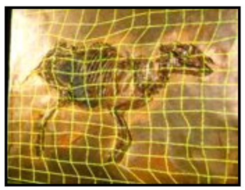
Multi-Projector Techniques for Real-Time Visualizations in

Outline

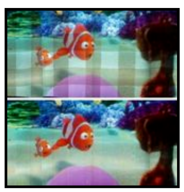
Outline

these slides:
www.uni-weimar.de/medien/AR

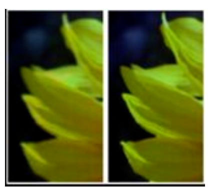
Introduction
Motivations and Applications



Geometric Correction
Planar, Non-Trivial, Complex Surfaces



Radiometric Compensation
Local and Global Light Effects



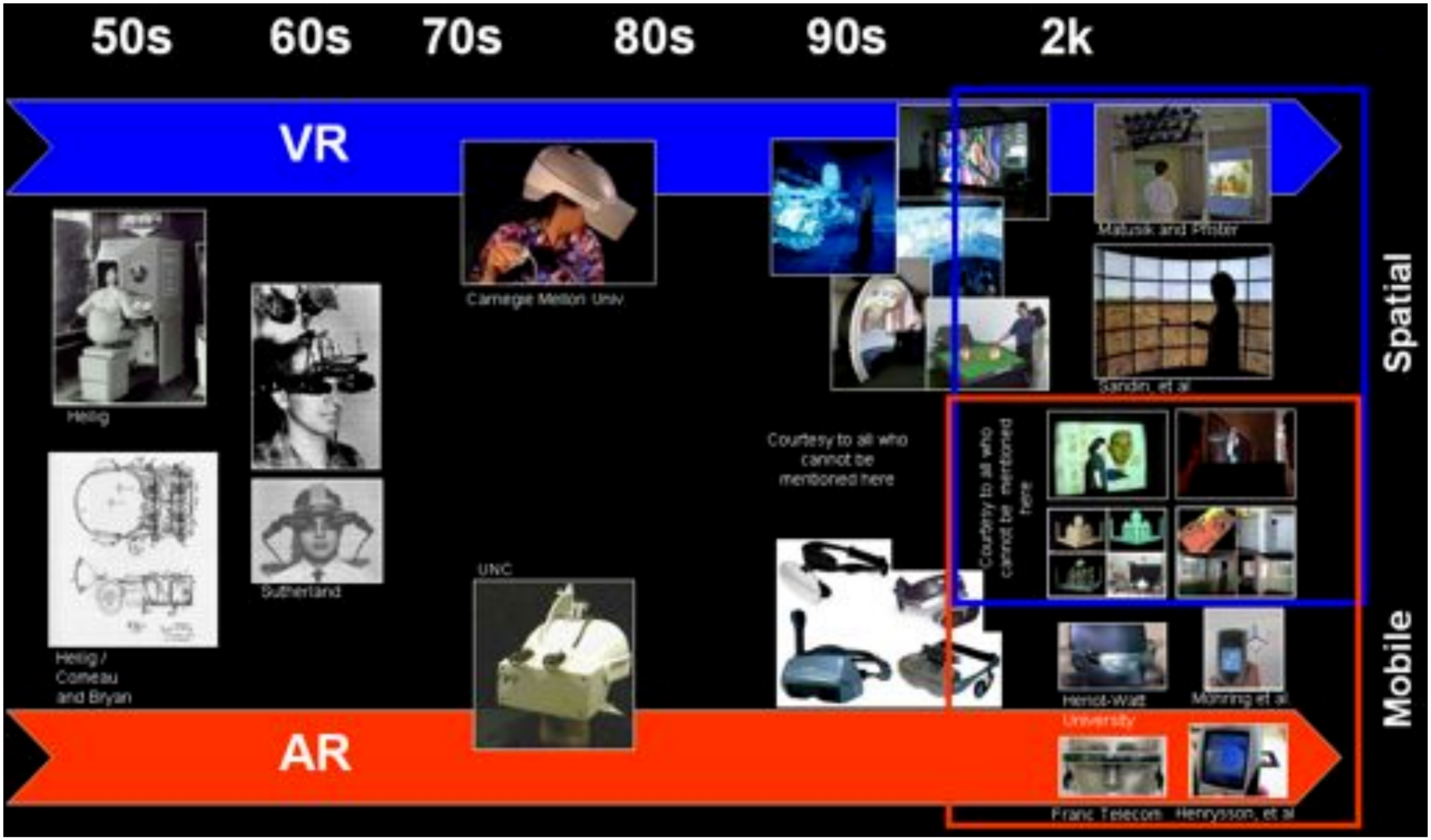
Advanced Techniques
View-Dependence, Multi-Focal Projection, Light Transport

Outlook
Limitations and Future Work

Introduction

Evolving Evolution

Evolving Evolution



Motivation: Projection

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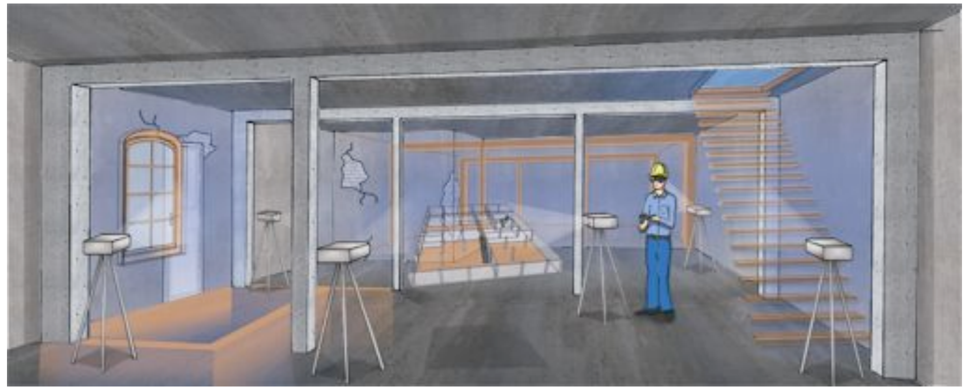

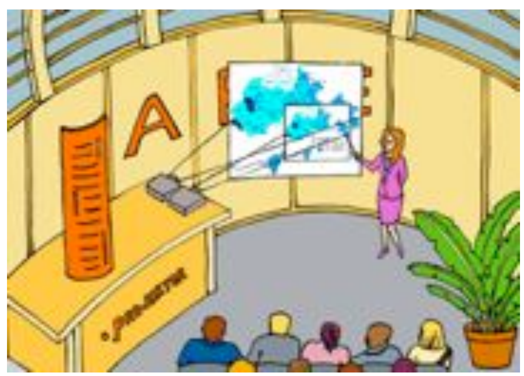

Application: Historic Sites and Museums

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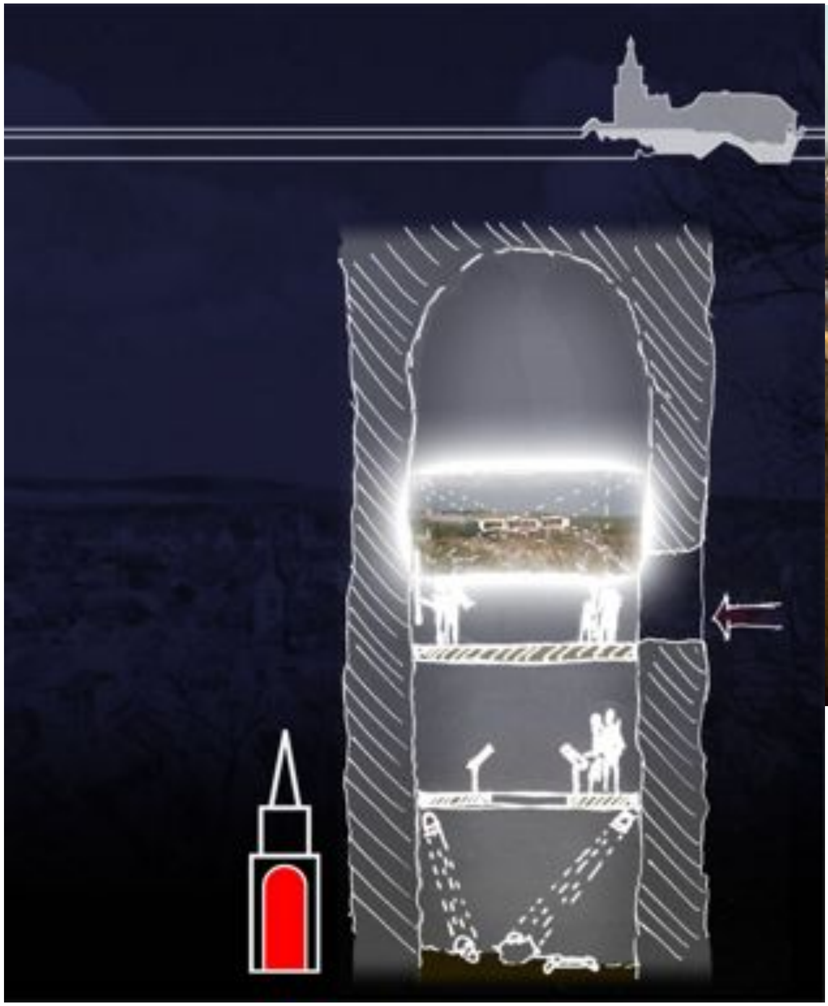

360° Surround Projection in Castel Tower (Running project in coop. with Bennert Group)

Application: Architectural Visualization

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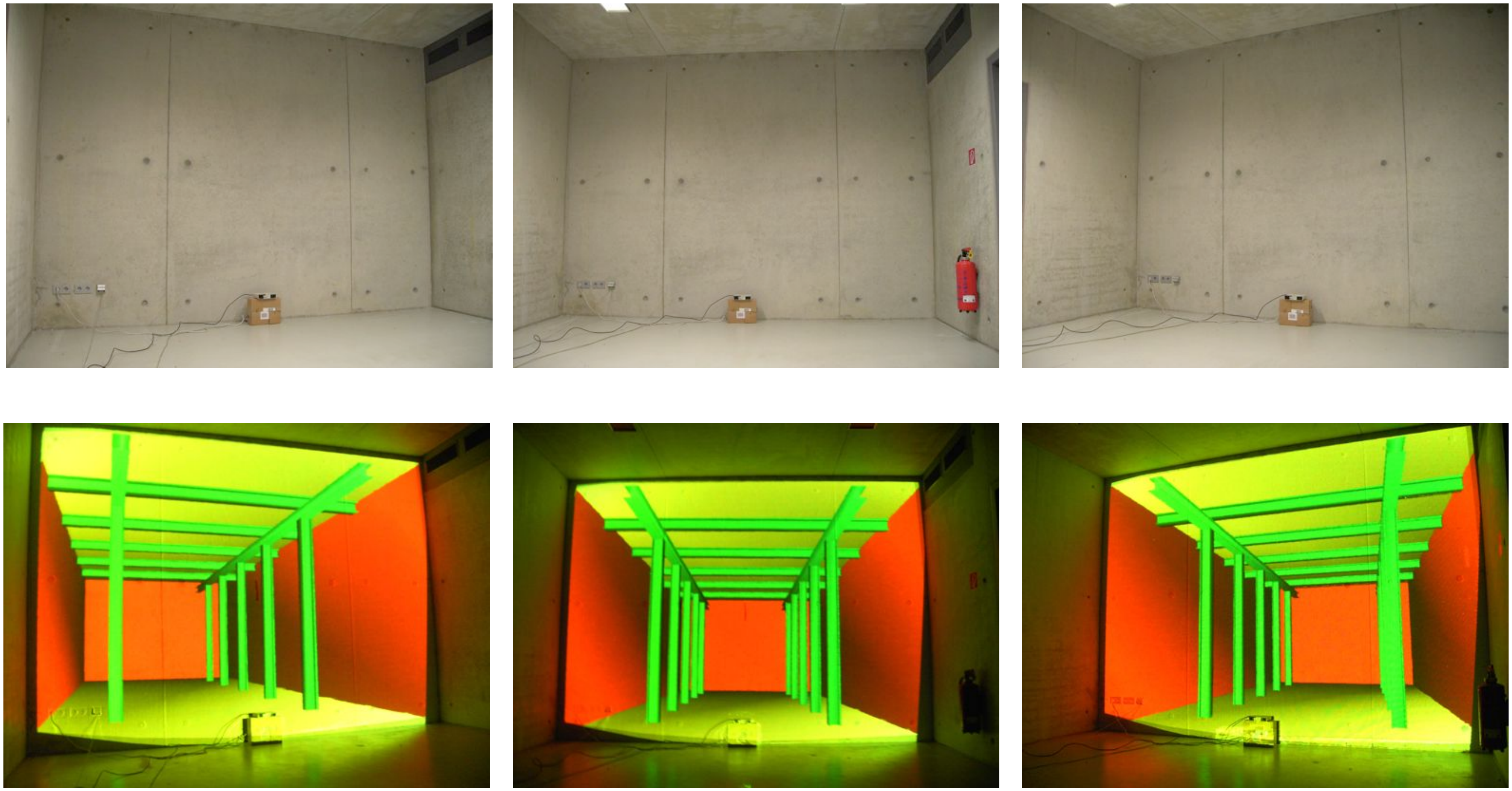


Bimber et al, IEEE/ACM
ISMAR 2005

On-Site Architectural Visualizations
(Running project in coop. with Architecture Faculty, BUW)

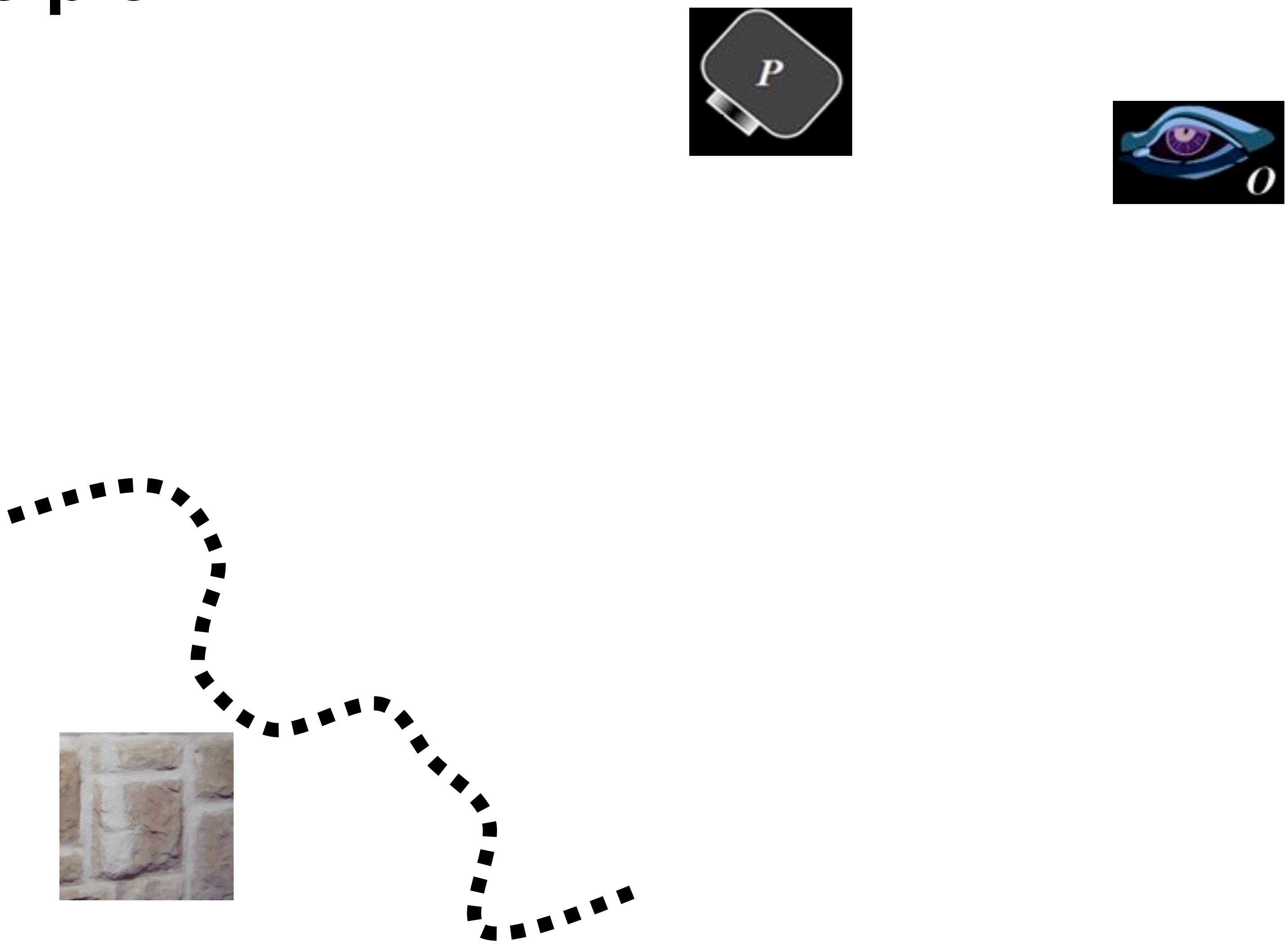
Application: Pocket Projectors

Application: Pocket Projectors

Courtesy: InFocus

Courtesy: Siemens

Principle



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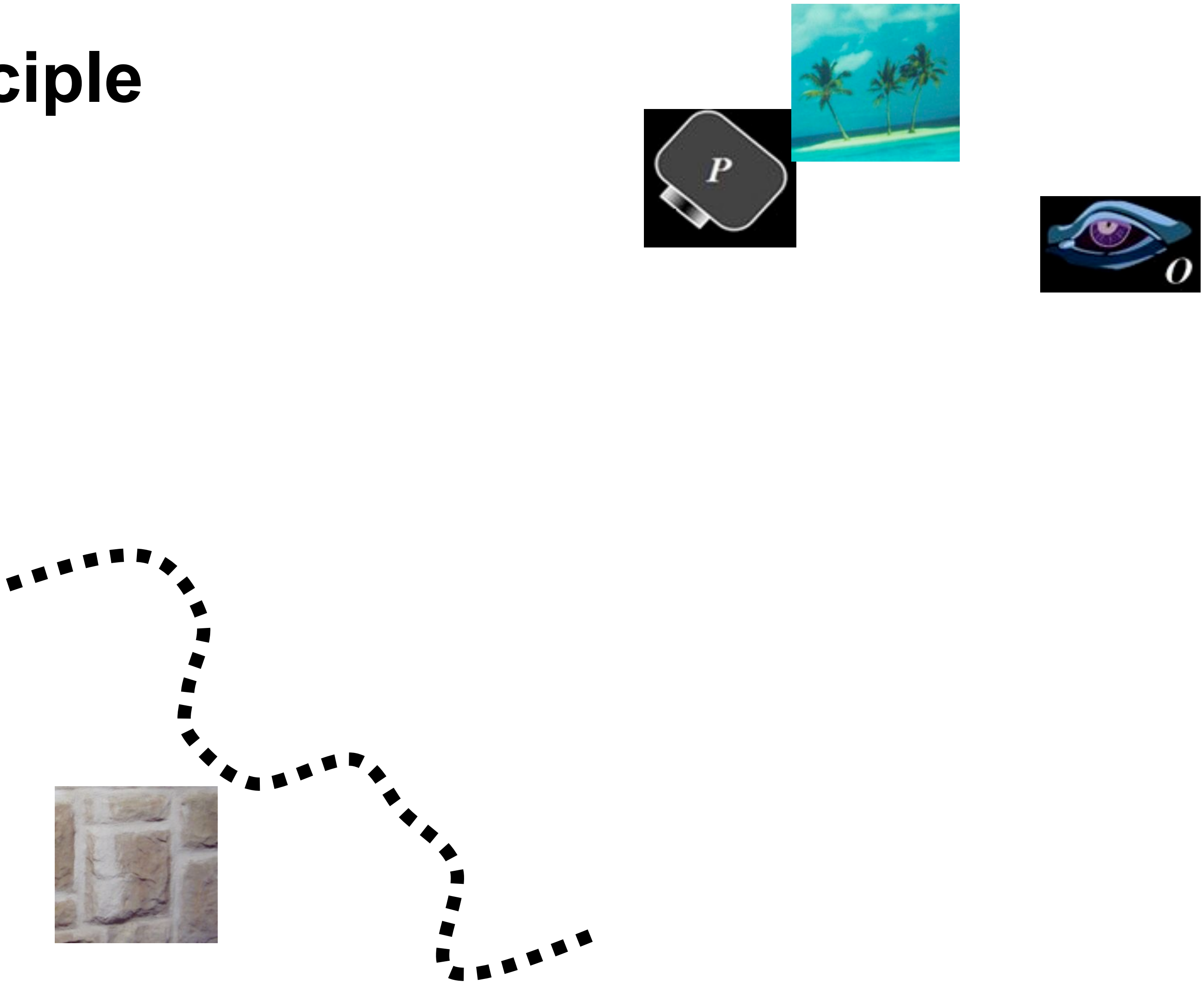

