Light field photography and videography

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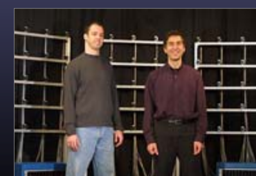
High performance imaging using large camera arrays

Bennett Wilburn, Neel Joshi, Vaibhav Vaish, Eino-Ville Talvala, Emilio Antunez, Adam Barth, Andrew Adams, Mark Horowitz, Marc Levoy



Stanford multi-camera array

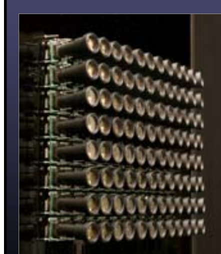
- 640 × 480 pixels × 30 fps × 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement

Ways to use large camera arrays

- widely spaced → light field capture
- tightly packed → high-performance imaging
- intermediate spacing → synthetic aperture photography

Tiled camera array

Can we match the image quality of a cinema camera?



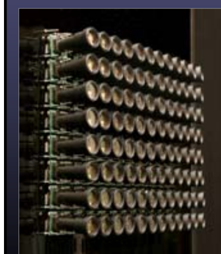
- world's largest video camera
- no parallax for distant objects
- poor lenses limit image quality
- seamless mosaicing isn't hard

Tiled panoramic image (before geometric or color calibration)

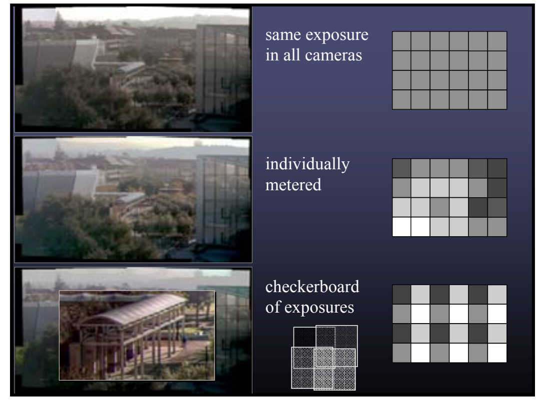
Tiled panoramic image (after calibration and blending)

Tiled camera array

Can we match the image quality of a cinema camera?



- world's largest video camera
- no parallax for distant objects
- poor lenses limit image quality
- seamless mosaicing isn't hard
- per-camera exposure metering
- HDR within and between tiles

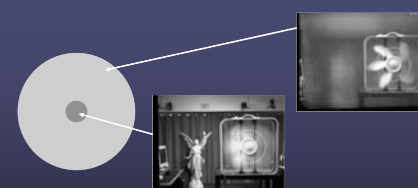


High-performance photography as multi-dimensional sampling

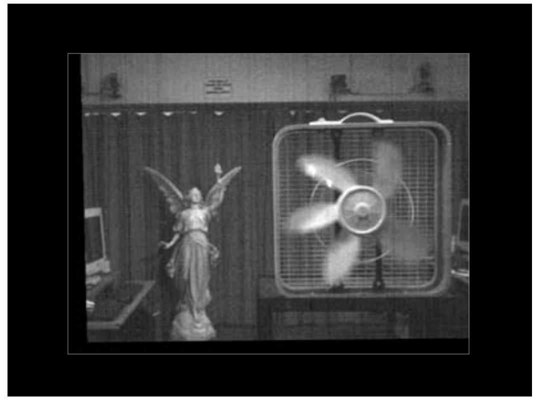
- spatial resolution
- field of view
- frame rate
- dynamic range
- bits of precision
- depth of field
- focus setting
- color sensitivity

