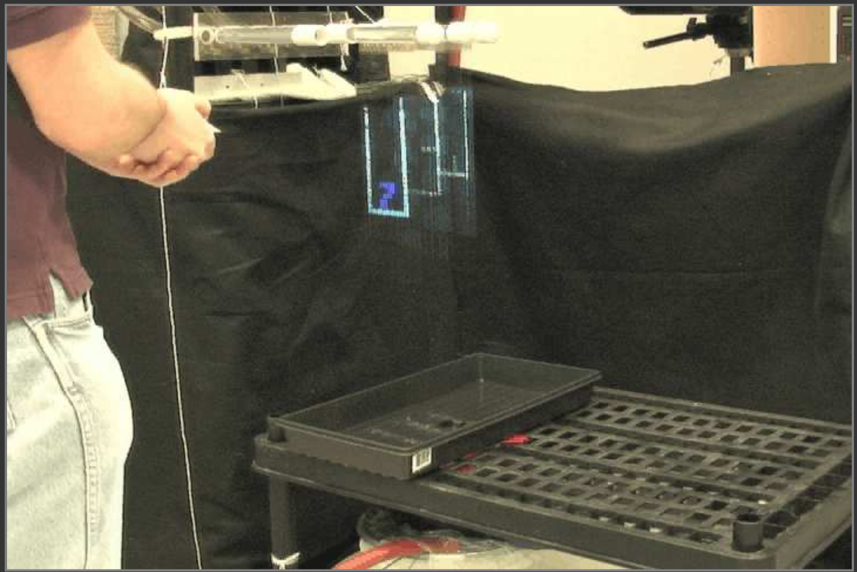
Three-layer Display in Action



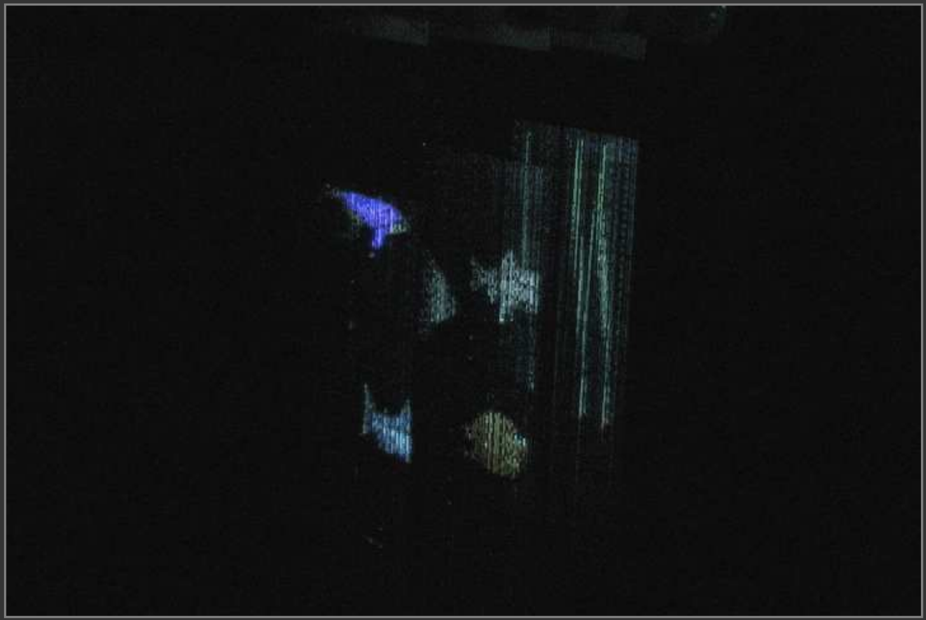
The Display in Action

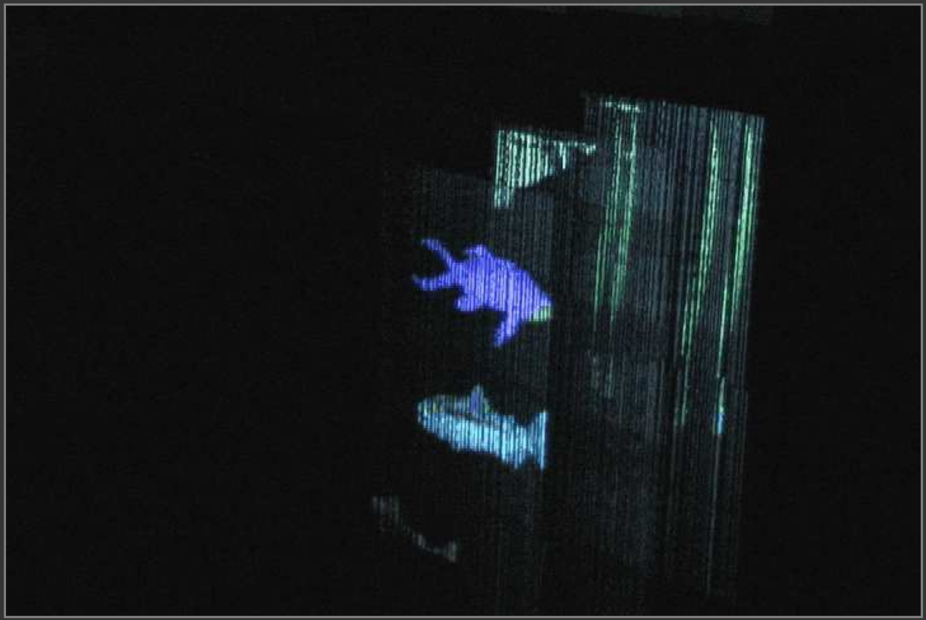






The Display in Action





Computational Illumination

- Light sources and cameras are optical duals.
- Greater variety of light sources than cameras but limited range.
- Many tasks easier when cameras are replaced by light sources.

PROCAMS Keynotes on Friday

- Some recent progress in hemispherical electronic eye cameras and related devices
  Prof. John Rogers, UIUC.

- The Future of Light and Lighting
  Dr. Kevin Dowling, MC 10 Inc.

- Projectors and Cameras for High Dynamic Range Imaging
  Prof. Wolfgang Heidrich, UBC.