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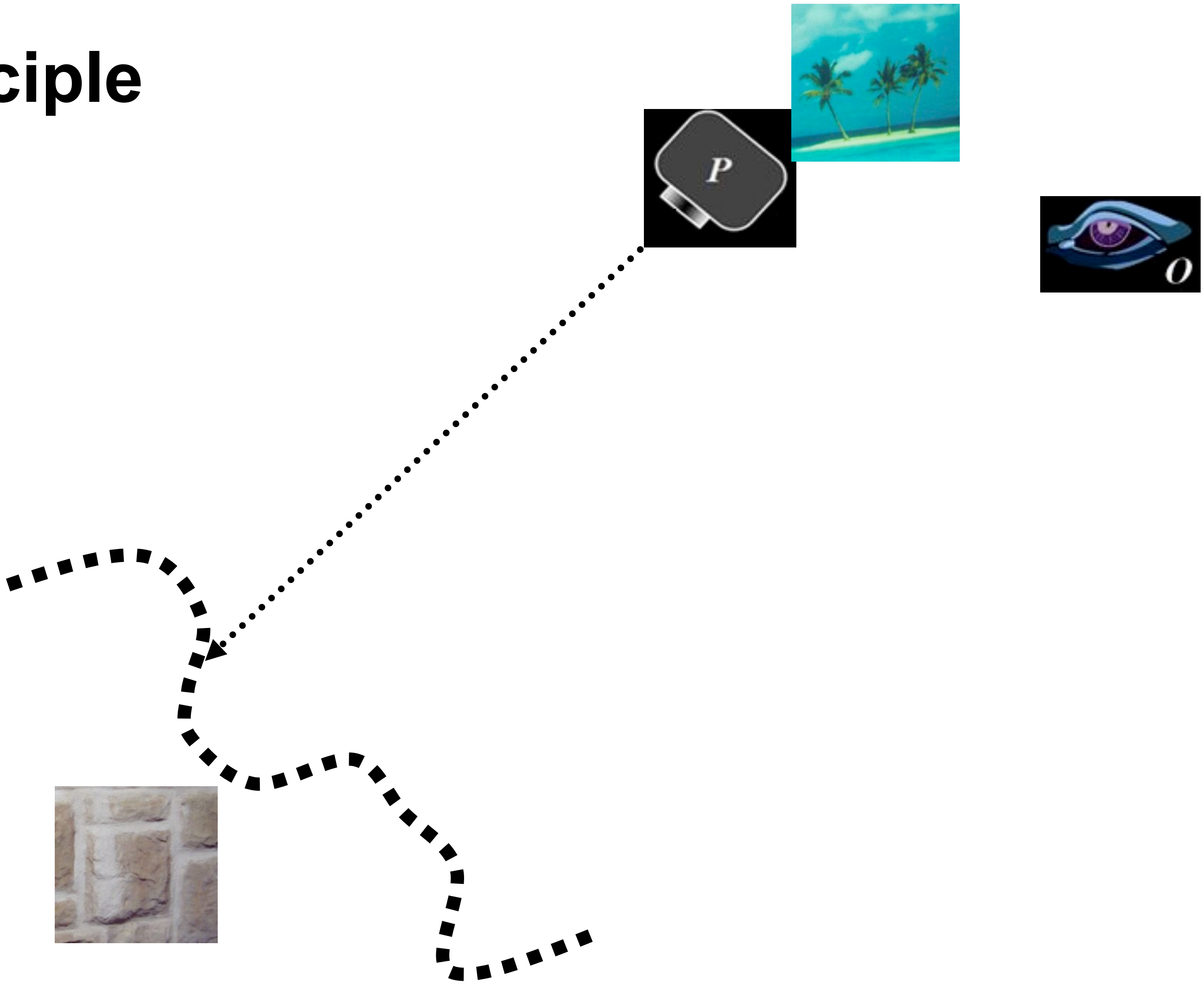

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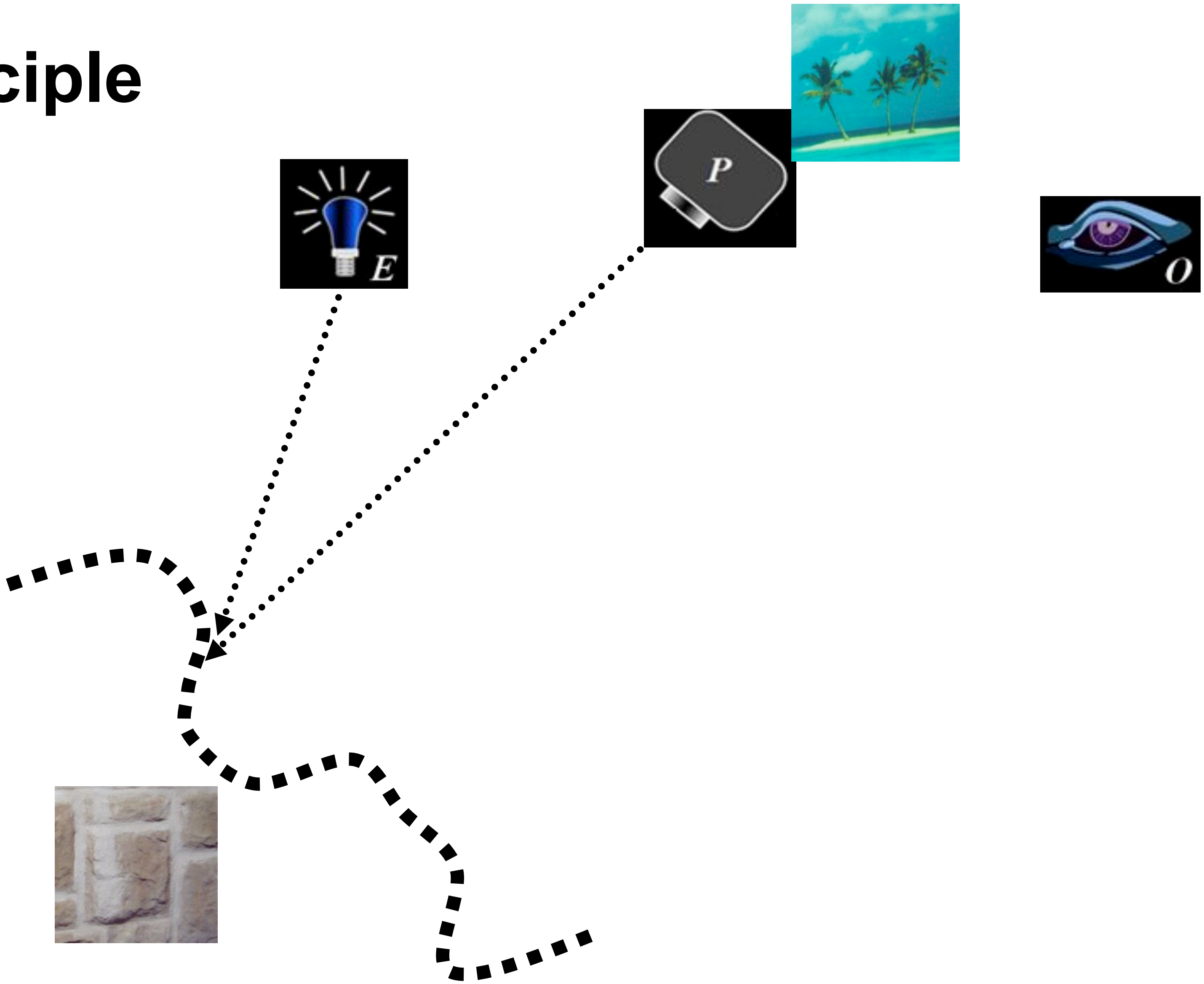

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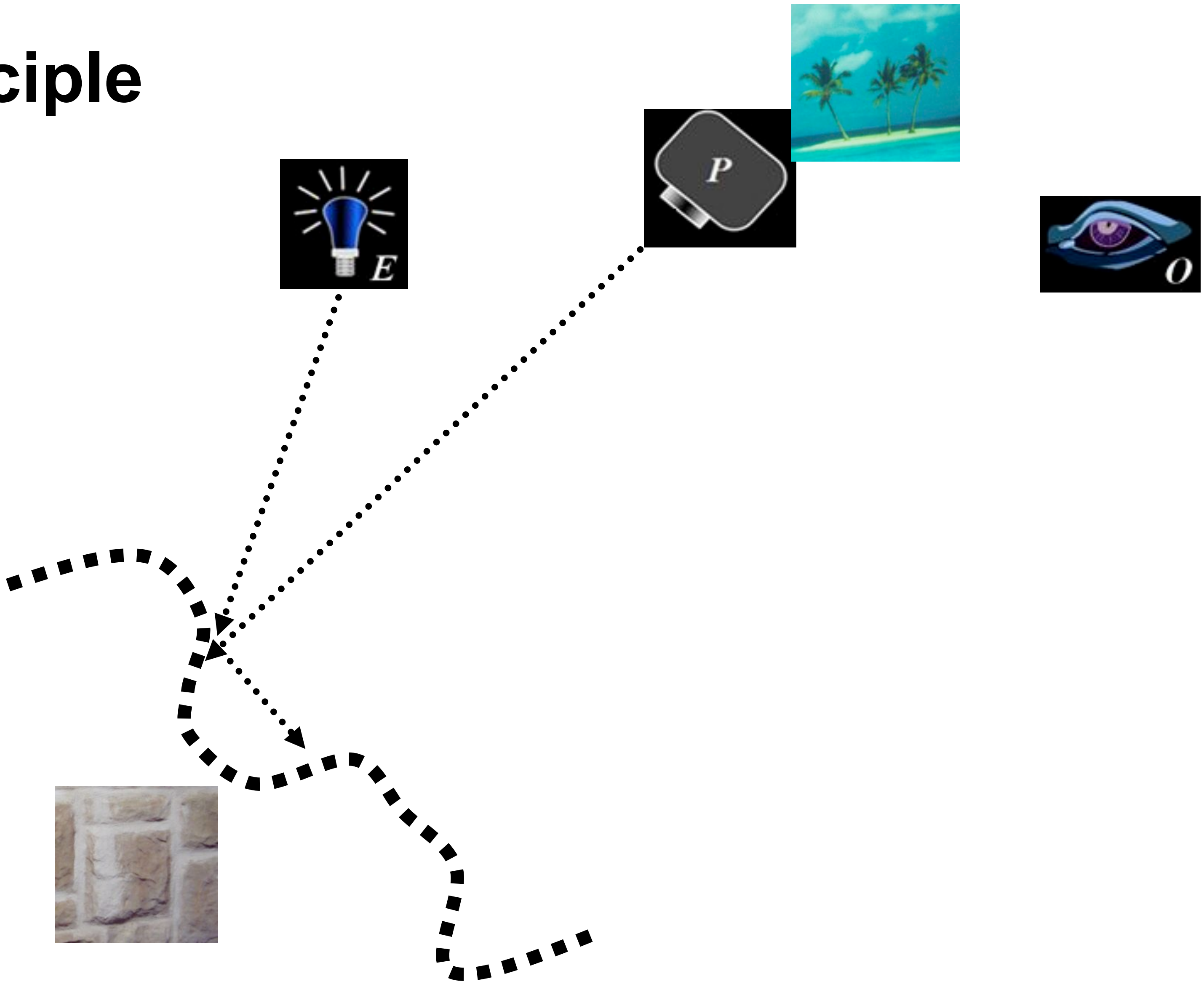

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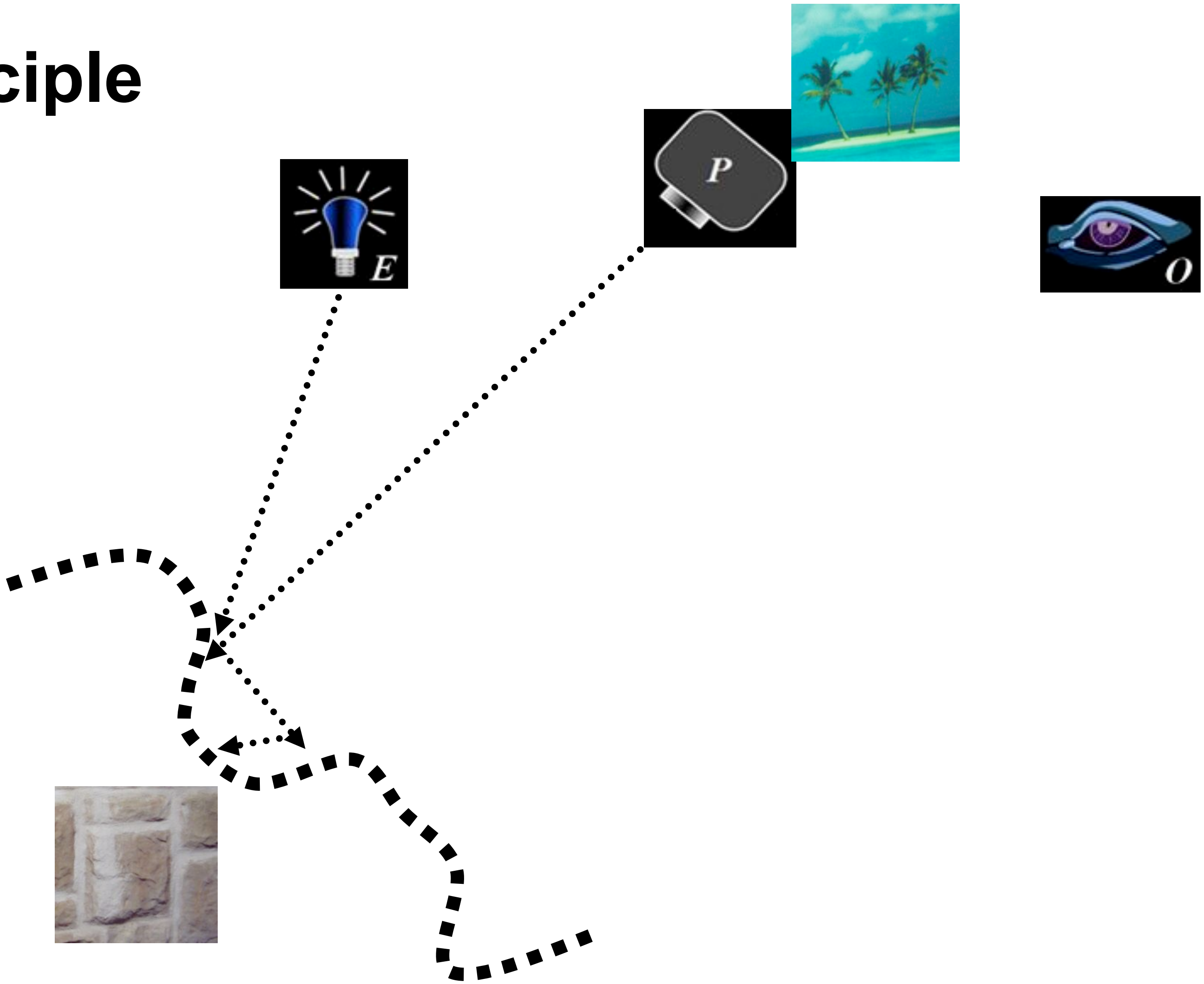

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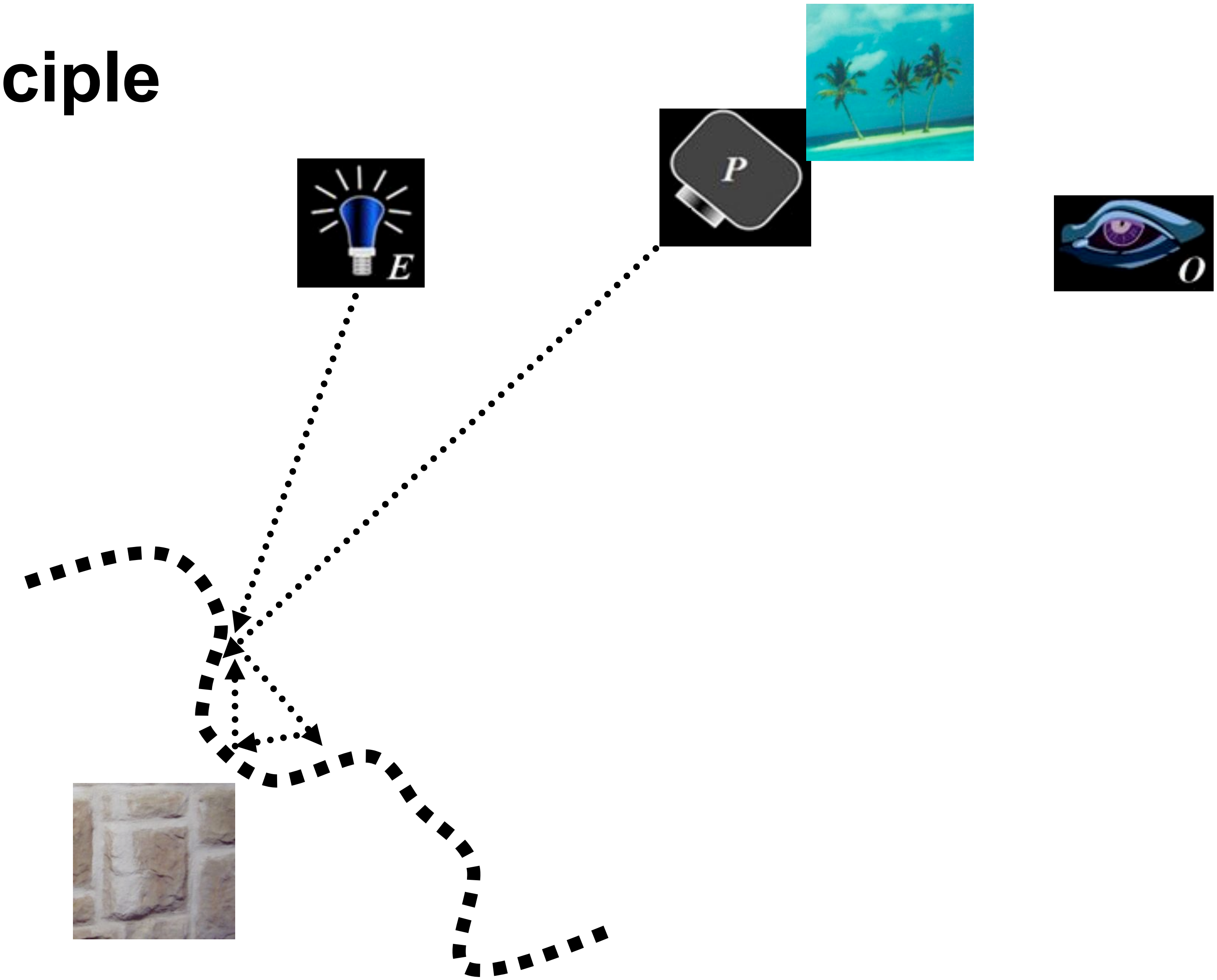

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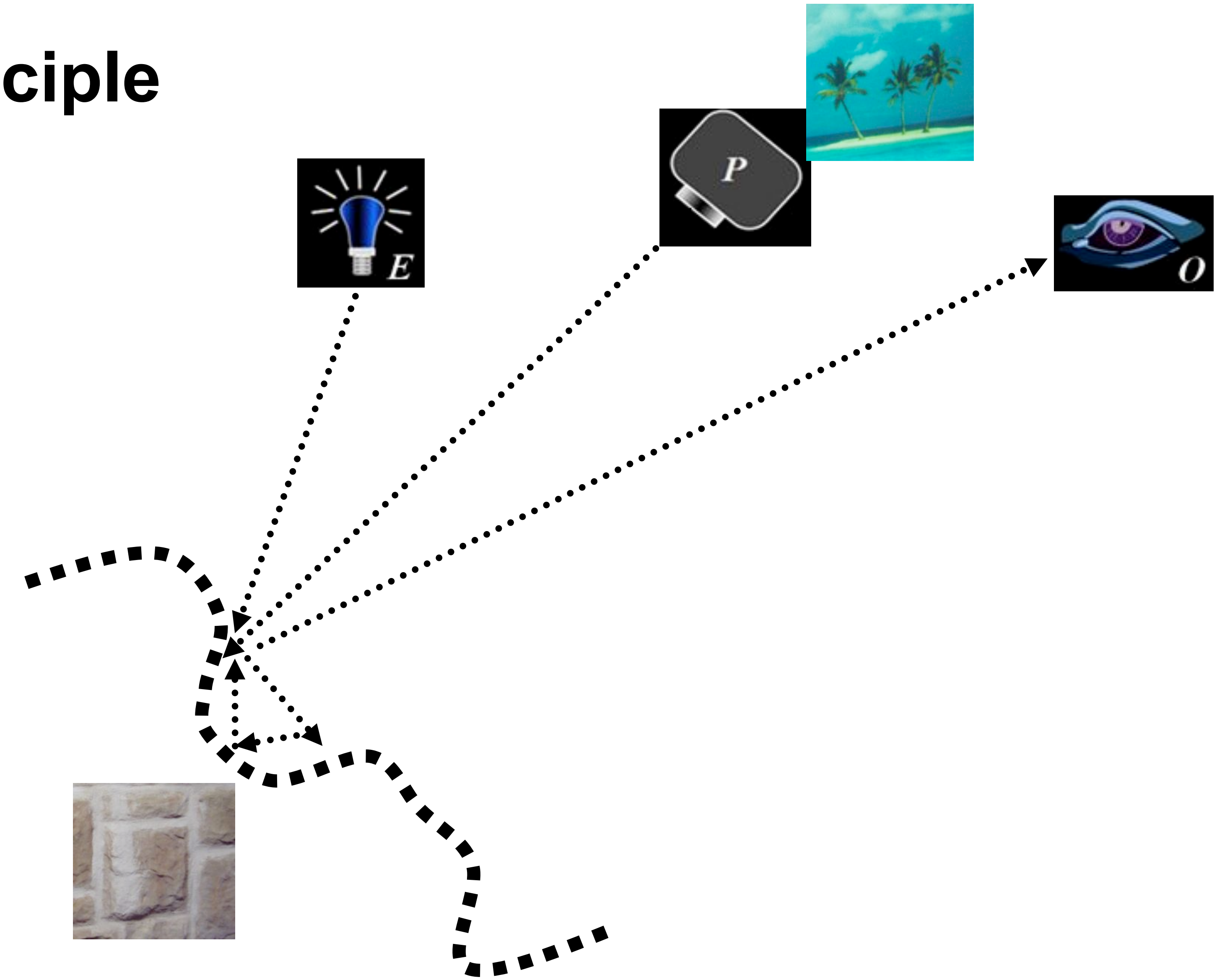