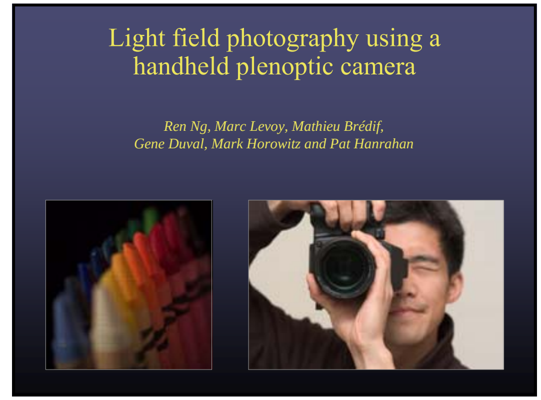
Spacetime aperture shaping

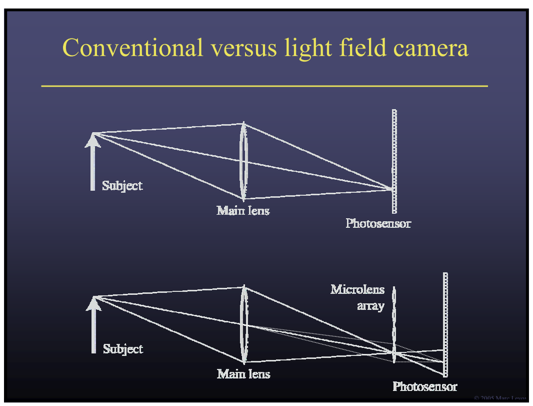
- shorten exposure time to freeze motion → dark
- stretch contrast to restore level → noisy
- increase (synthetic) aperture to capture more light → decreases depth of field

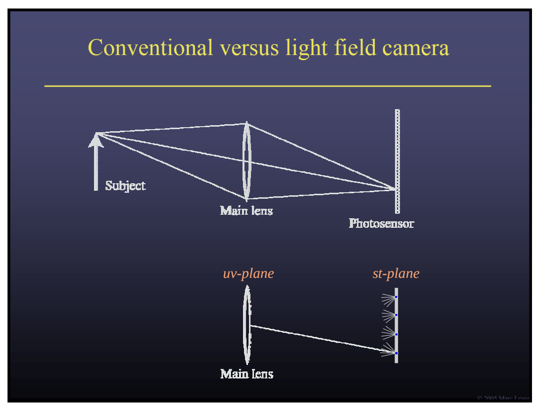


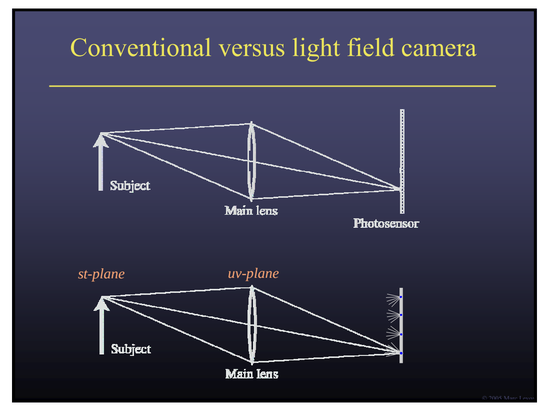
- center of aperture: few cameras, long exposure → high depth of field, low noise, but action is blurred
- periphery of aperture: many cameras, short exposure → freezes action, low noise, but low depth of field

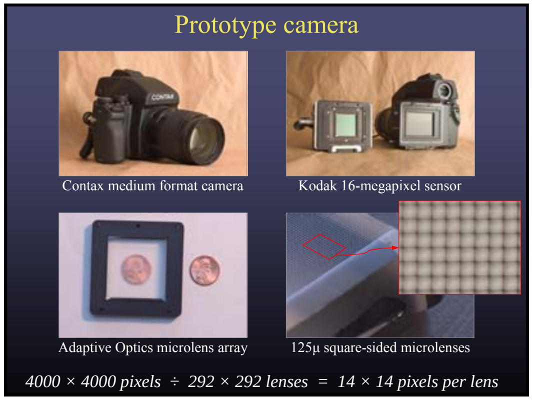


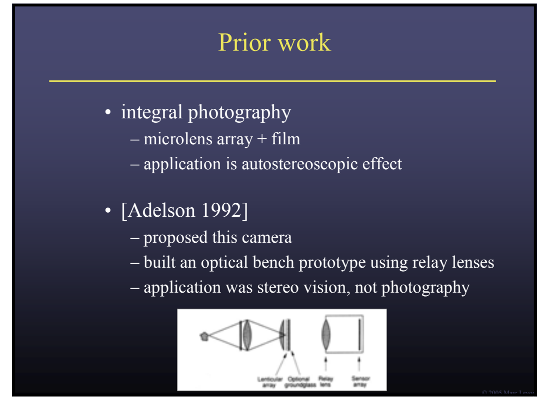

Light field photography using a handheld plenoptic camera
Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan

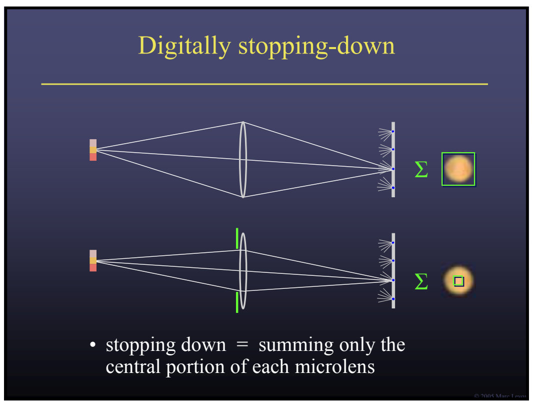

Conventional versus light field camera
Subject
Main lens
Photosensor
Microlens array
Subject
Main lens
Photosensor

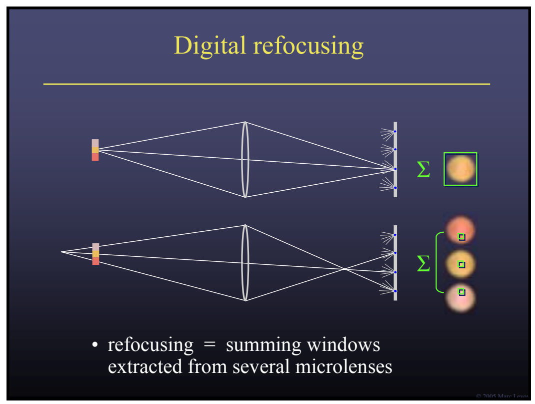

Conventional versus light field camera
Subject
Main lens
Photosensor
uv-plane
st-plane
Main lens

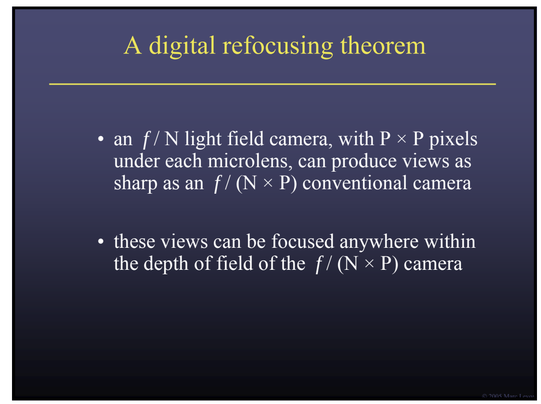

Conventional versus light field camera
Subject
Main lens
Photosensor
st-plane
uv-plane
Subject
Main lens

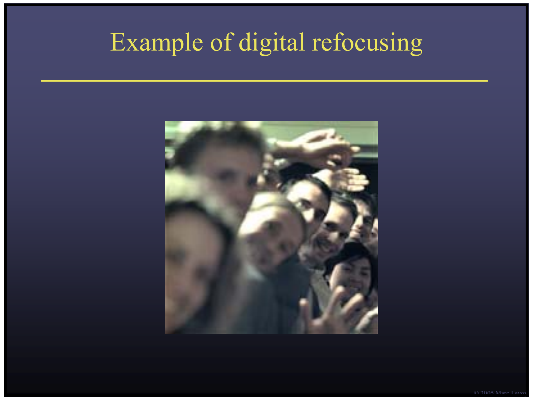

Prototype camera
Contax medium format camera
Kodak 16-megapixel sensor
Adaptive Optics microlens array
125μ square-sided microlenses
4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