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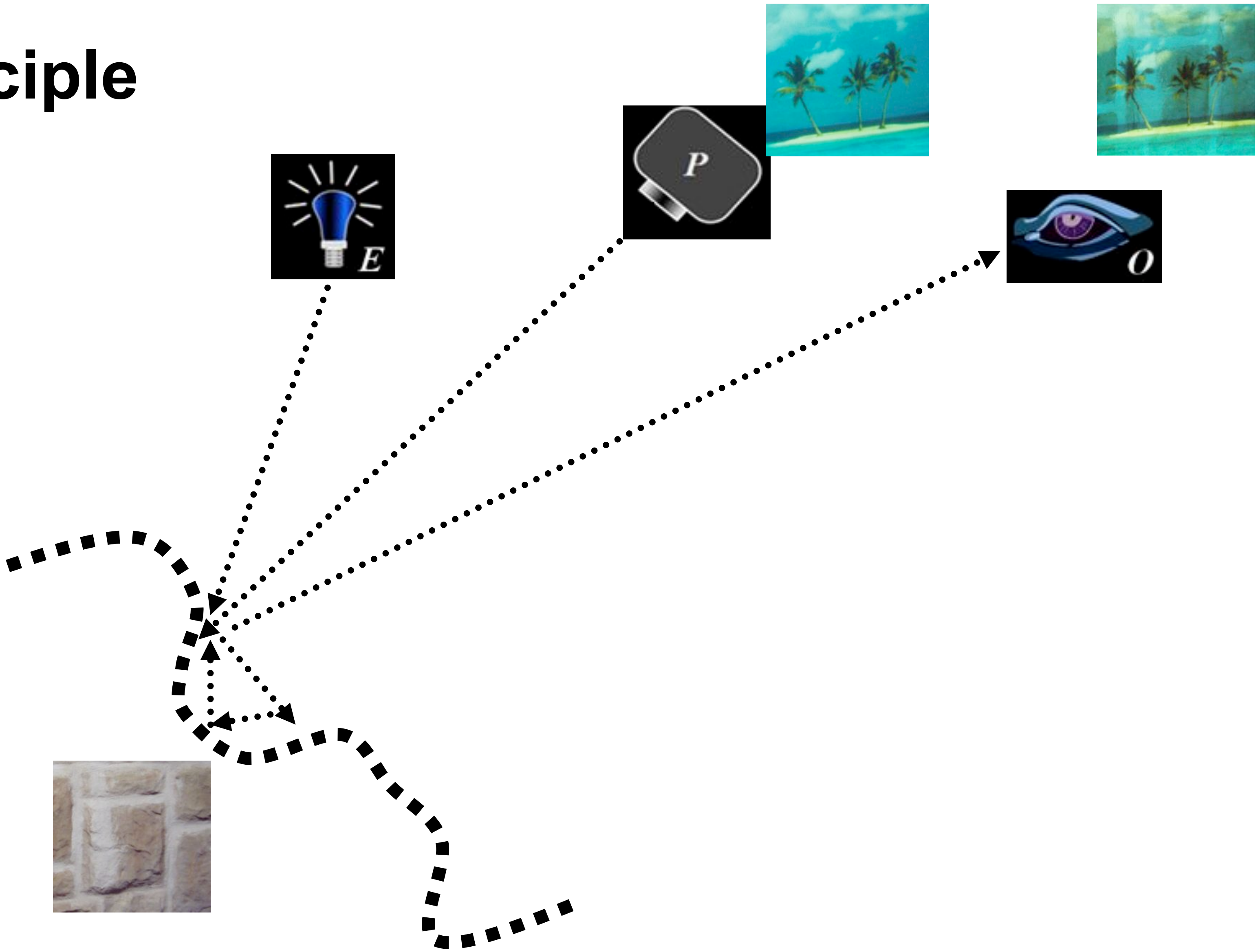

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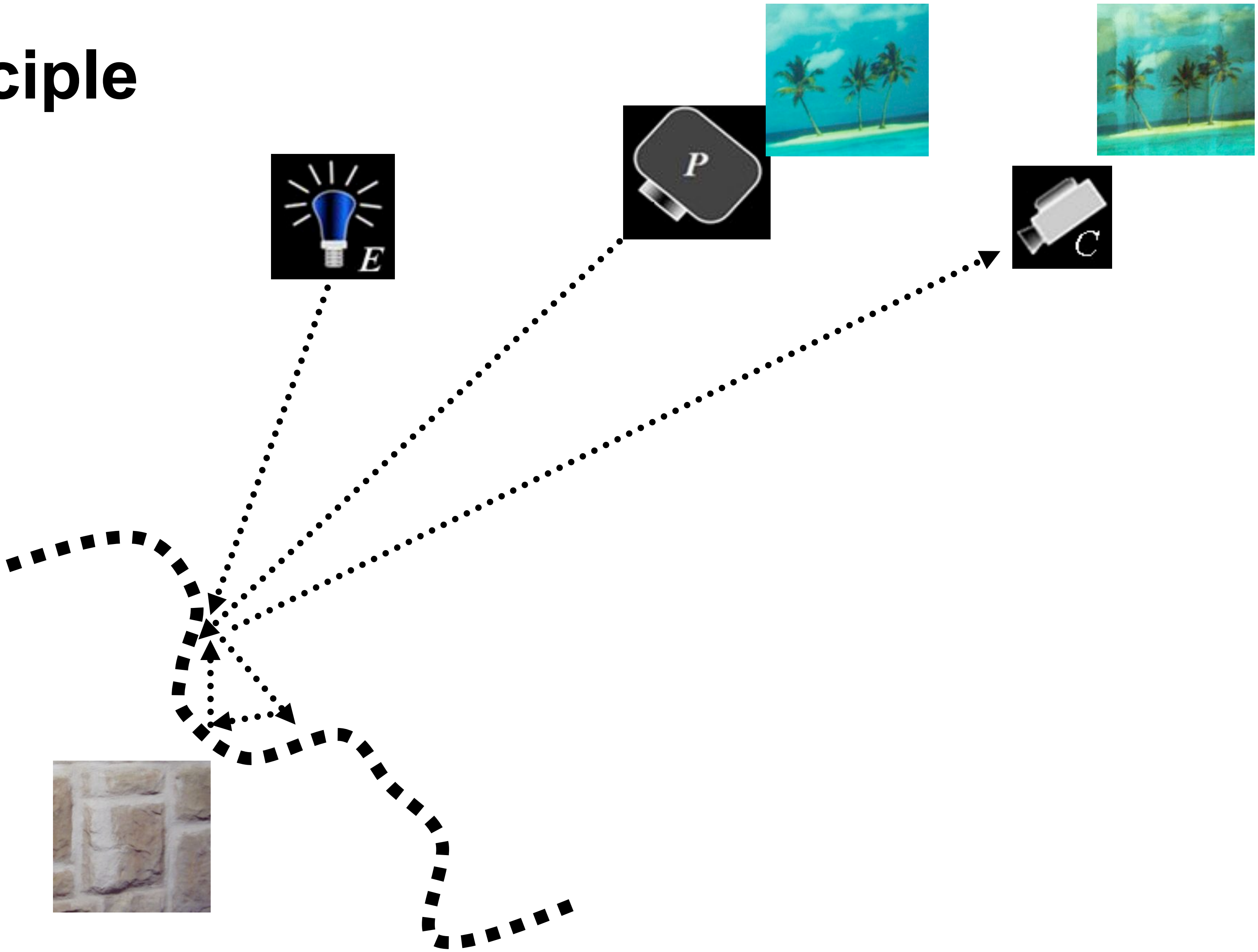

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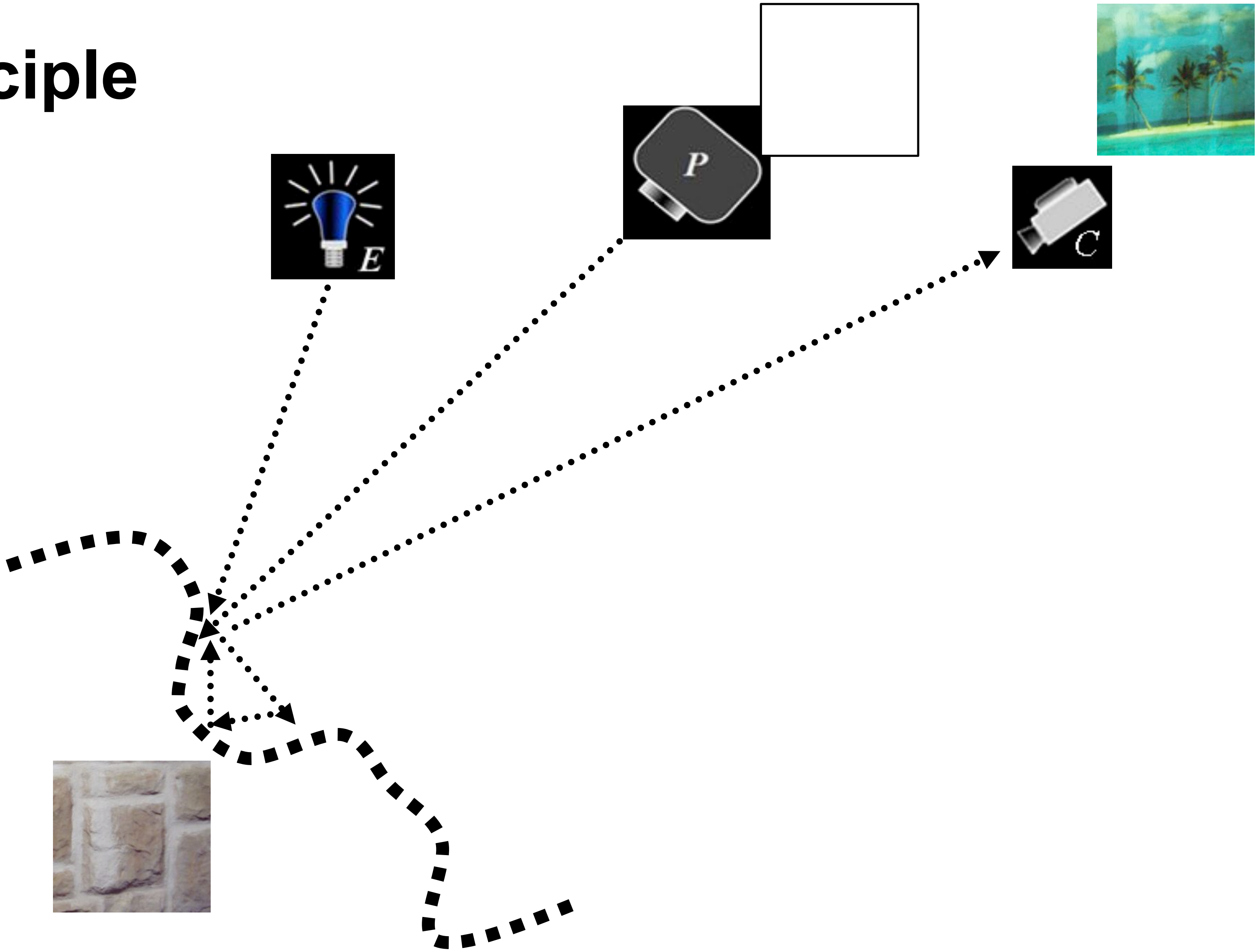

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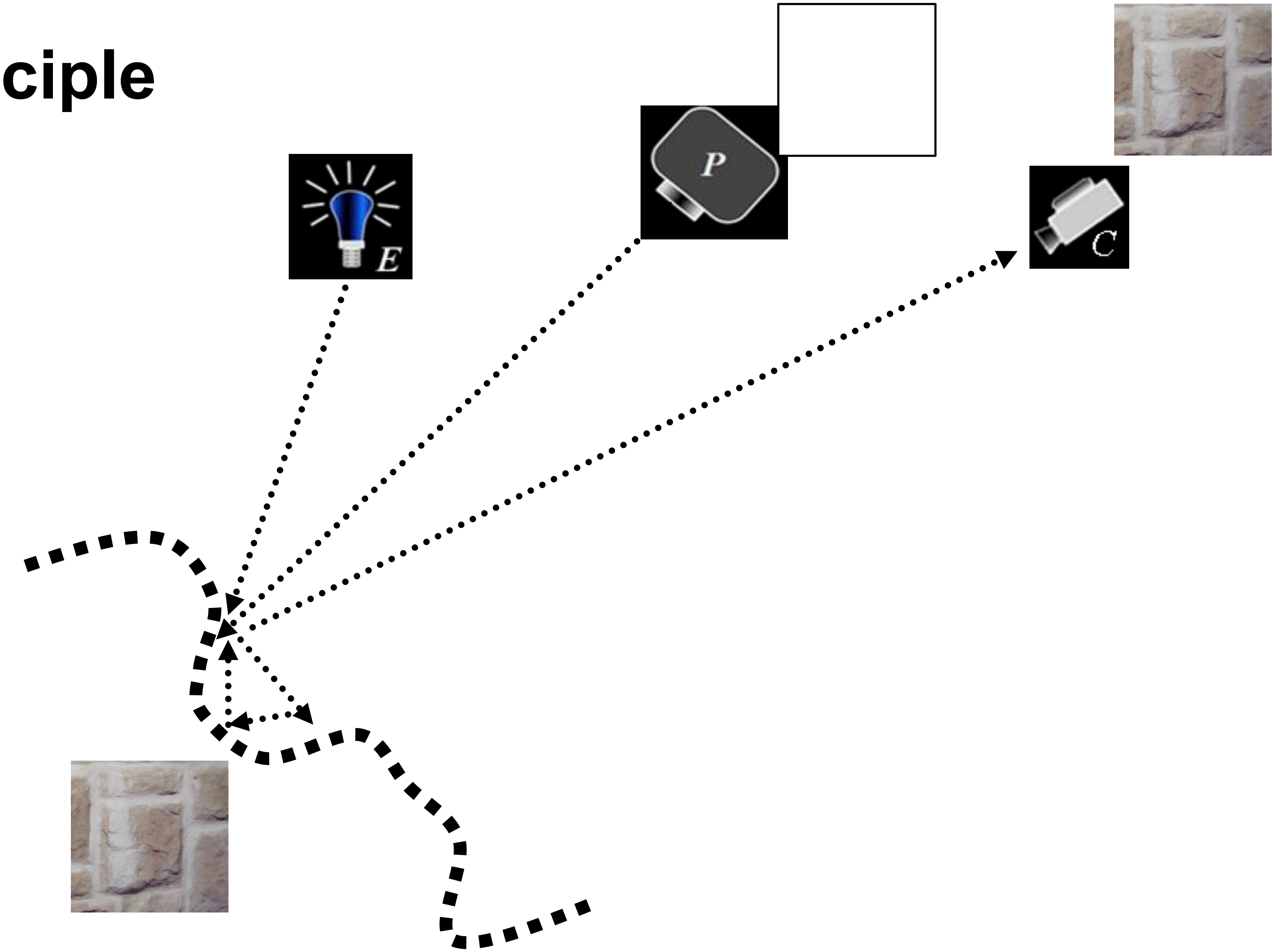

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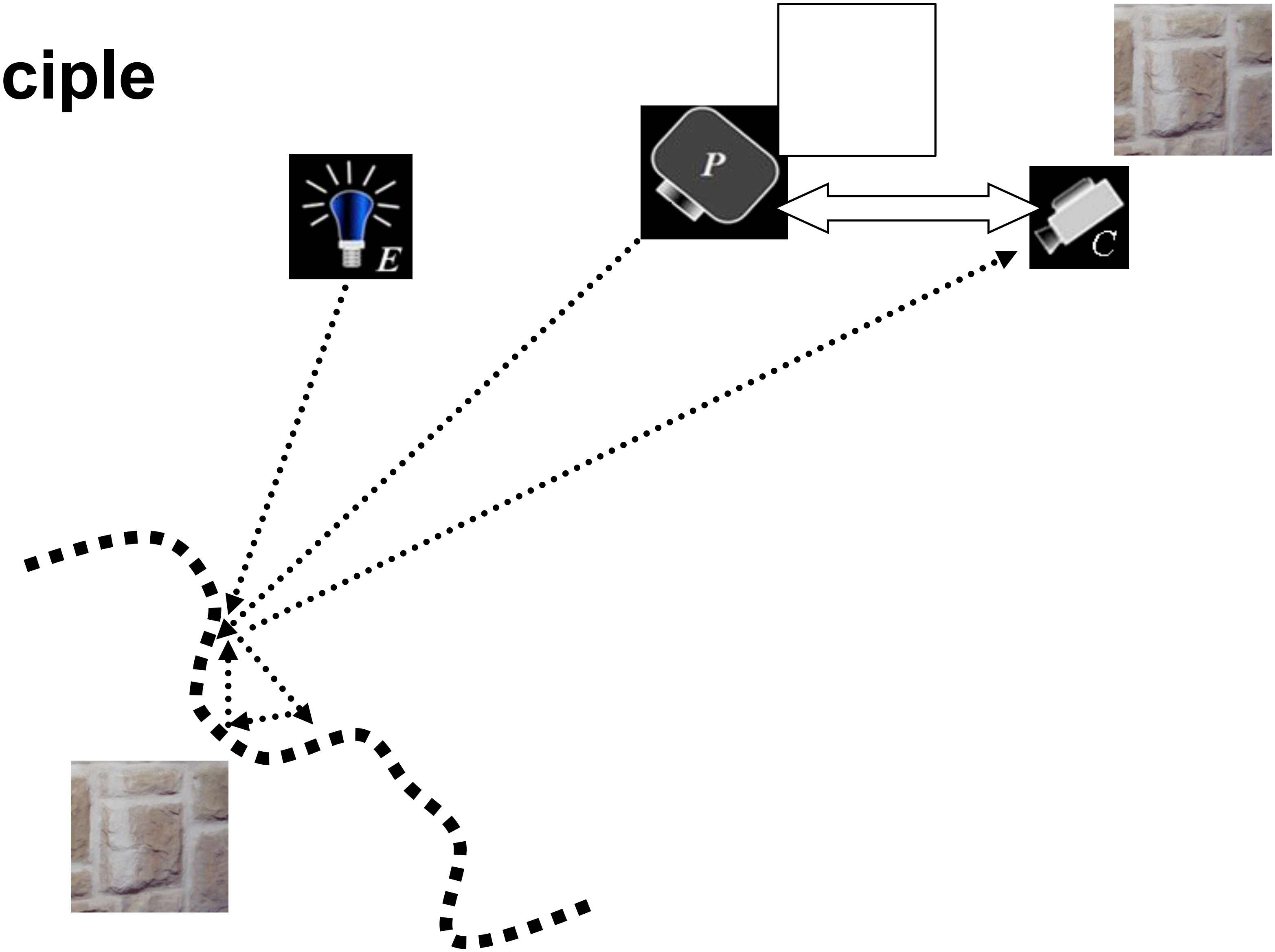

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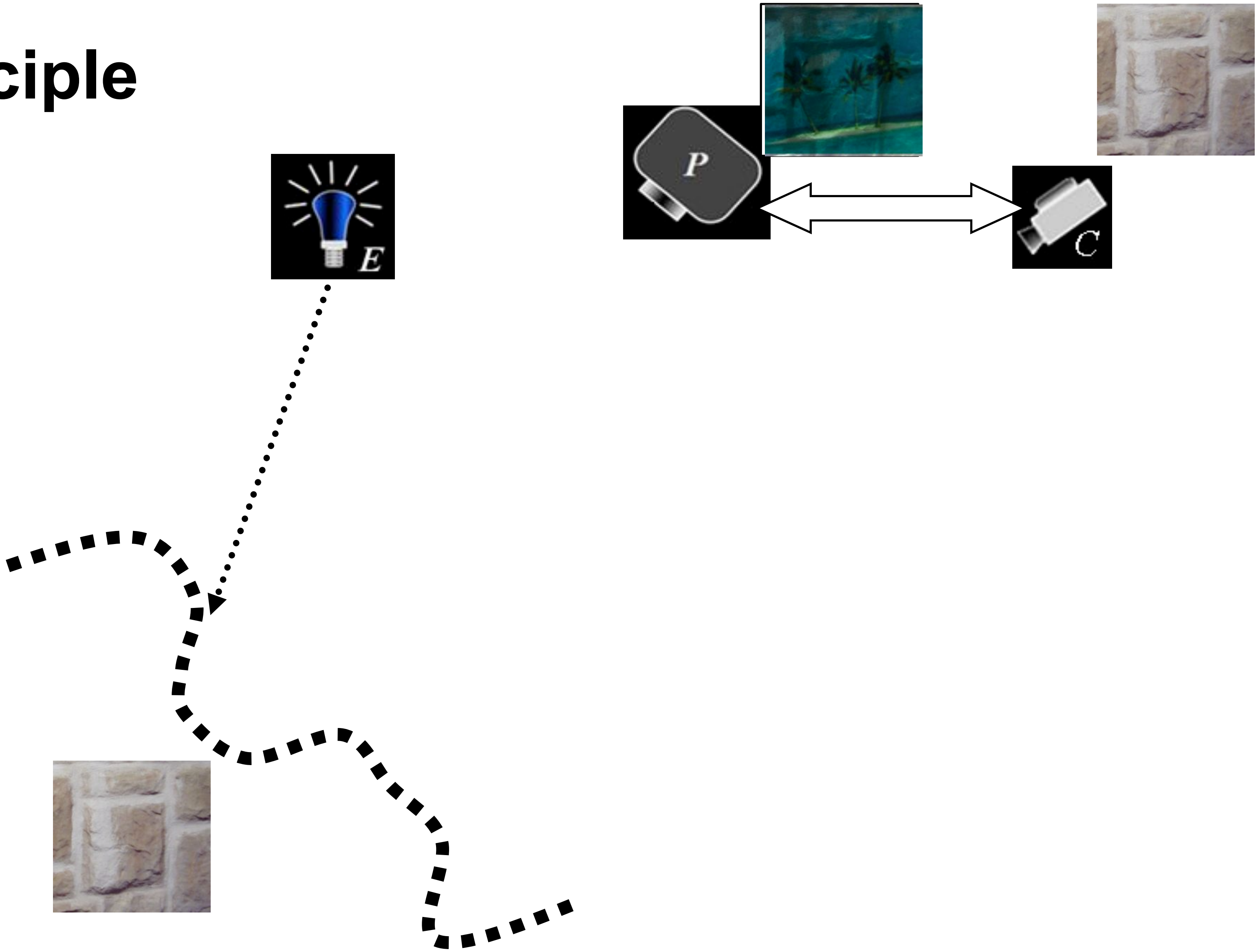