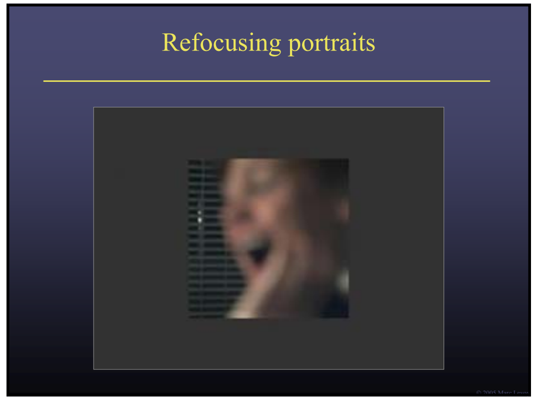

Prior work
• integral photography
– microlens array + film
– application is autostereoscopic effect
• [Adelson 1992]
– proposed this camera
– built an optical bench prototype using relay lenses
– application was stereo vision, not photography


Digitally stopping-down
Σ
Σ
• stopping down = summing only the central portion of each microlens

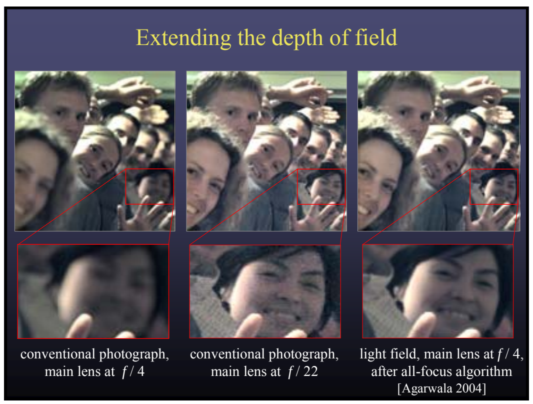

Digital refocusing
Σ
Σ
• refocusing = summing windows extracted from several microlenses

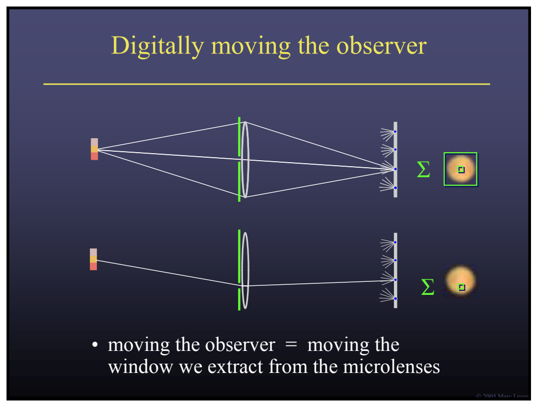

A digital refocusing theorem
• an f / N light field camera, with P × P pixels under each microlens, can produce views as sharp as an f / (N × P) conventional camera
• these views can be focused anywhere within the depth of field of the f / (N × P) camera

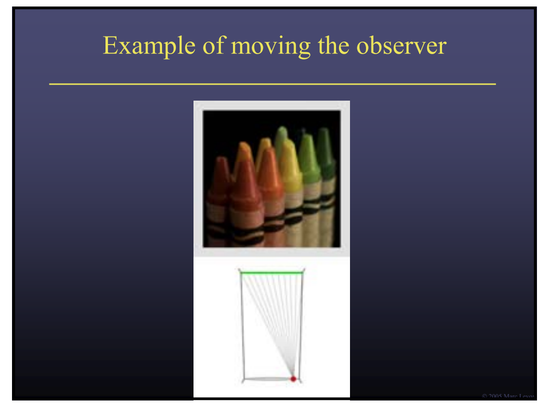

Example of digital refocusing


Refocusing portraits

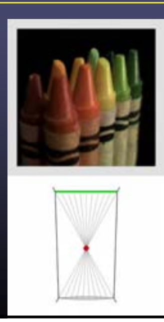

Action photography
Focusing through a splash of water


Extending the depth of field
conventional photograph, main lens at f / 4
conventional photograph, main lens at f / 22
light field, main lens at f / 4, after all-focus algorithm [Agarwala 2004]