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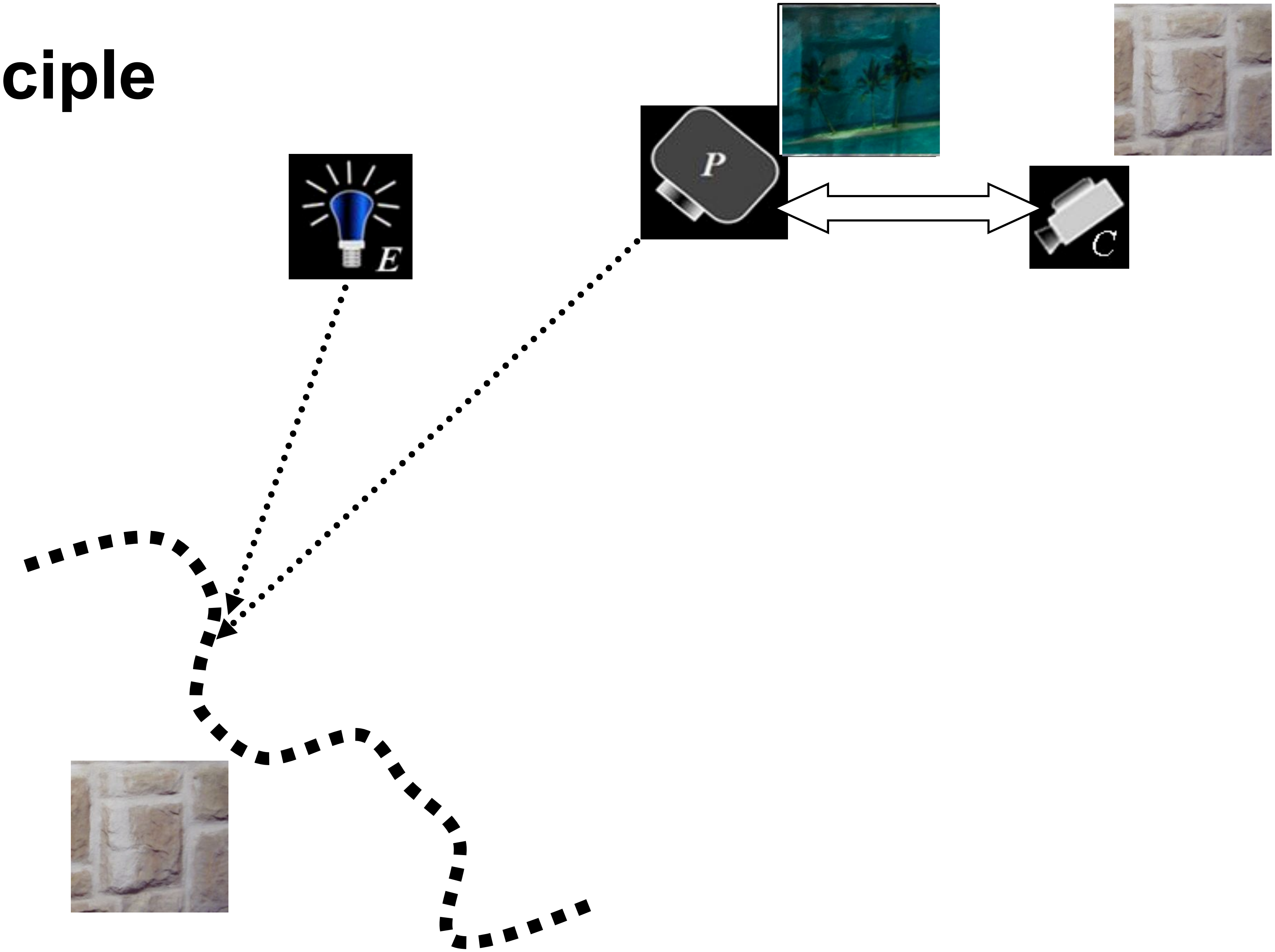

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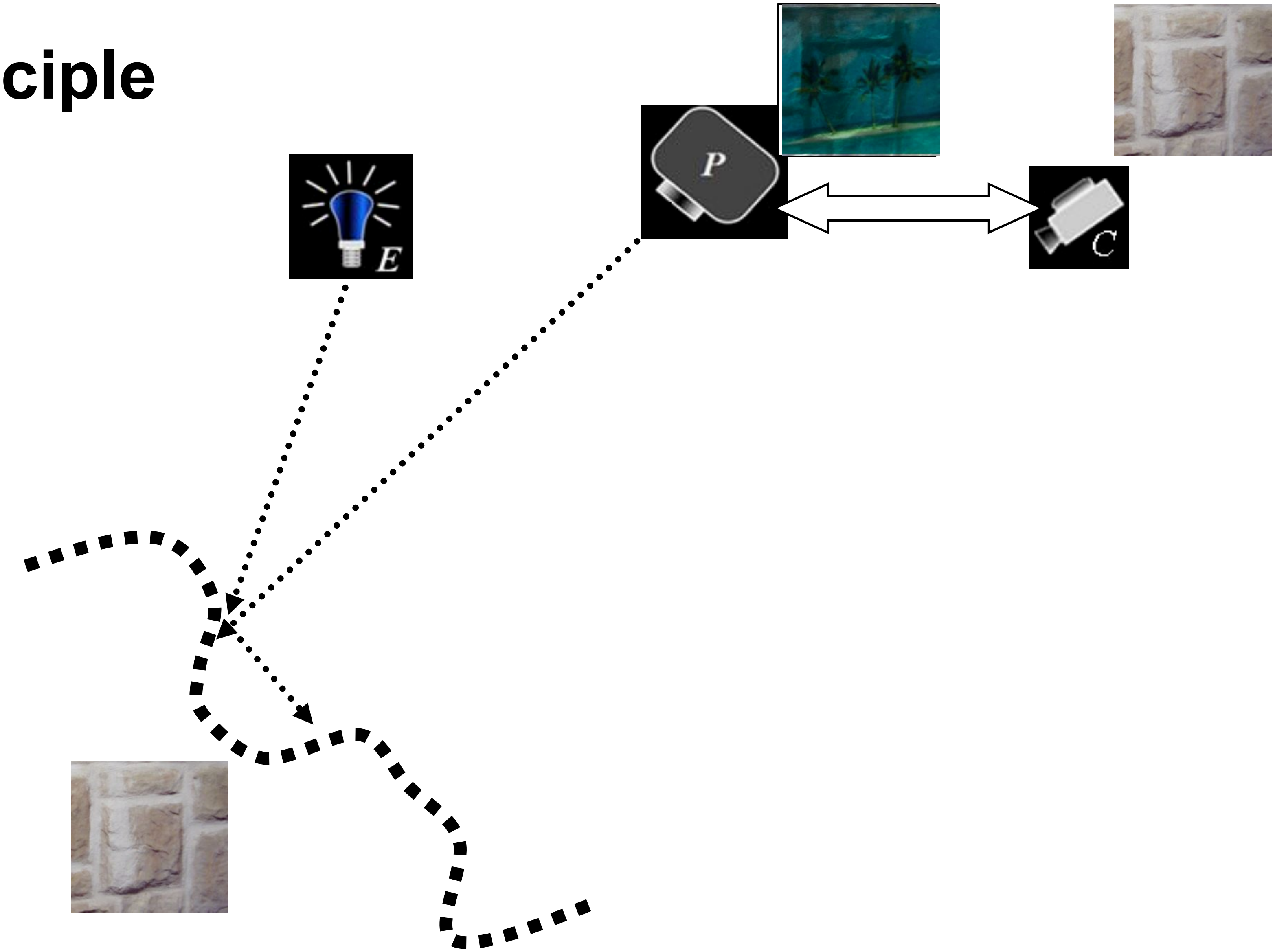

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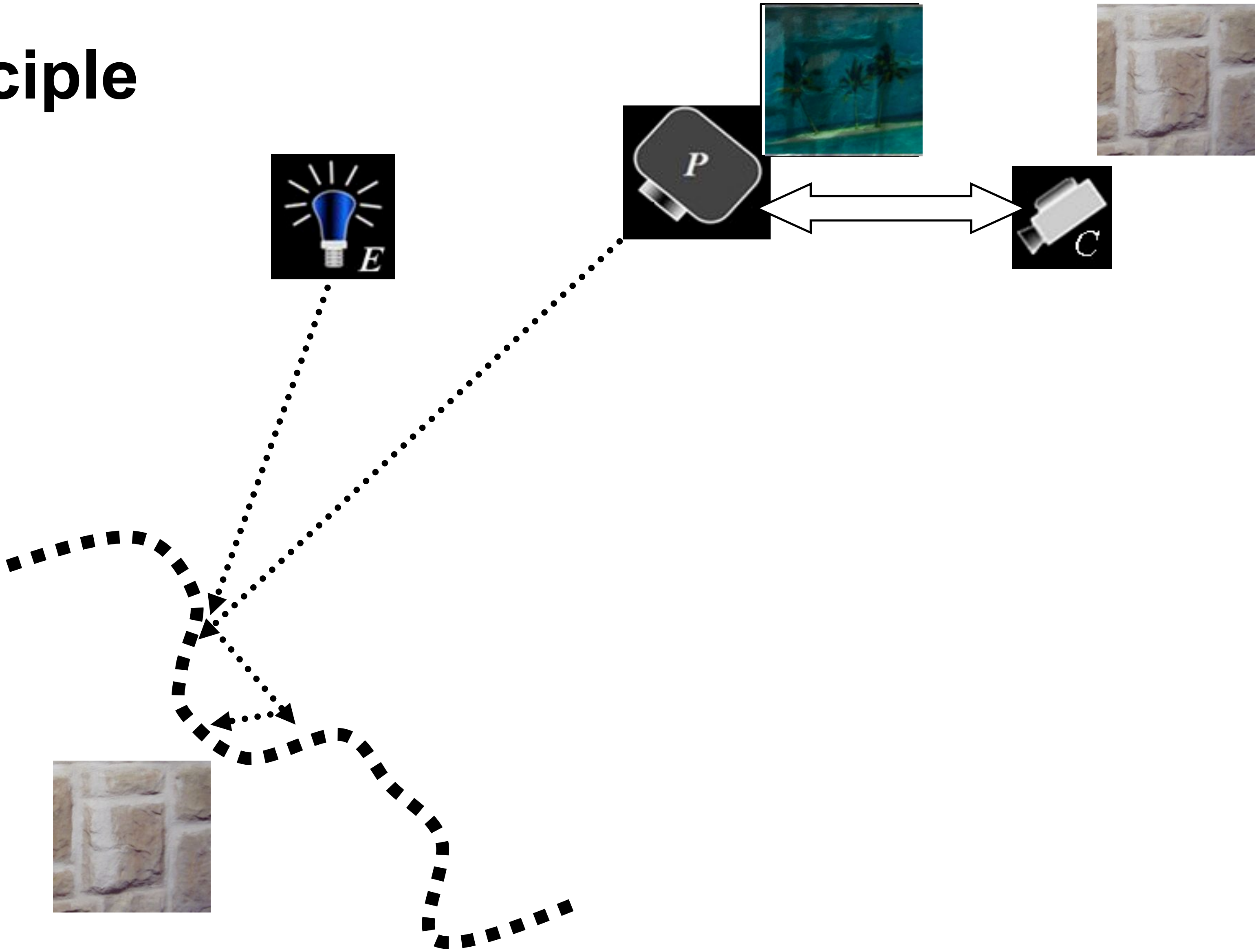

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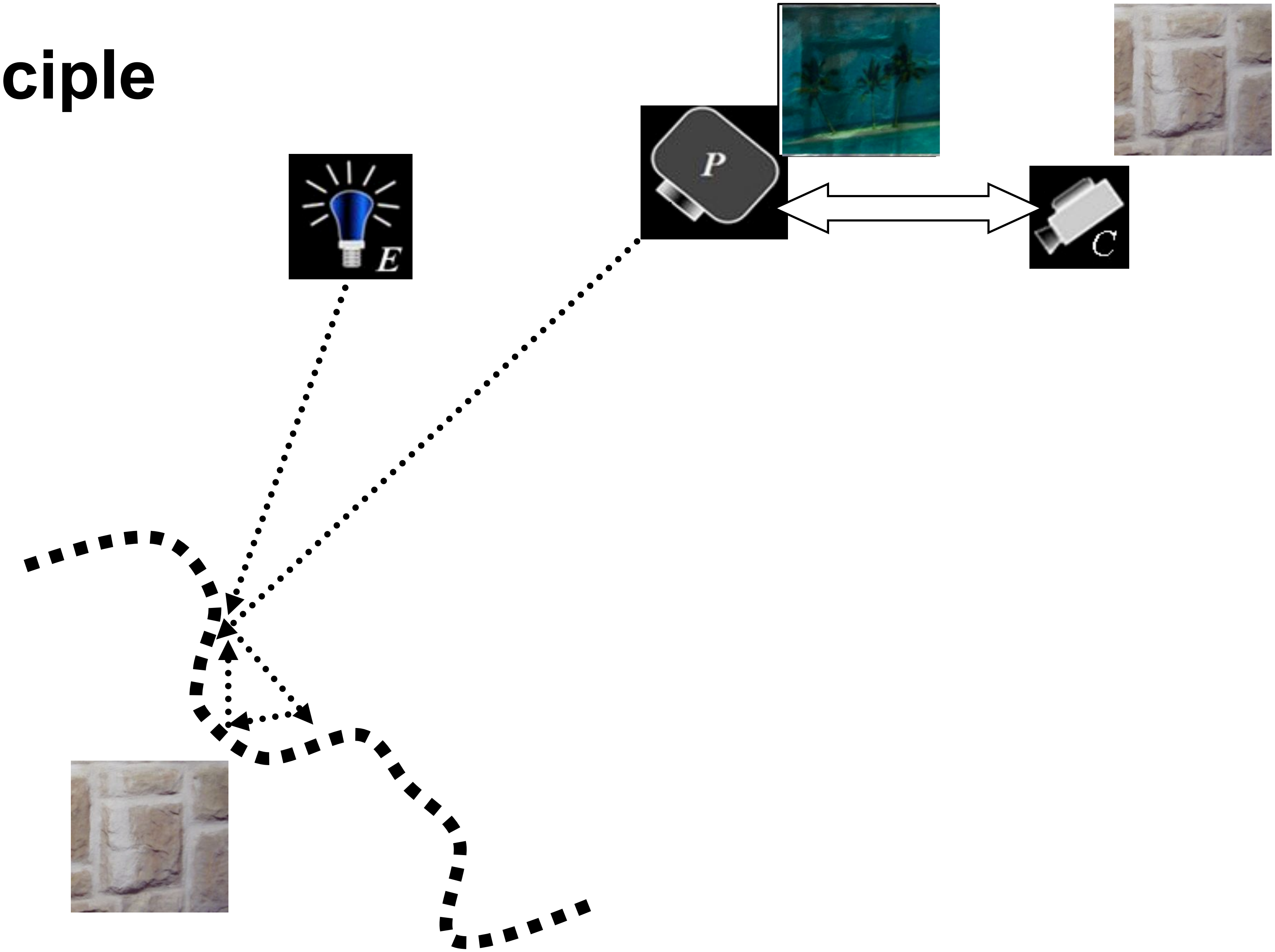

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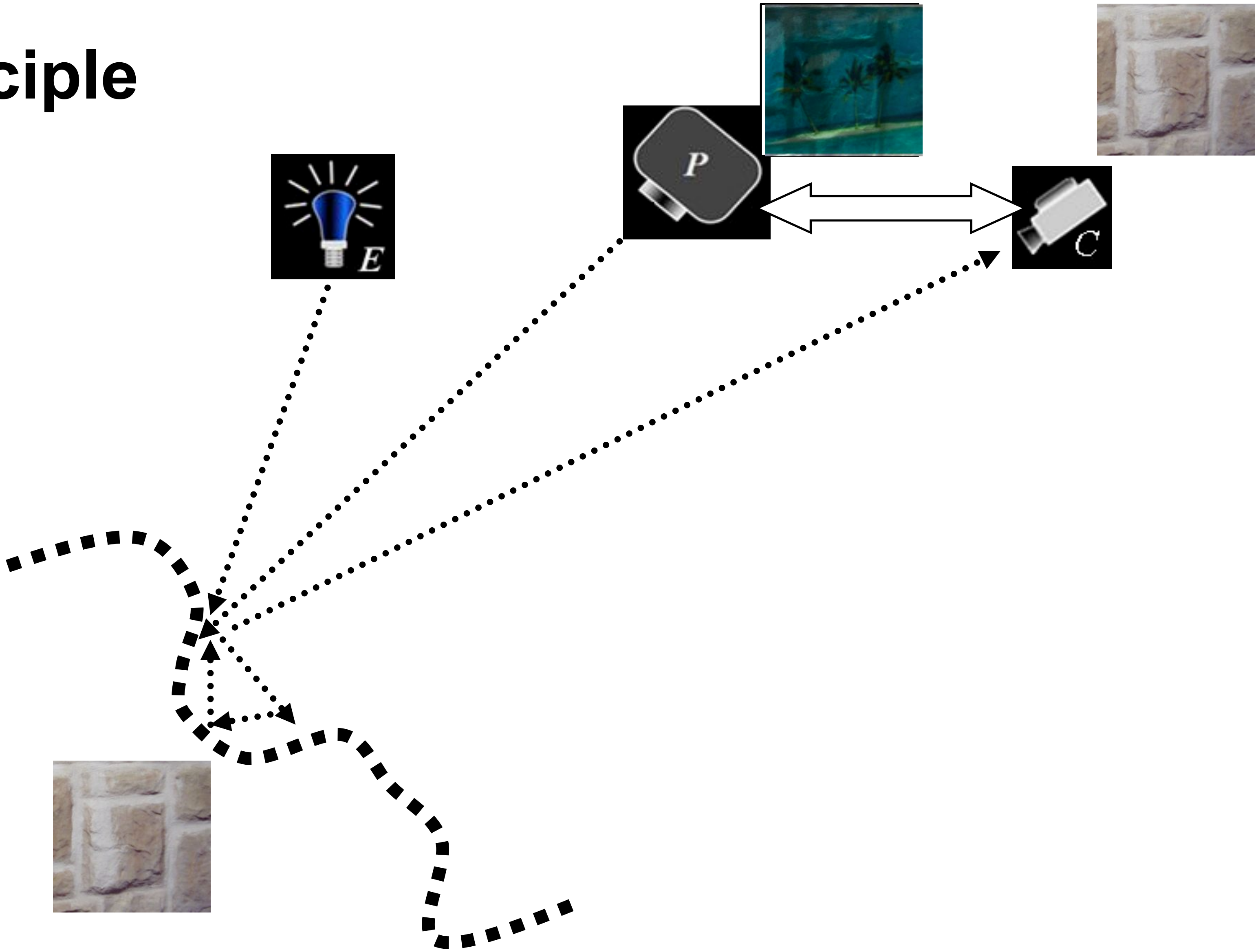

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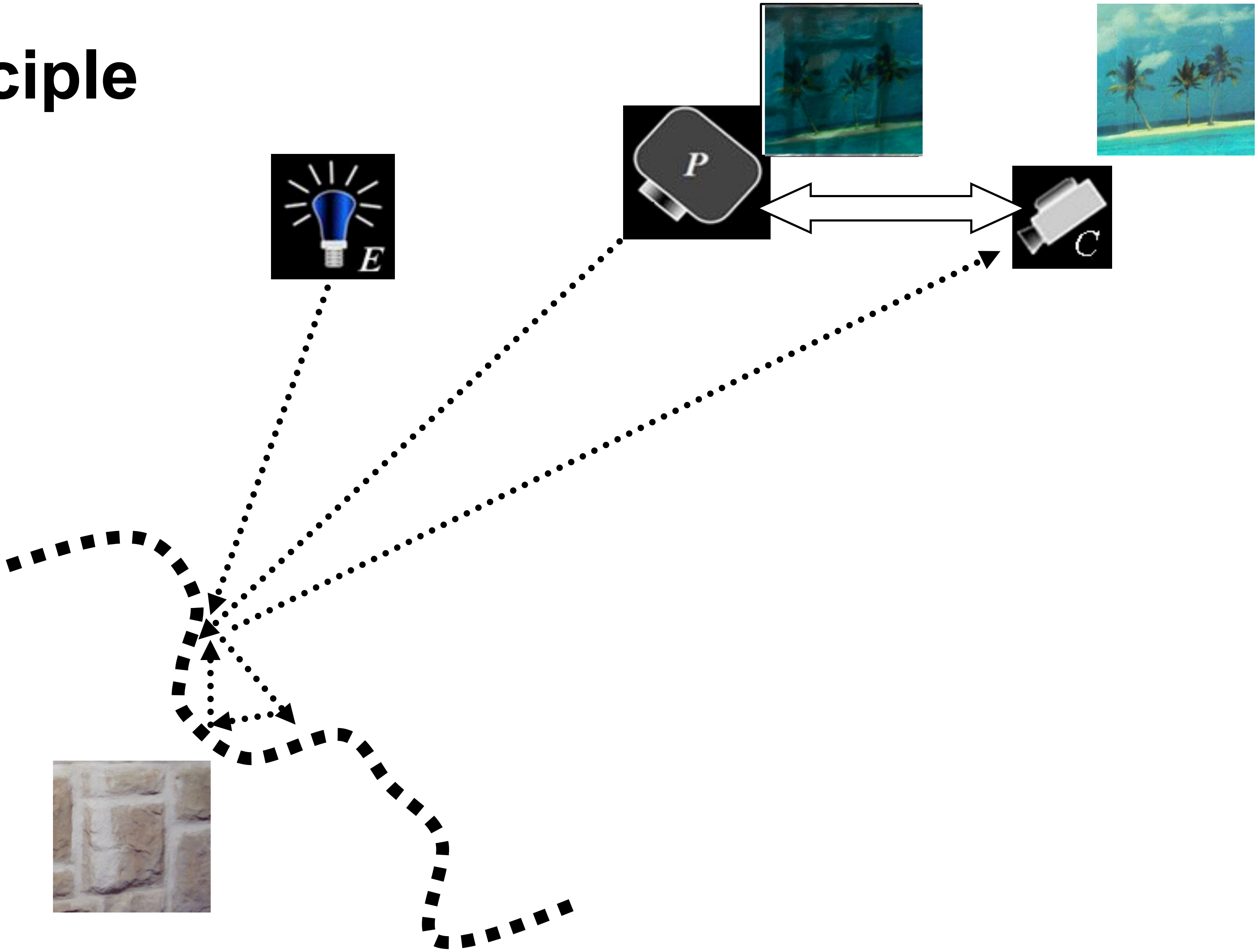

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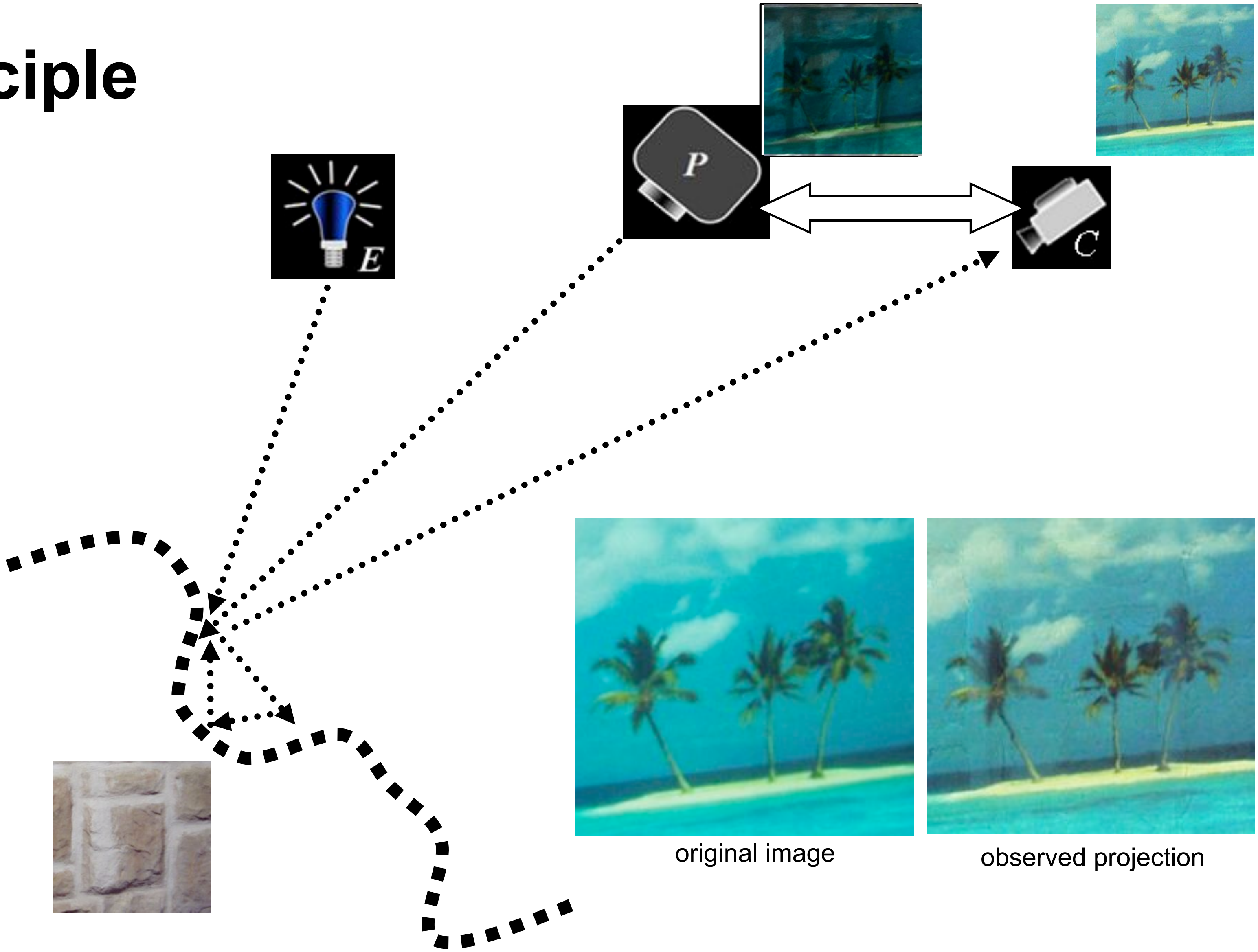

Some Challenges

Some Challenges

color blending

Some Challenges


color blending


geometric warping

Some Challenges


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geometric warping

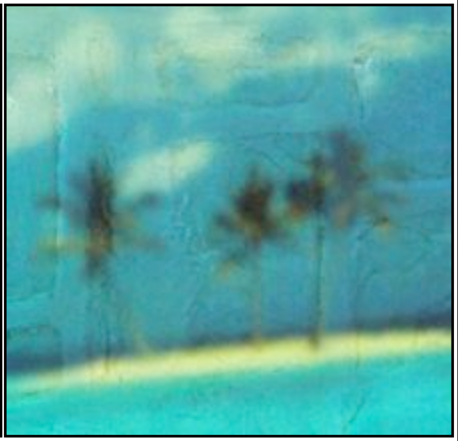

misregistration

Some Challenges


color blending


geometric warping


misregistration

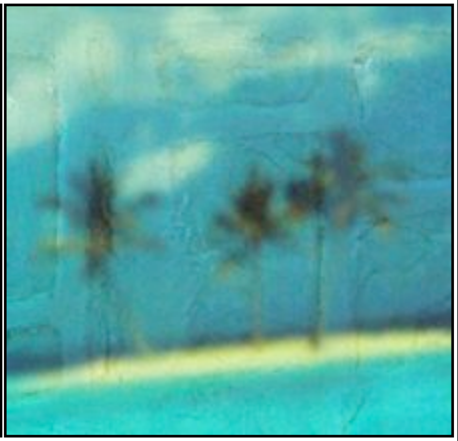

regional defocus

Some Challenges


color blending


geometric warping


misregistration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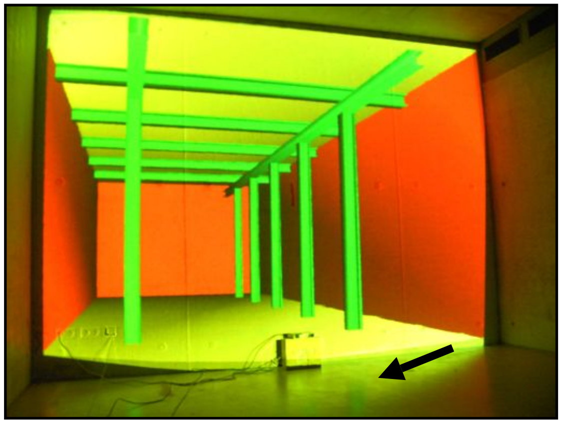
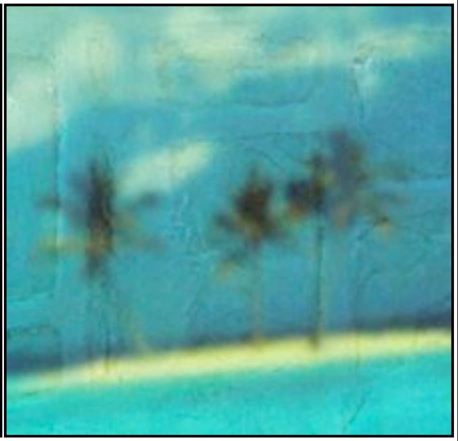

scattering

Some Challenges


color blending


geometric warping


misregistration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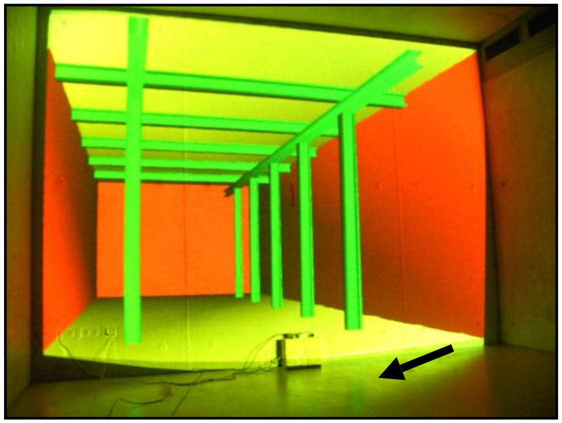
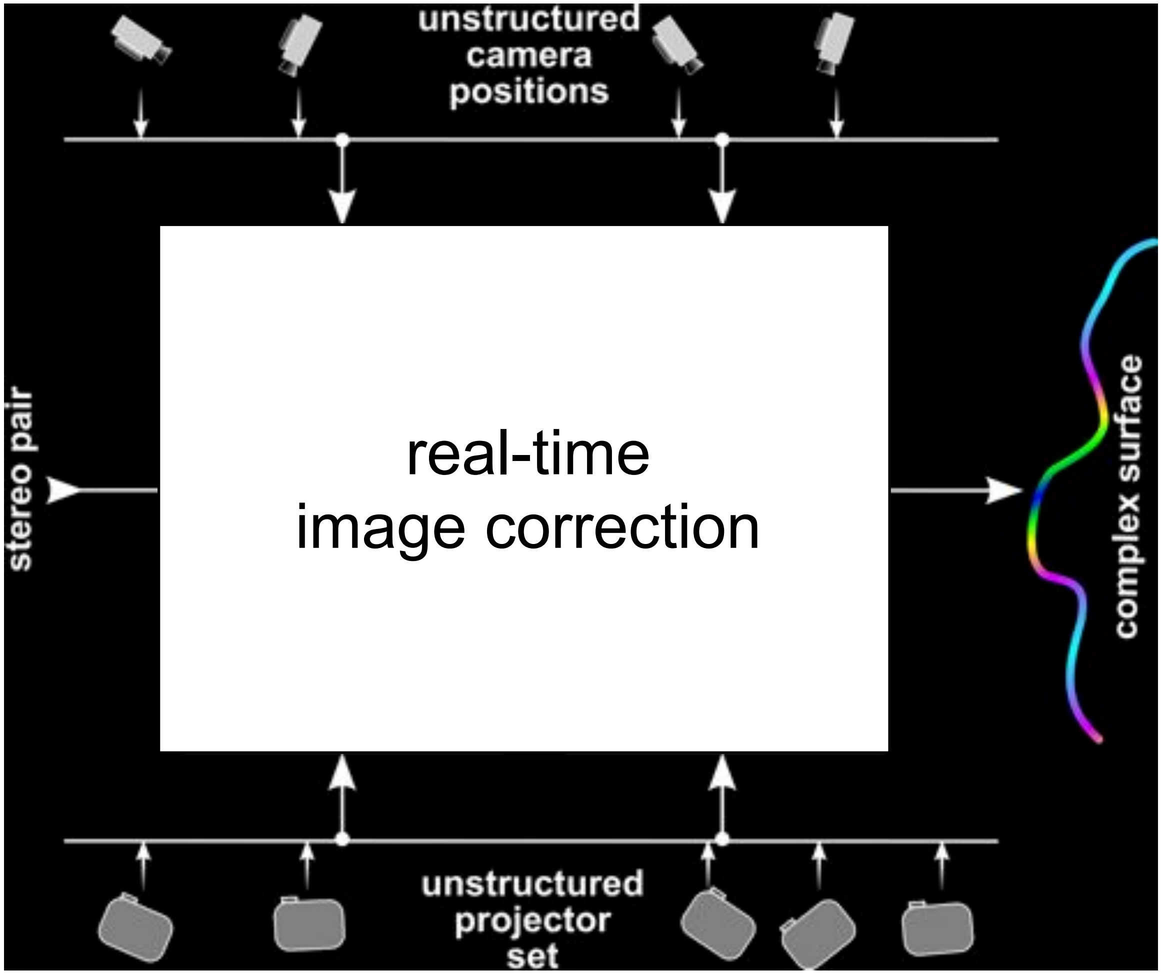
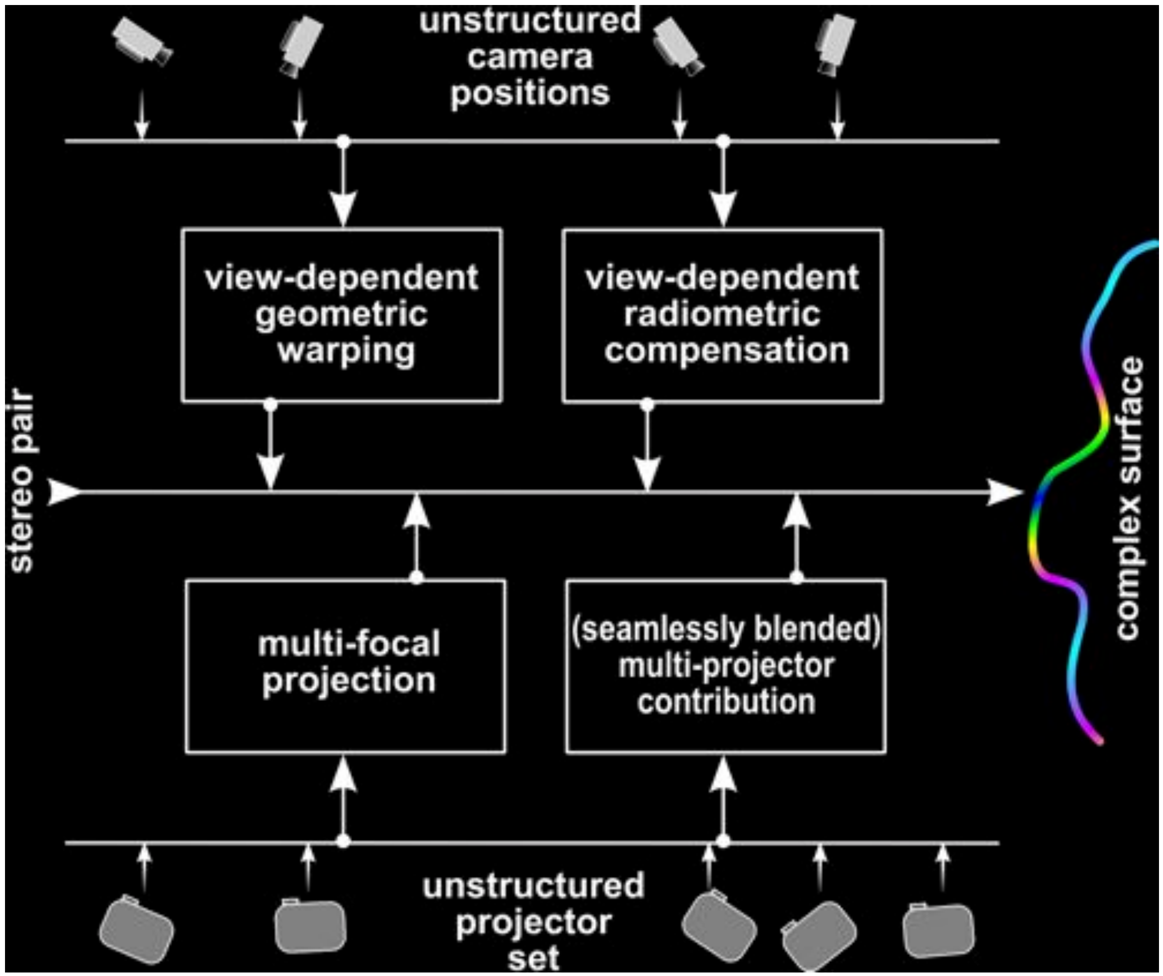

scattering


specular reflection, refraction, sub-surface scattering, inter-reflections, dispersion, diffraction, etc.

A Multi-Projector-Camera Approach

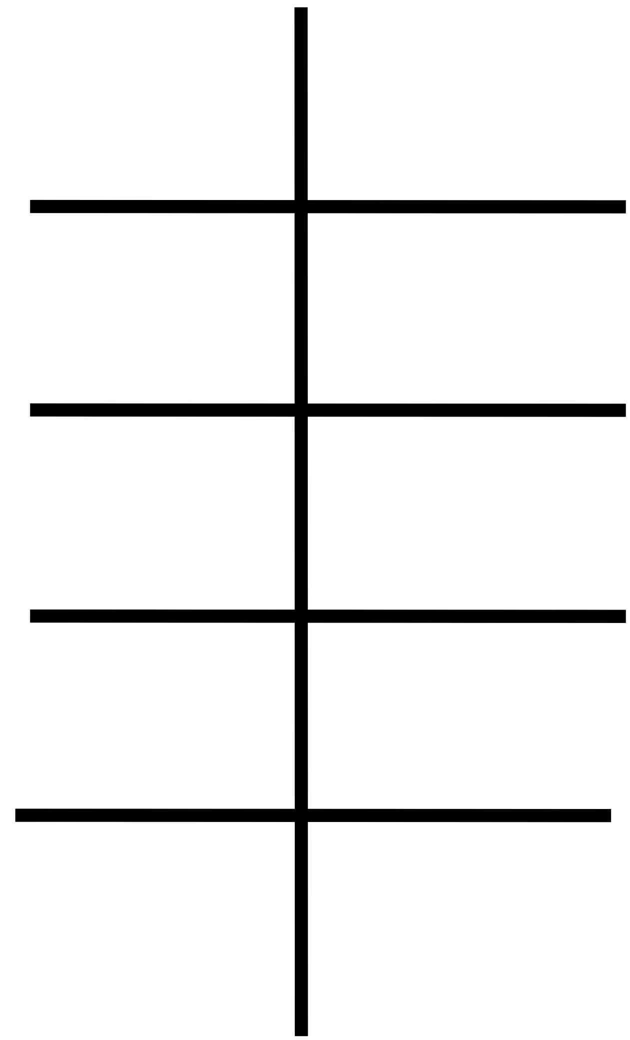


A Multi-Projector-Camera Approach

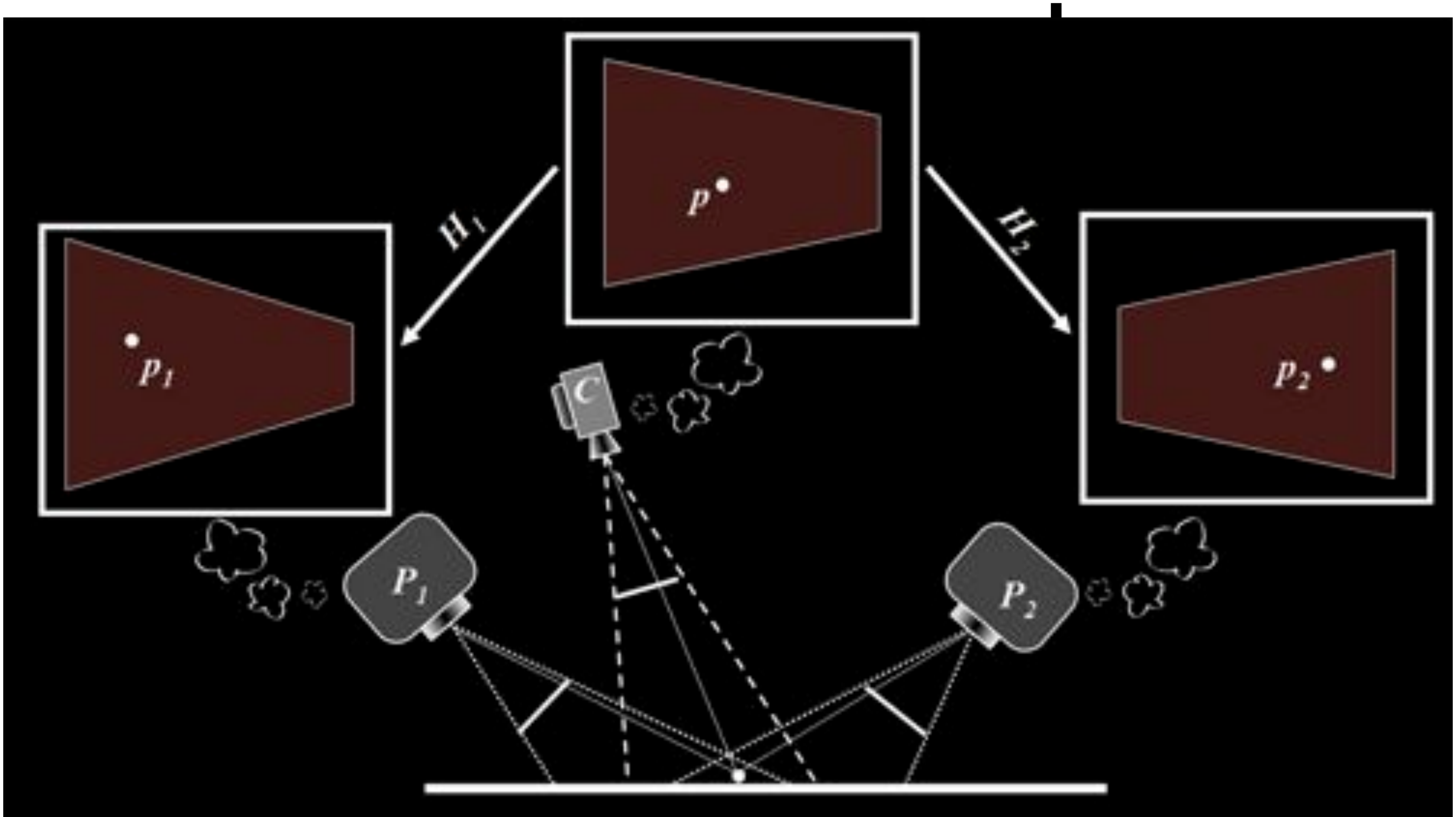


Geometric Correction

Planar Surfaces



Planar Surfaces



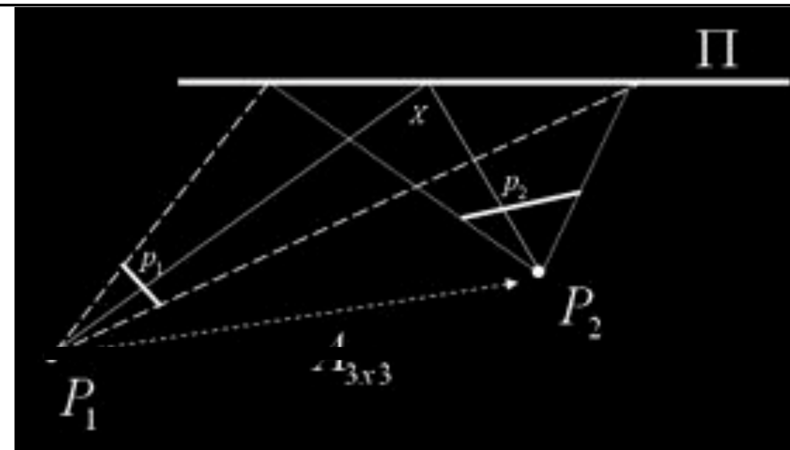
Homography

Homography

- homography is a mapping between two projections over a plane
- can map pixel coordinates from one perspective to another
- equation system has to be solved to determine 8 parameters of matrix A
- can be used directly in transformation pipeline by multiplying the following matrix after projection (without perspective division):

$$A_{4x4} = \begin{bmatrix} a_{11} & a_{12} & 0 & a_{13} \\ a_{21} & a_{22} & 0 & a_{23} \\ 0 & 0 & 1 & 0 \\ a_{31} & a_{32} & 0 & 1 \end{bmatrix}$$