Digitally moving the observer
Σ
Σ
• moving the observer = moving the window we extract from the microlenses


Example of moving the observer

Moving backward and forward



Implications

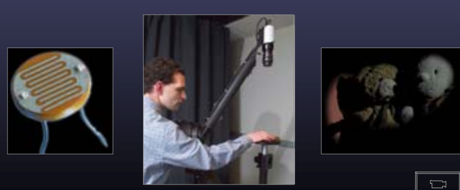
- cuts the unwanted link between exposure (due to the aperture) and depth of field
- trades off (excess) spatial resolution for ability to refocus and adjust the perspective
- sensor pixels should be made even smaller, subject to the diffraction limit
  - 36mm × 24mm ÷ 2.5μ pixels = 266 megapixels
  - 20K × 13K pixels
  - 4000 × 2666 pixels × 20 × 20 rays per pixel

Can we build a light field microscope?

- ability to photograph moving specimens
- digital refocusing → focal stack → deconvolution microscopy → volume data

Dual Photography

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

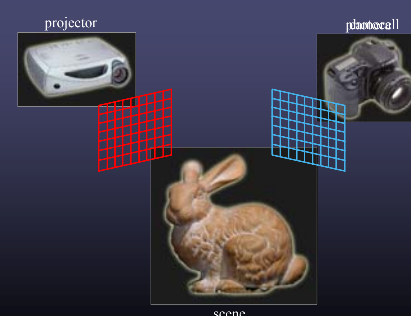


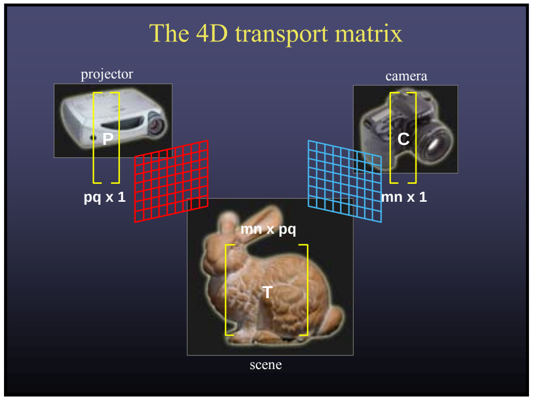
Related imaging methods

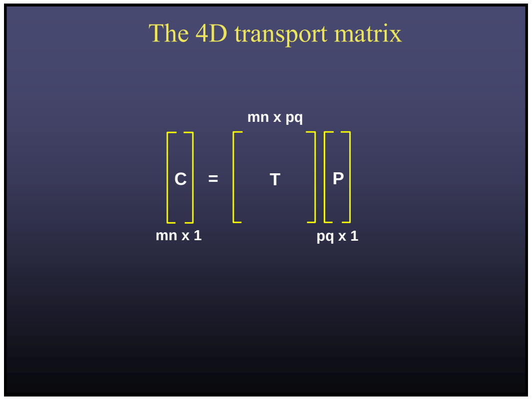
- time-of-flight scanner
  - if they return reflectance as well as range
  - but their light source and sensor are typically coaxial
- scanning electron microscope

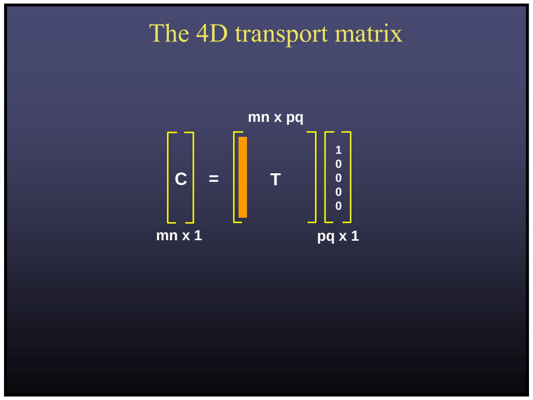
Velcro® at 35x magnification, Museum of Science, Boston