- ensure intact depth values with (approximately)



$$p_2 \cong A_{3x3} p_1$$

$$\begin{bmatrix} p_{2x} \\ p_{2y} \\ 1 \end{bmatrix} \cong \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & 1 \end{bmatrix} \begin{bmatrix} p_{1x} \\ p_{1y} \\ 1 \end{bmatrix}$$

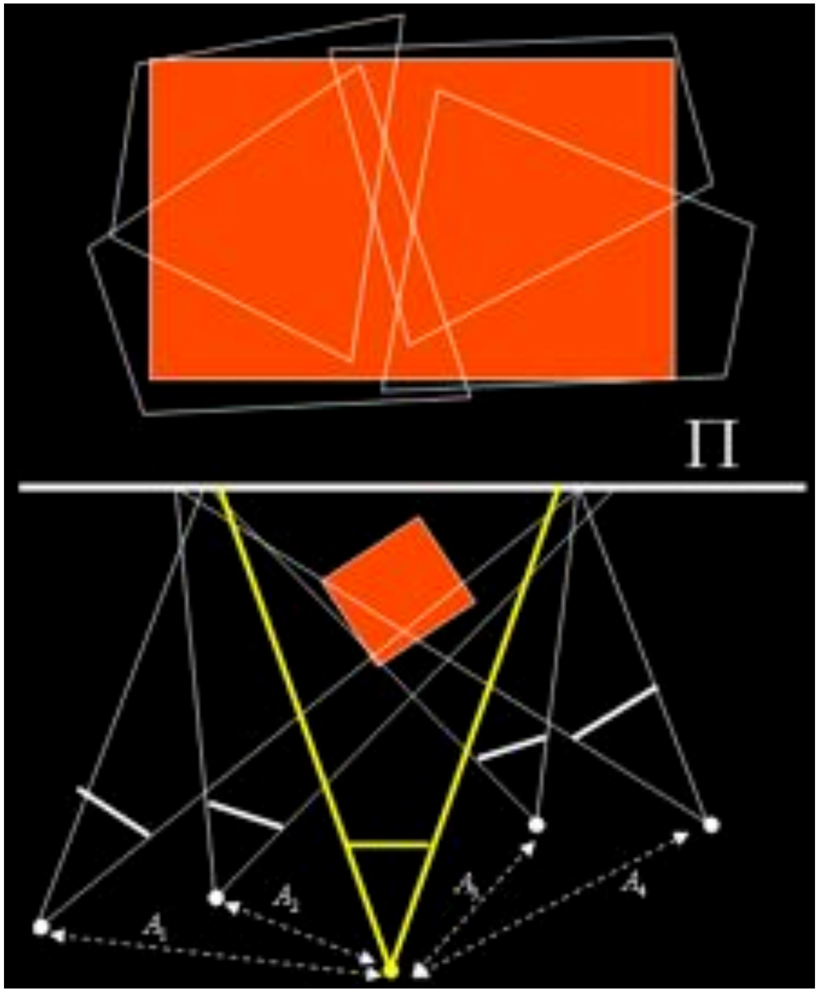
$$p_{2z} = \frac{p_{1z}}{(a_{31}p_{1x} + a_{32}p_{1y} + p_{1w})} \in [-1,1]$$

$$A_{4x4} = \begin{bmatrix} a_{11} & a_{12} & 0 & a_{13} \\ a_{21} & a_{22} & 0 & a_{23} \\ 0 & 0 & 1-|a_{31}|-|a_{32}| & 0 \\ a_{31} & a_{32} & 0 & 1 \end{bmatrix}$$

Multi-Projector Registration

Multi-Projector Registration

- registering multiple projectors onto a common planar surface
- map all perspective into a single target perspective via homographies
- target perspective can be camera perspective
  - automatic determination of matrix parameters via structured light
- rendering
  - render image for target perspective (if target perspective is **orthogonal** to plane, then it can be done with an off-axis projection of an observer!)
  - map pixels into individual projector views (i.e., multiply 4x4 version of homography matrix onto matrix stack [after projection] and ensure that depth values remain intact!)



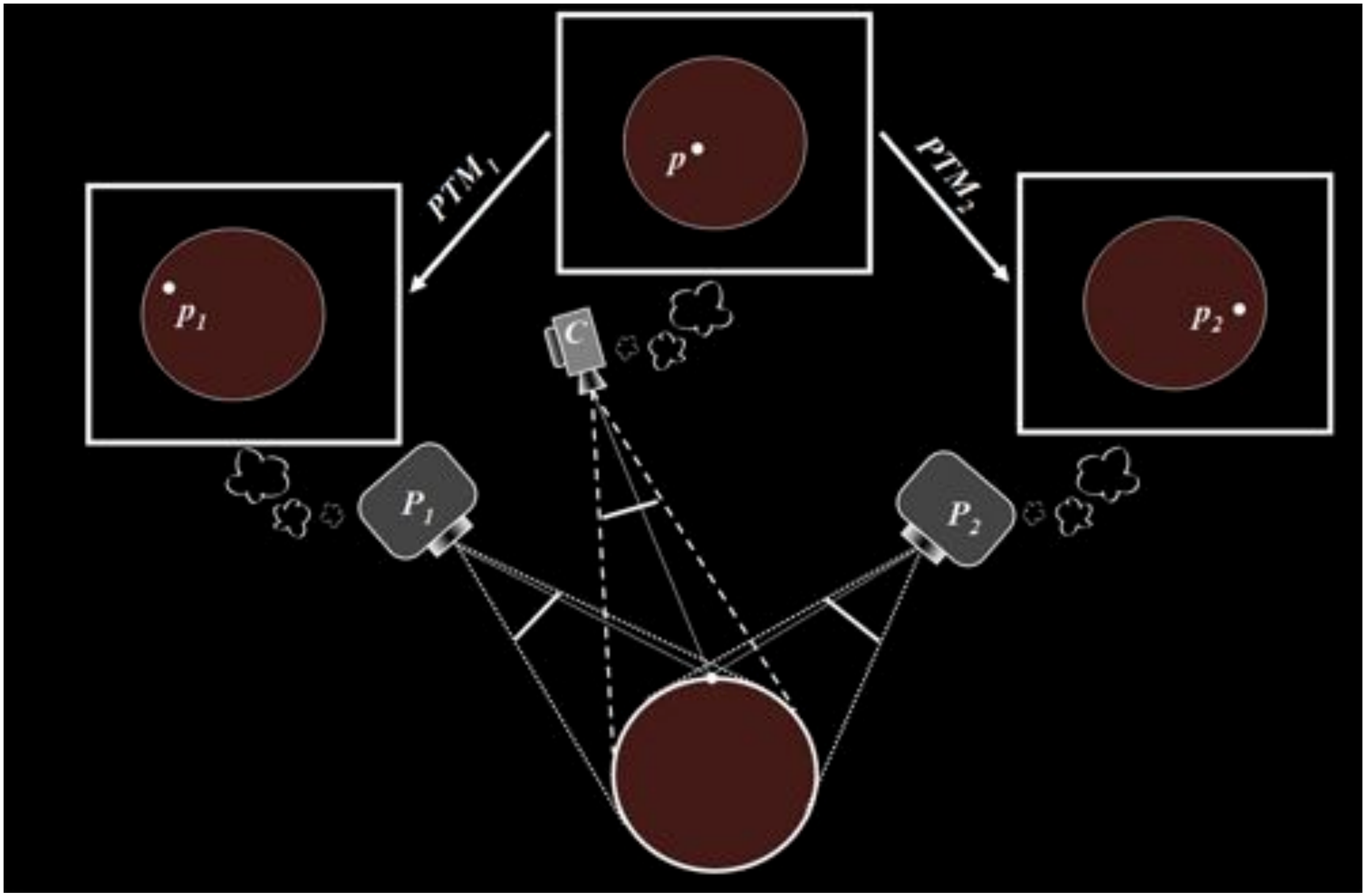
Example: Tiled Projection Screens

Example: Tiled Projection Screens

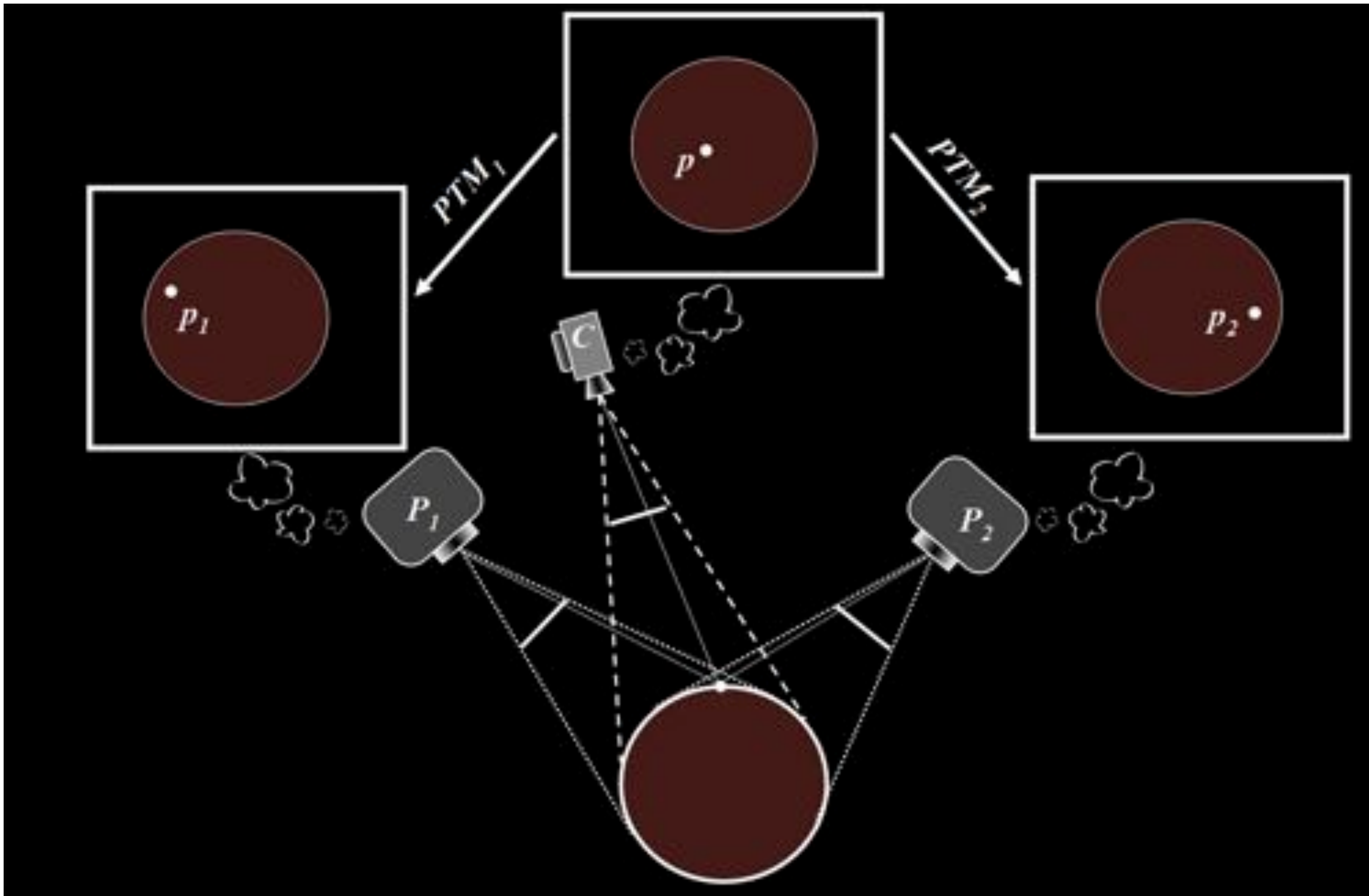
Courtesy: Brown, et al.,
IEEE TVCG, 2005

Non-Trivial Surfaces

Non-Trivial Surfaces



Non-Trivial Surfaces



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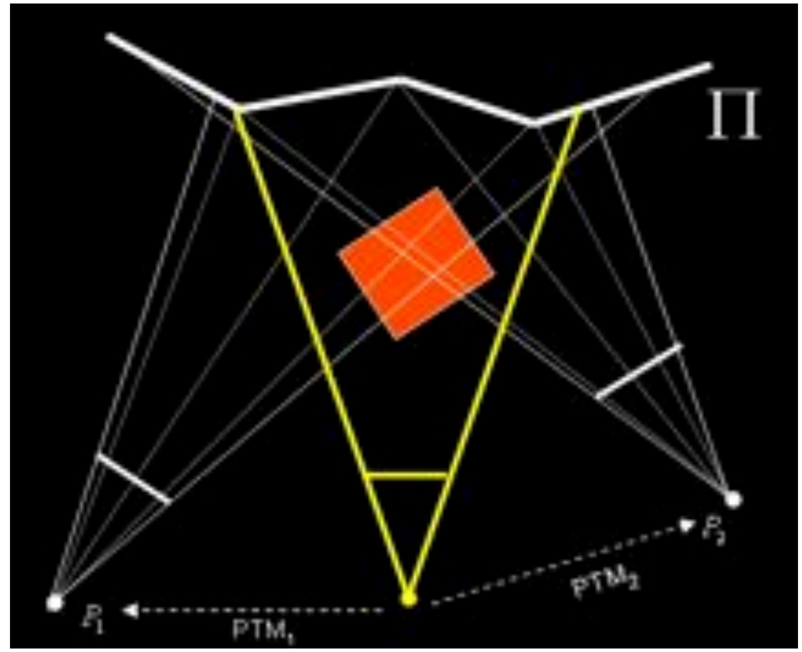
Projective Texture Mapping

Projective Texture Mapping

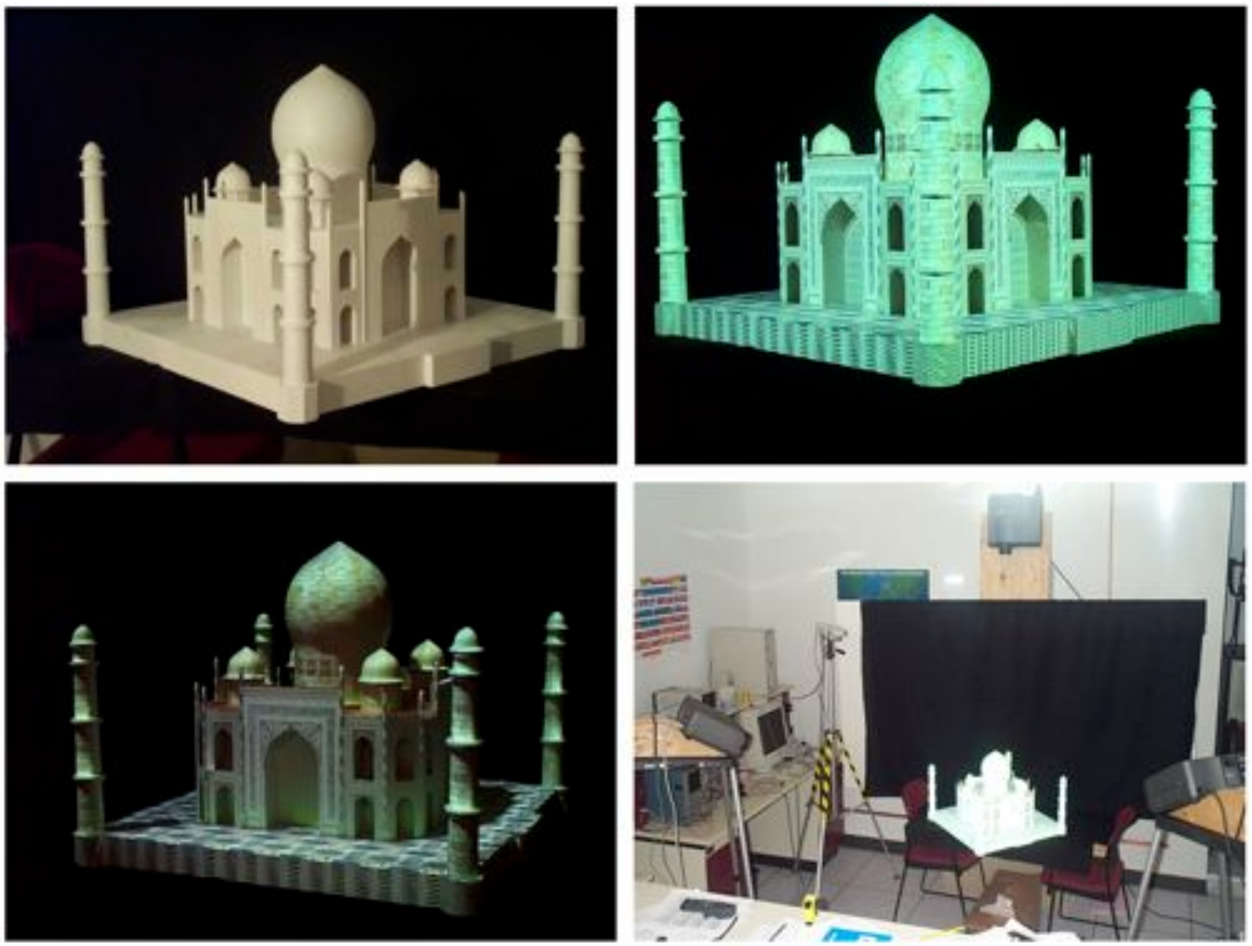
- given a geometric definition of the surface
  - scan or model
- determine intrinsic and extrinsic of projectors with respect to surface
  - measure projections of known 3D surface points on image plane of projector and solve equation system to determine parameters of matrix
- define virtual camera with same parameter for each projector
- render 3D model of surface, textured with images, from perspective of projectors/ virtual cameras
- texture coordinates can be automatically generated from target perspective via projective texture mapping



$$\begin{pmatrix} wx \\ wy \\ wz \\ w \end{pmatrix} = \begin{bmatrix} f & \cdot & \cdot & \cdot \\ \cdot & f & \cdot & \cdot \\ \cdot & \cdot & \cdot & 1 \\ \cdot & \cdot & 1 & \cdot \end{bmatrix} \begin{bmatrix} R_{11} & R_{12} & R_{13} & t_x \\ R_{21} & R_{22} & R_{23} & t_y \\ R_{31} & R_{32} & R_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

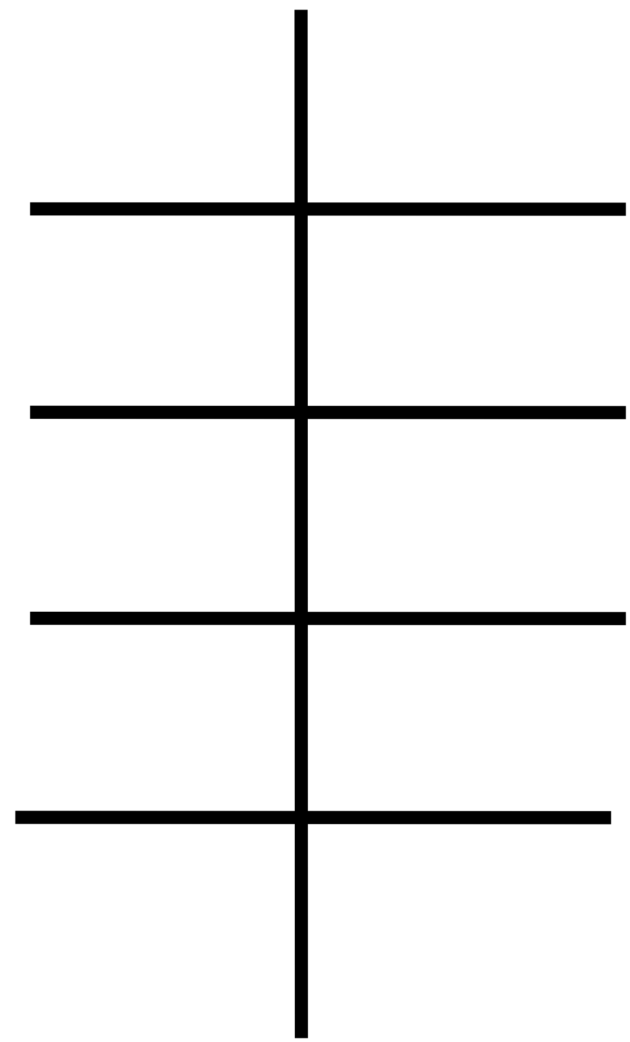
Example: Shader Lamps

Example: Shader Lamps



Courtesy: Raskar, et al., EGRW 2001

Complex Surfaces



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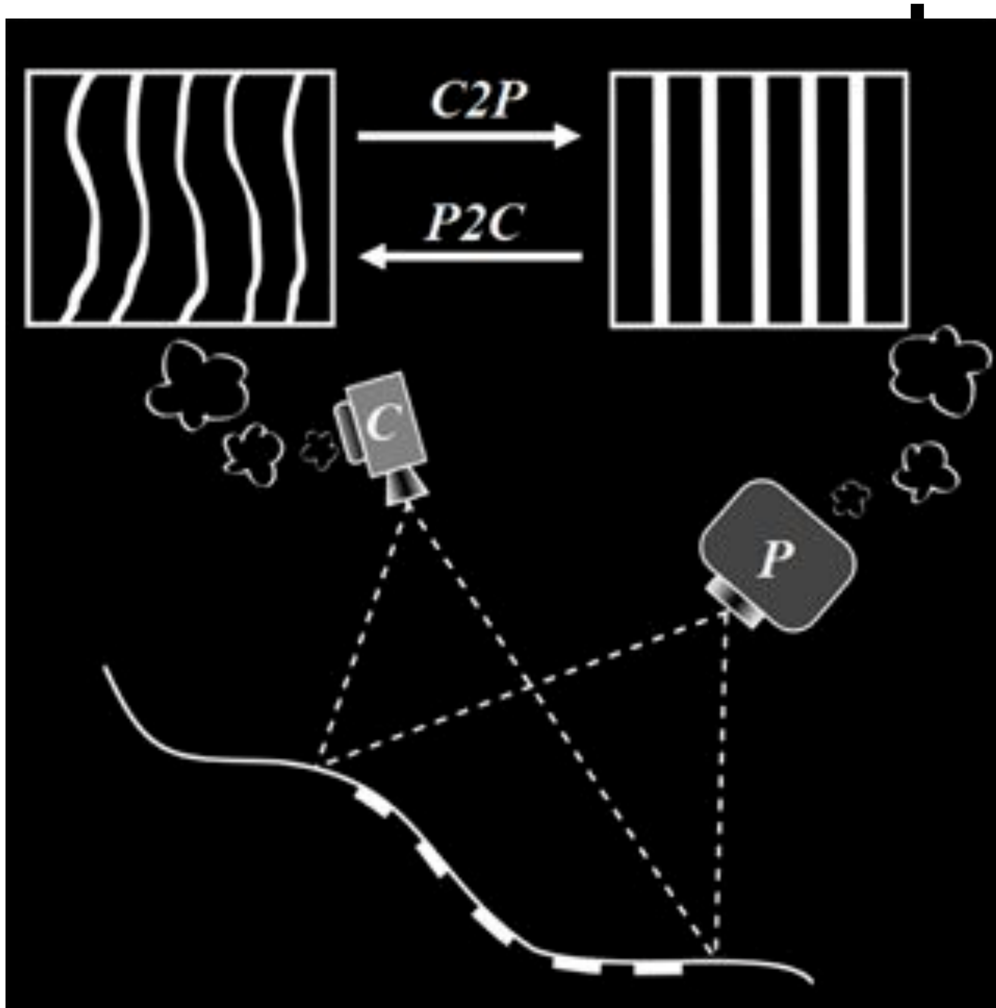
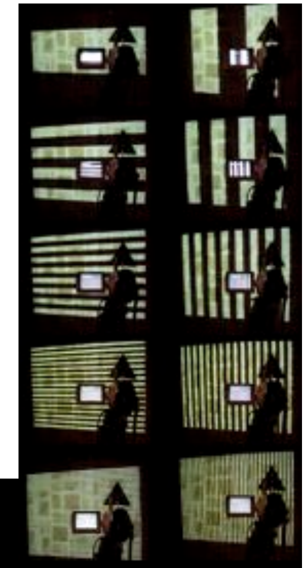
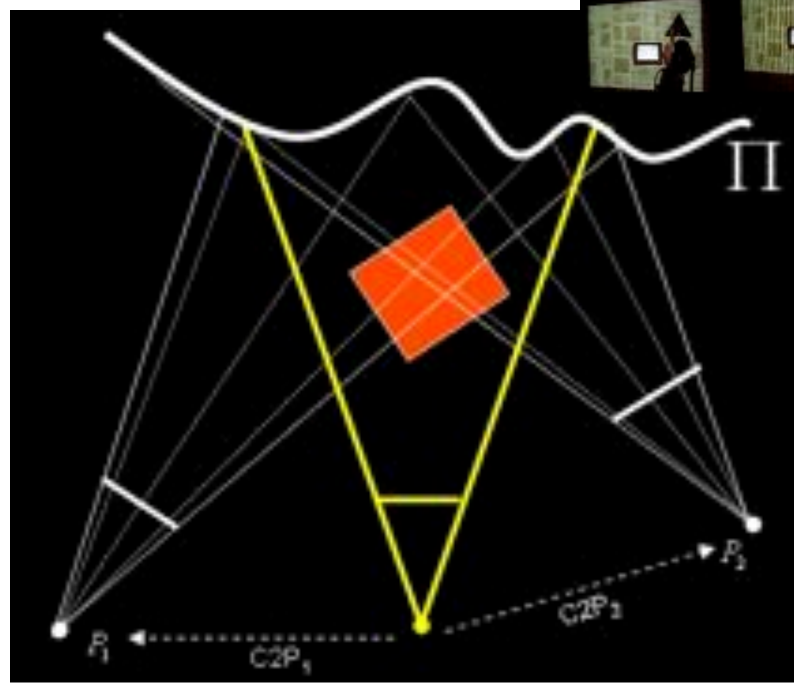


Pixel Displacement Mapping

Pixel Displacement Mapping

- registering projections to such a surface by determining their intrinsic and extrinsic is too imprecise
  - non-linear lens distortion
  - errors in measuring fiducials
- rendering of 3D surface representation from perspective of projector might be to slow
  - high geometric complexity of model
  - many triangles to render
    - project, raster, texture
- measure per-pixel mapping between projector perspectives and target perspective (e.g., camera)
- render image from target perspective and map it (look-up) into perspective of projectors (e.g., pixel-shading)





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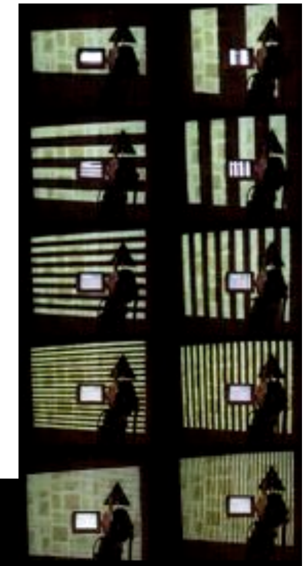
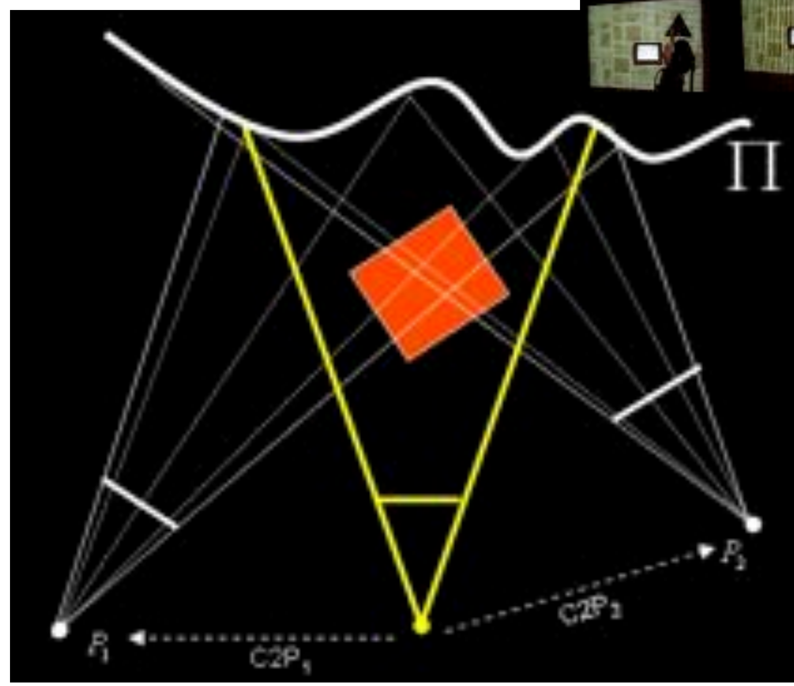
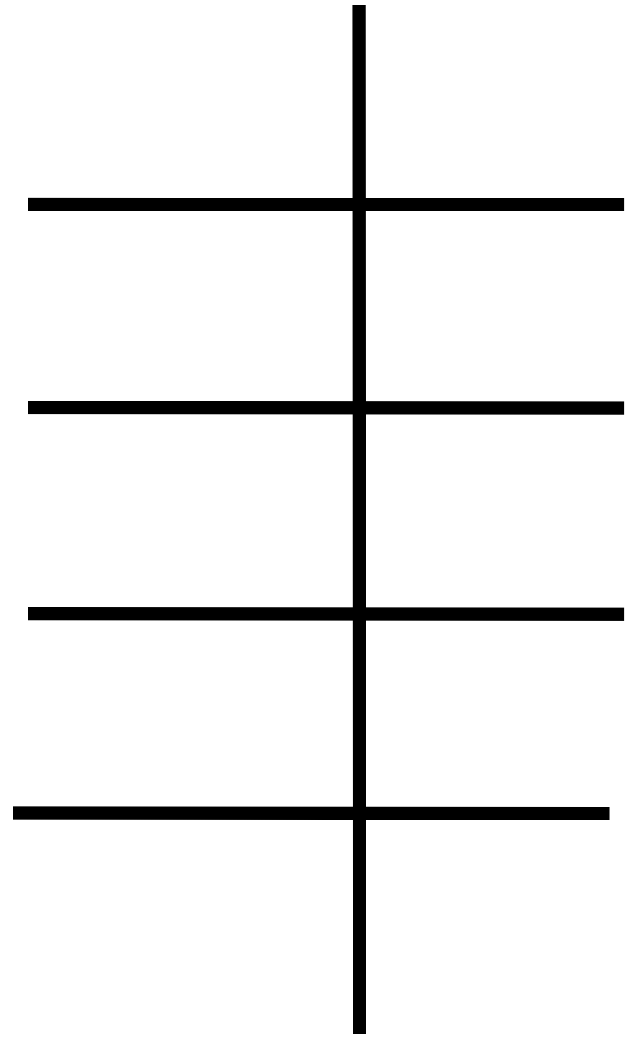
problem:
works only for static target perspective!
(but image-based rendering approaches exist)





Example: Stucco Wall



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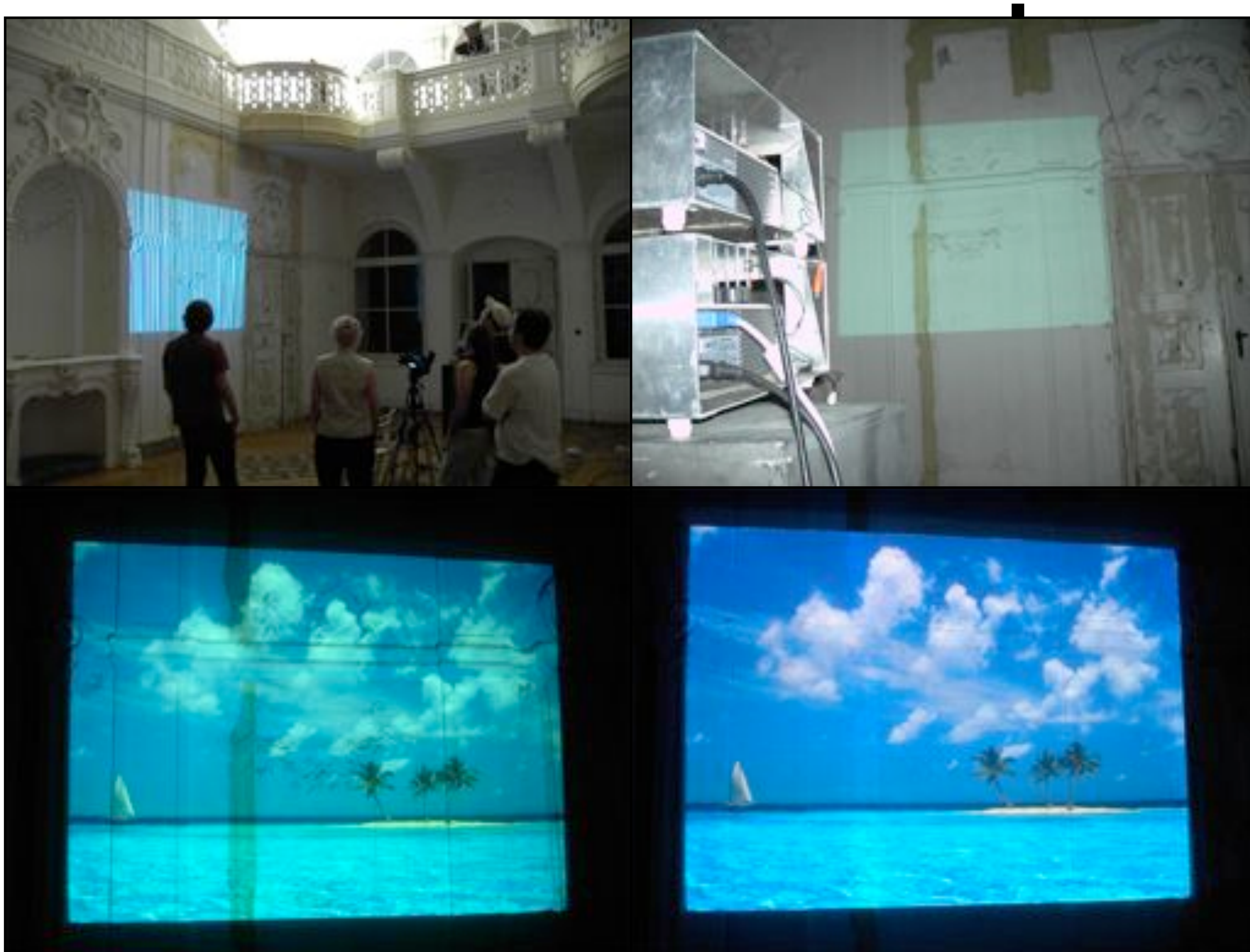
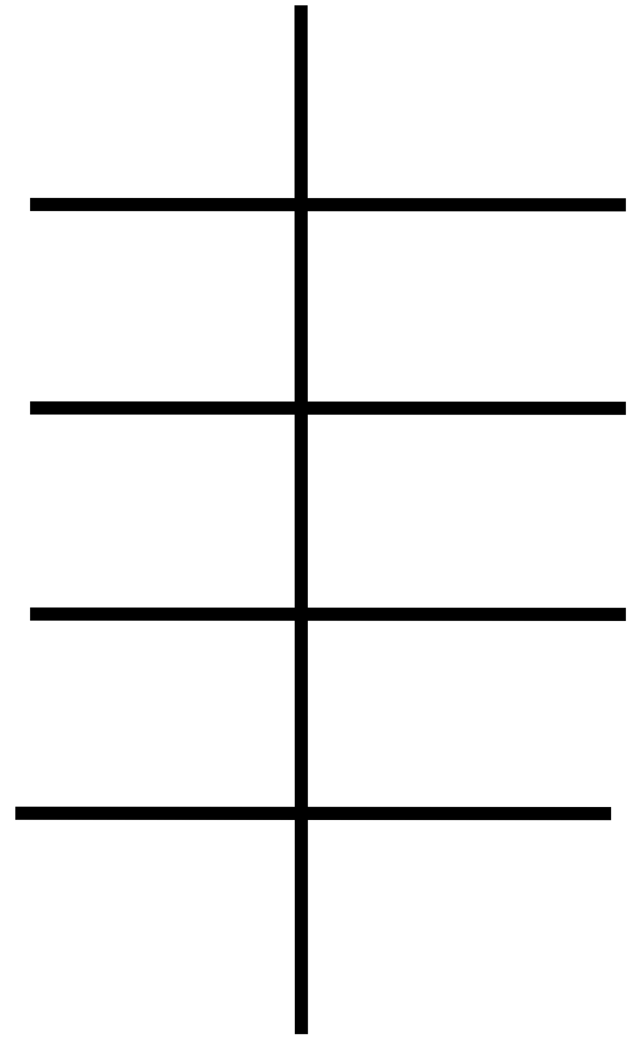