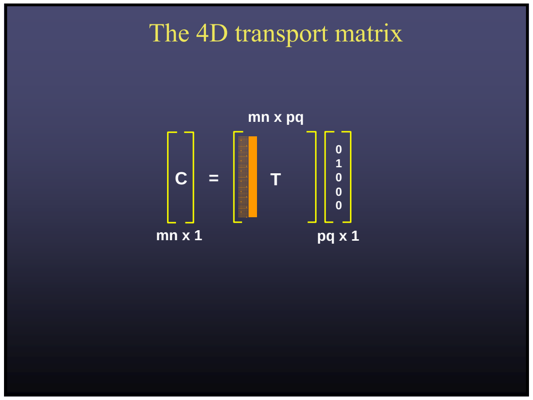
The 4D transport matrix

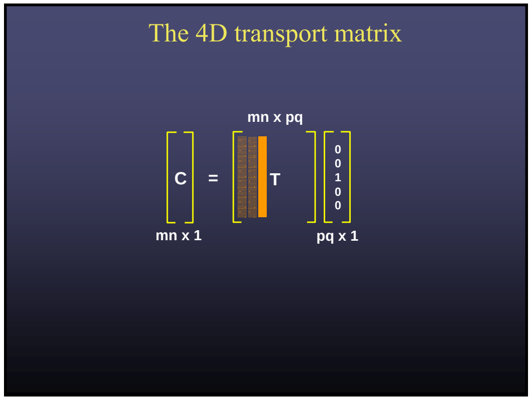


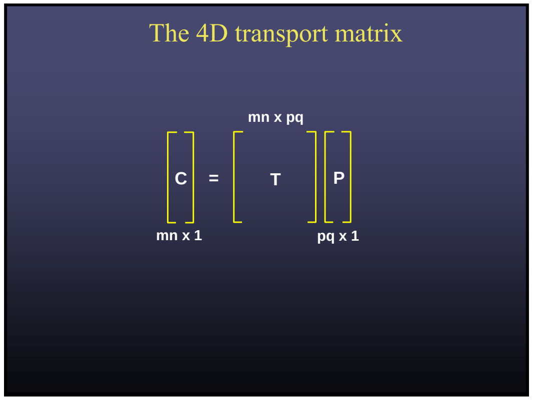

The 4D transport matrix
projector
camera
P
C
pq x 1
mn x 1
mn x pq
T
scene

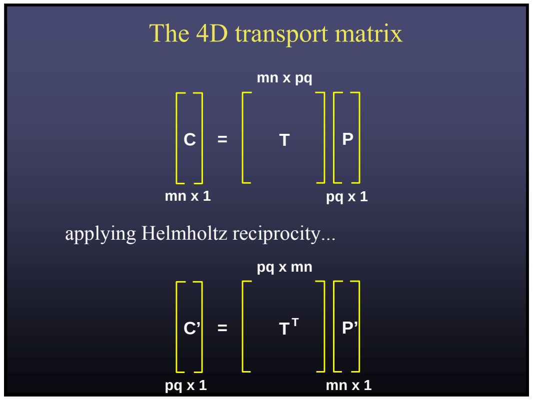

The 4D transport matrix
mn x pq
C
=
T
P
mn x 1
pq x 1

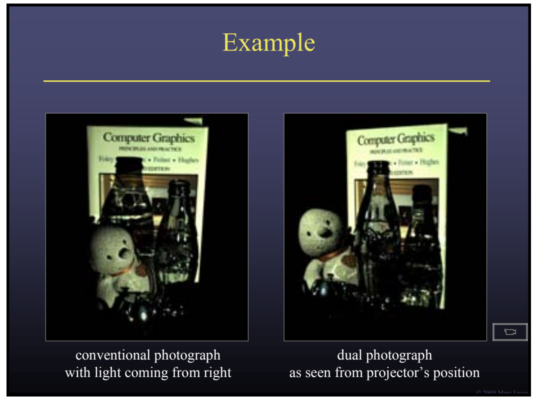

The 4D transport matrix
mn x pq
C
=
T
1
0
0
0
0
mn x 1
pq x 1

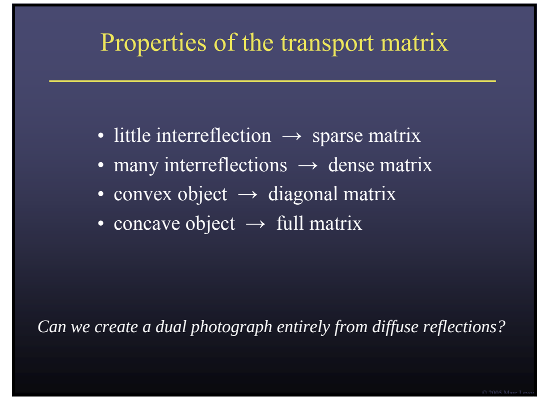

The 4D transport matrix
mn x pq
C
=
T
0
1
0
0
0
mn x 1
pq x 1

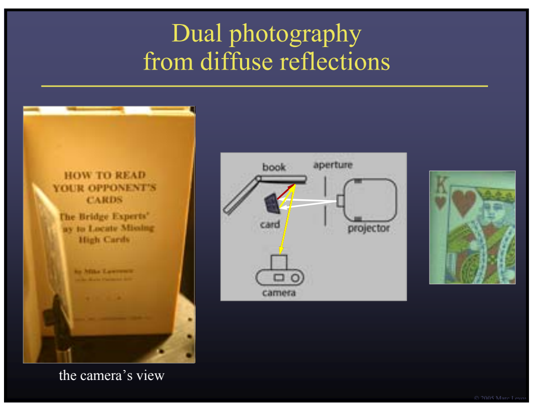

The 4D transport matrix
mn x pq
C
=
T
0
0
1
0
0
mn x 1
pq x 1

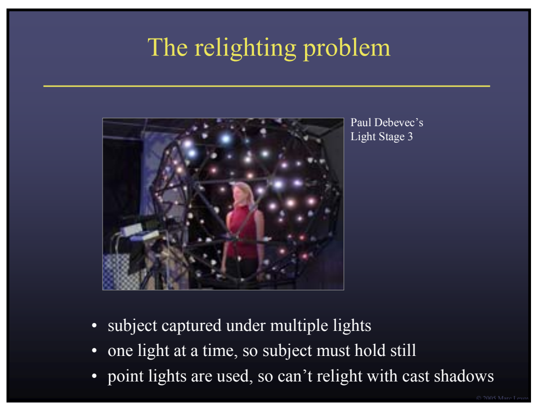

The 4D transport matrix
mn x pq
C
=
T
P
mn x 1
pq x 1

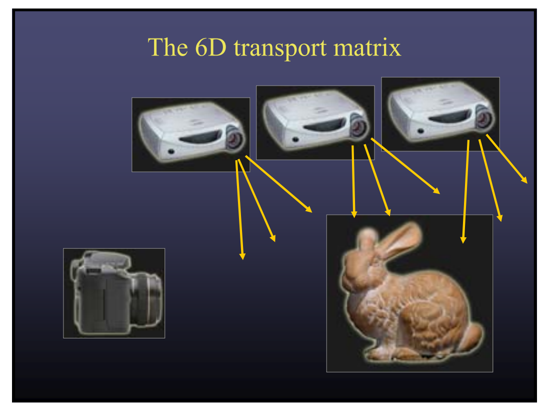

The 4D transport matrix
mn x pq
C = T P
mn x 1
pq x 1
applying Helmholtz reciprocity...
pq x mn
C' = T^T P'
pq x 1
mn x 1

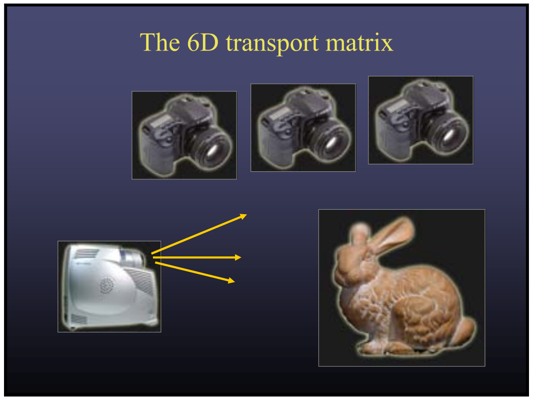

Example
conventional photograph
with light coming from right
dual photograph
as seen from projector's position


Properties of the transport matrix
• little interreflection → sparse matrix
• many interreflections → 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
book
aperture
card
projector
camera
the camera's view

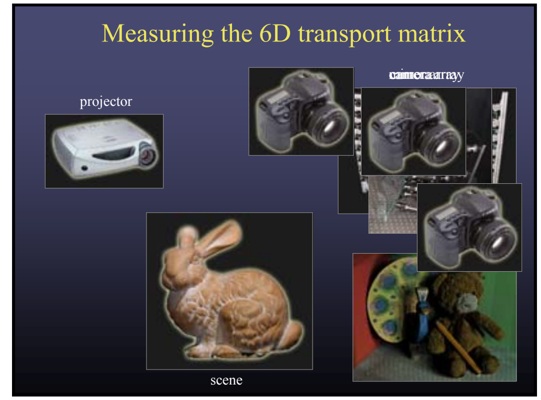

The relighting problem
Paul Debevec's
Light Stage 3
• subject captured under multiple lights
• one light at a time, so subject must hold still
• point lights are used, so can't relight with cast shadows

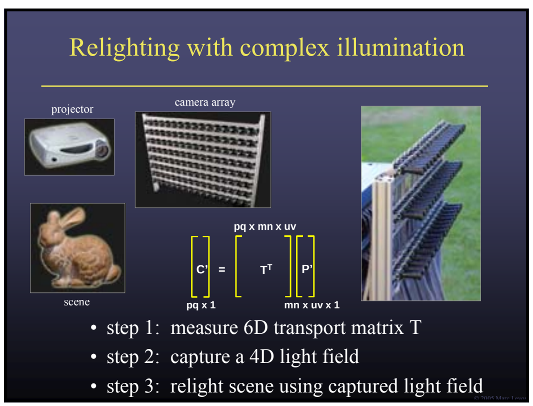

The 6D transport matrix



The advantage of dual photography

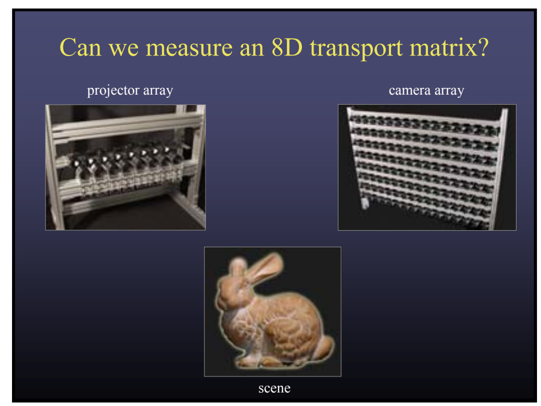
- capture of a scene as illuminated by different lights cannot be parallelized
- capture of a scene as viewed by different cameras can be parallelized

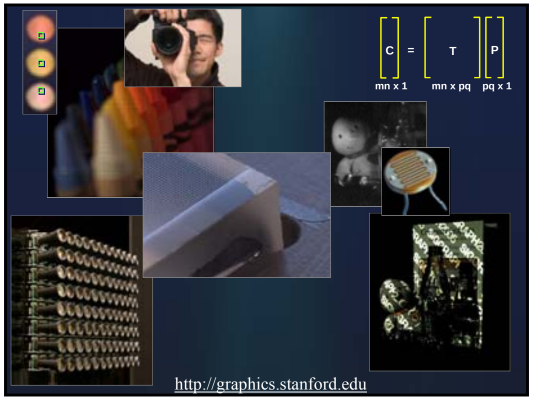




Running time

- 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




C = T P
mn x 1
mn x pq
pq x 1
http://graphics.stanford.edu