In coop. with castle Ettersburg

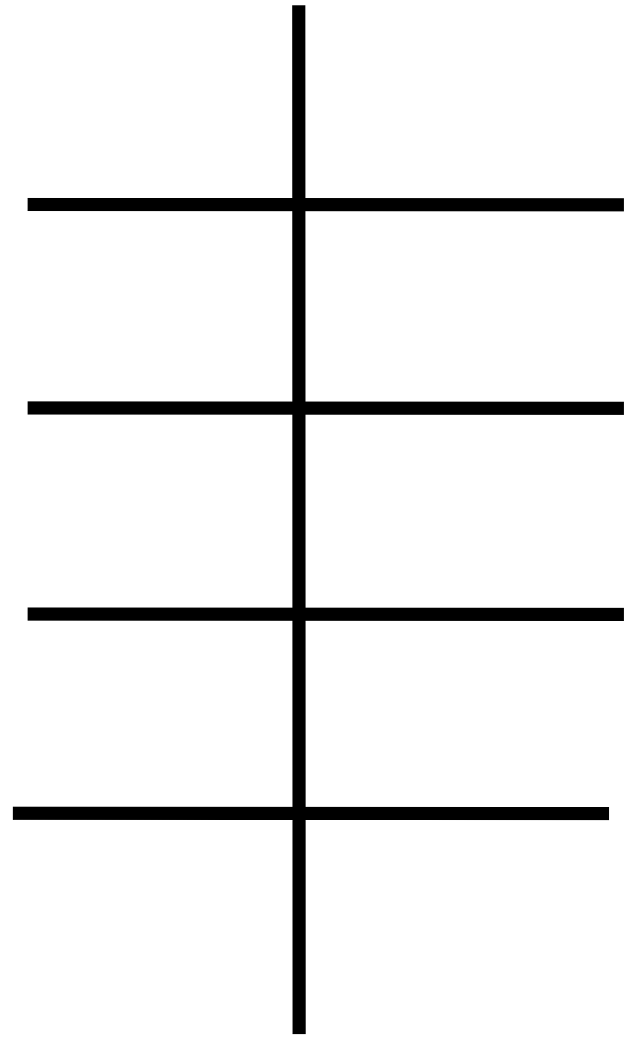
Example: Fossil Cast



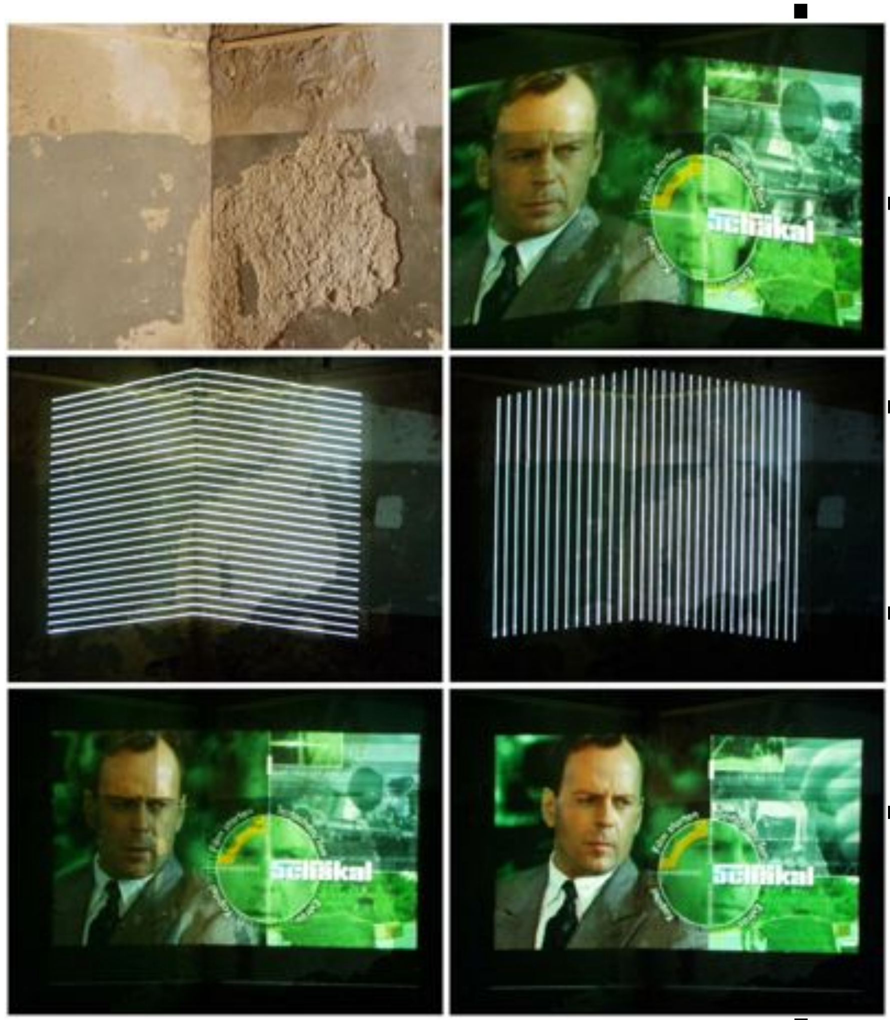
Example: Fossil Cast

In coop. with Senckenberg Museum

Example: Scruffy Room Corner



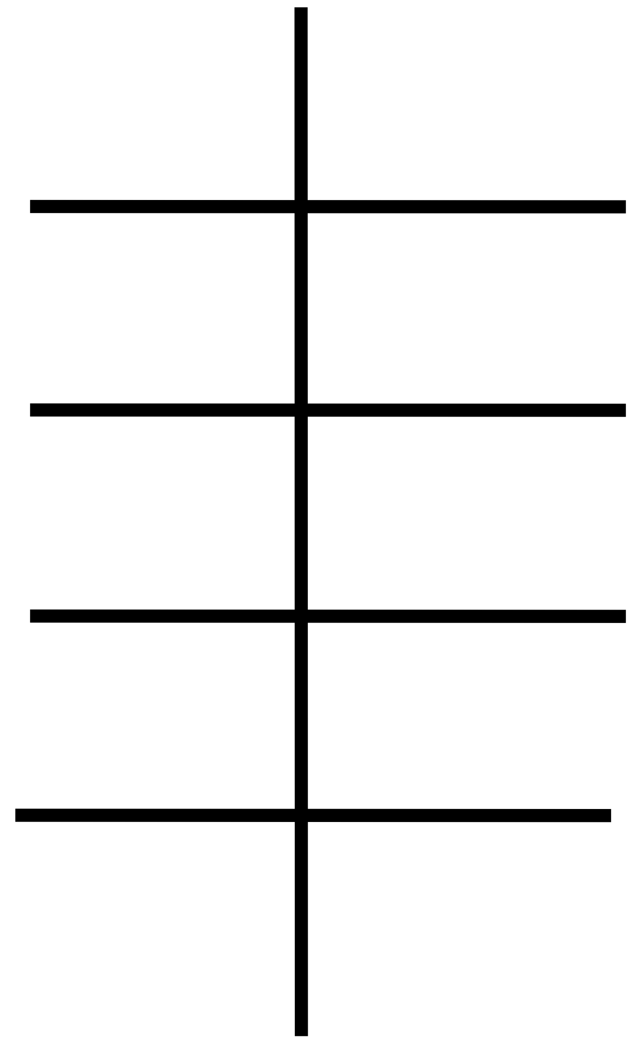
Example: Scruffy Room Corner



Bimber et al.,
IEEE Computer
2005

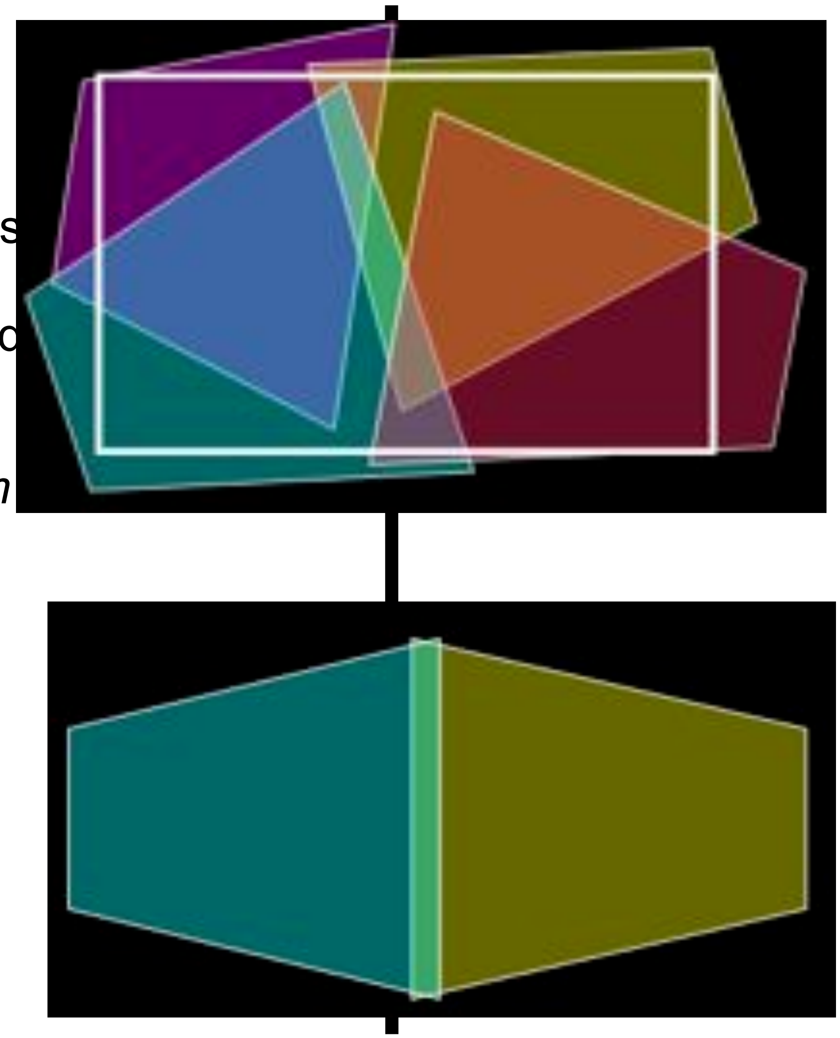
Radiometric Compensation

Photometric Calibration

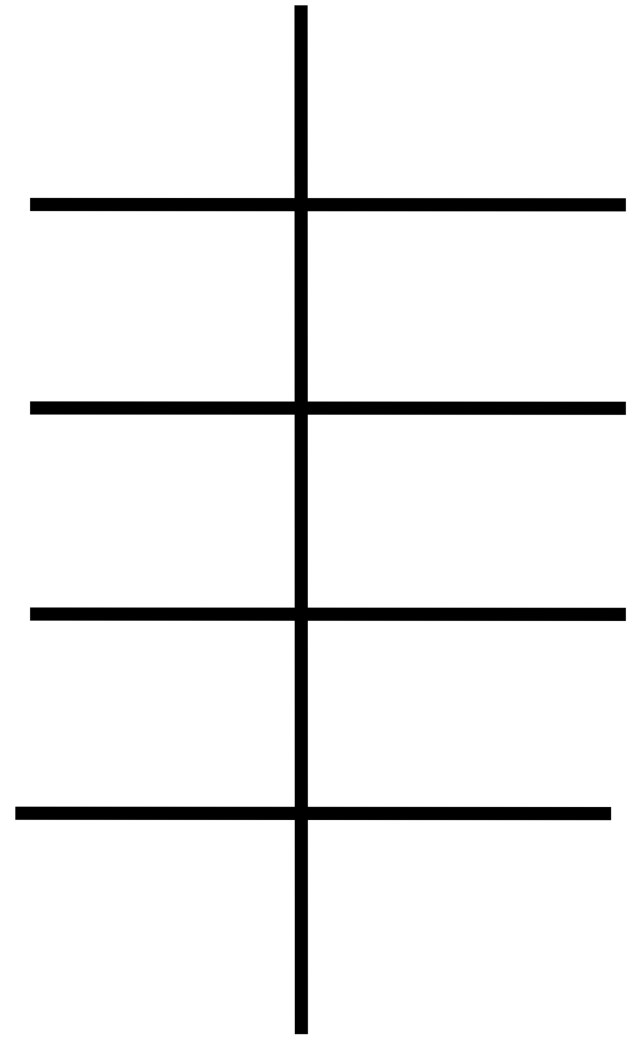


Photometric Calibration

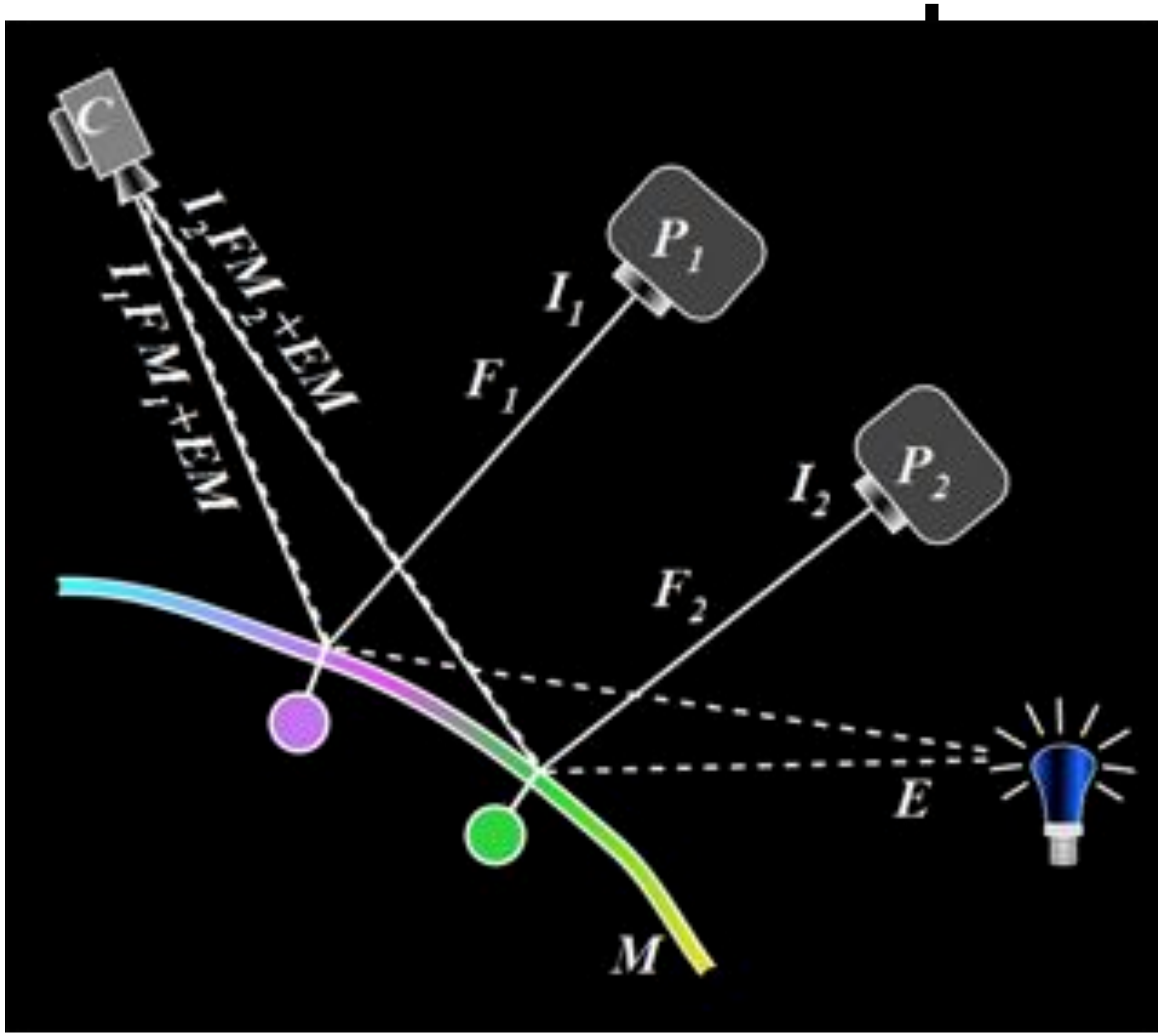
- regions of display surfaces that are illuminated by multiple projectors simultaneously appear brighter
- projectors can have different brightness and can cover a different color space
- result: inconsistent image (intensity and color)
- humans can perceive 2% difference in brightness and a color variation of 2*nm*
- variations in brightness is more critical than variation in color
- solutions: intensity blending and color space mapping
- **these techniques are not explained here!**
- **we assume that projectors and cameras are linearized and color mapped**



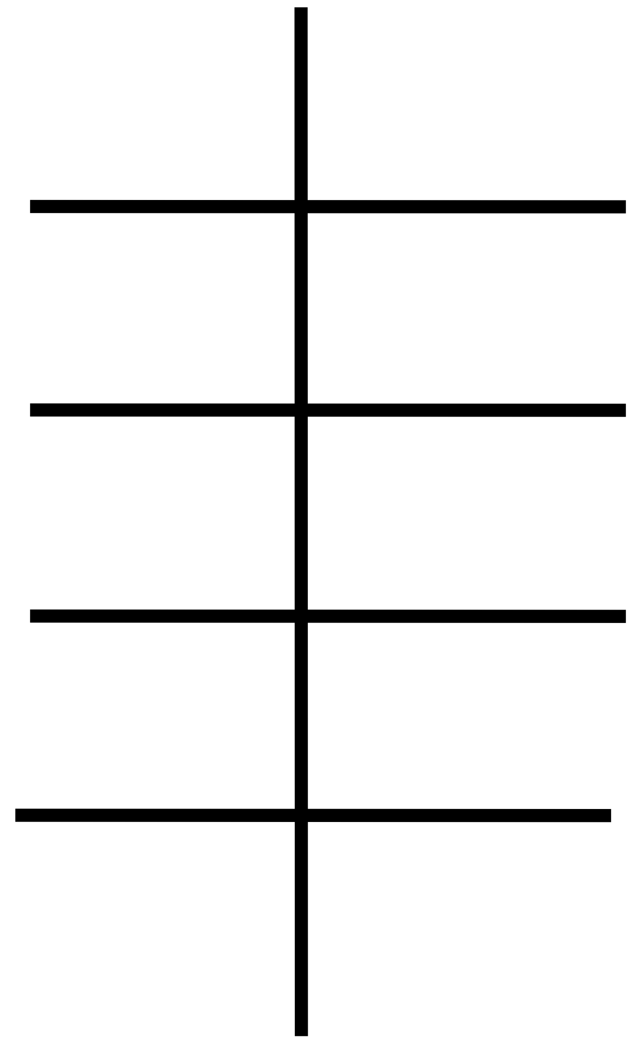
Compensating Local Light Effects



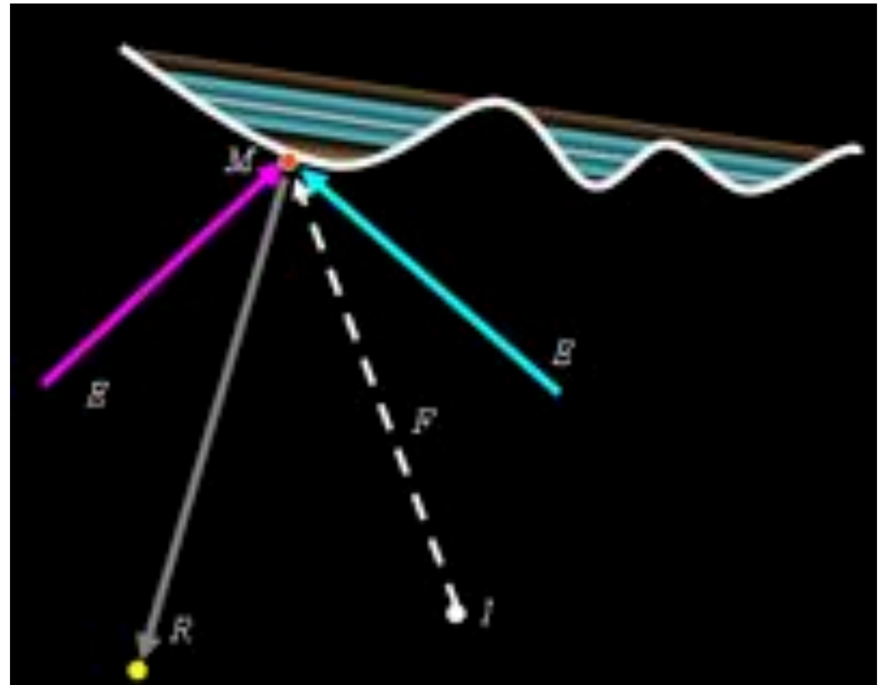
Compensating Local Light Effects



Single Projector



Single Projector

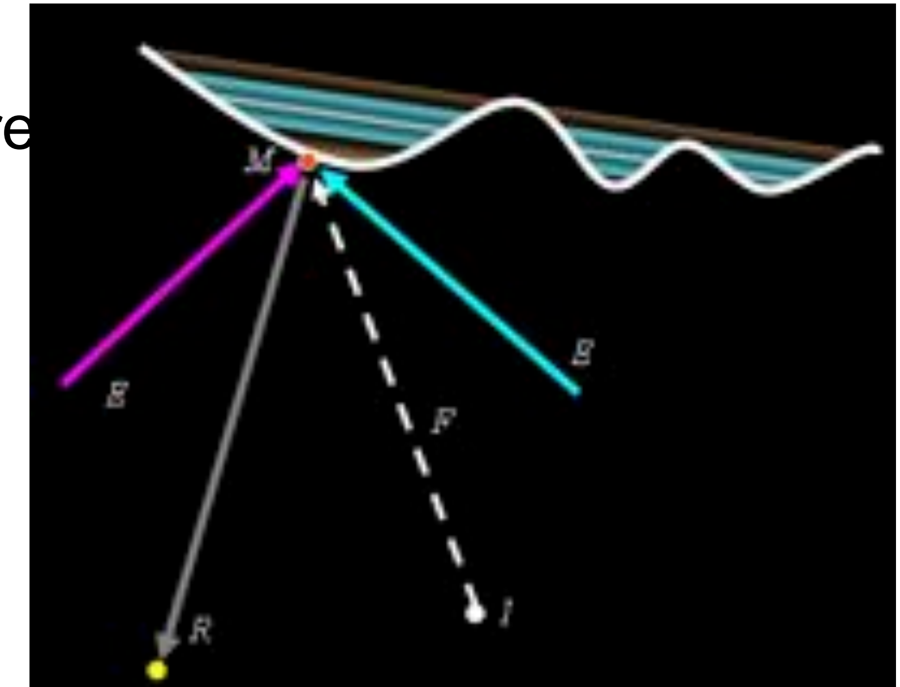


R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture



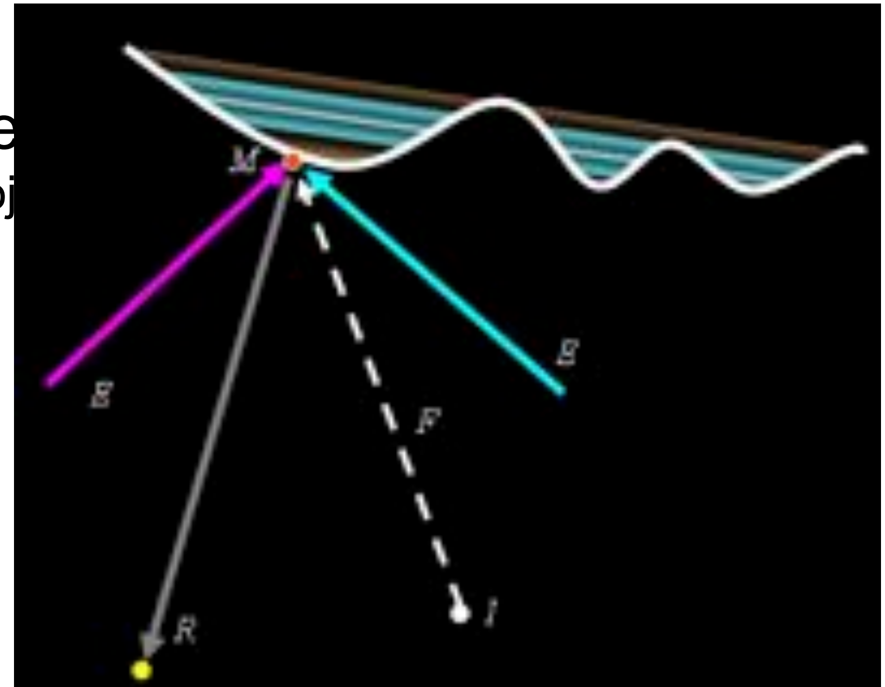
R=IFM+EM

- I → projected image
- B → black-level
- F → projector-2-surface form factor
- E → environment light
- M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image



R=IFM+EM

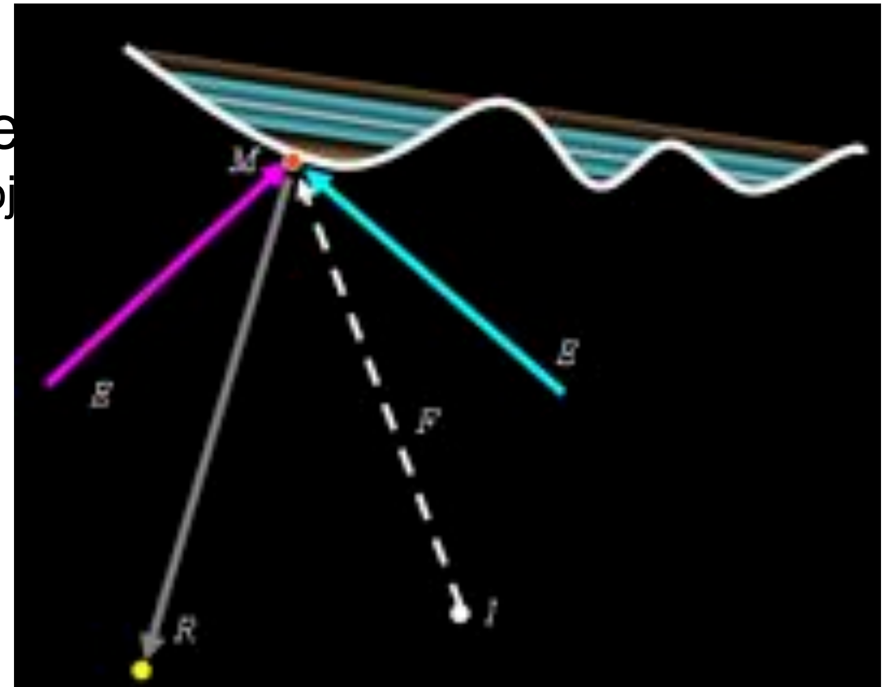
I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

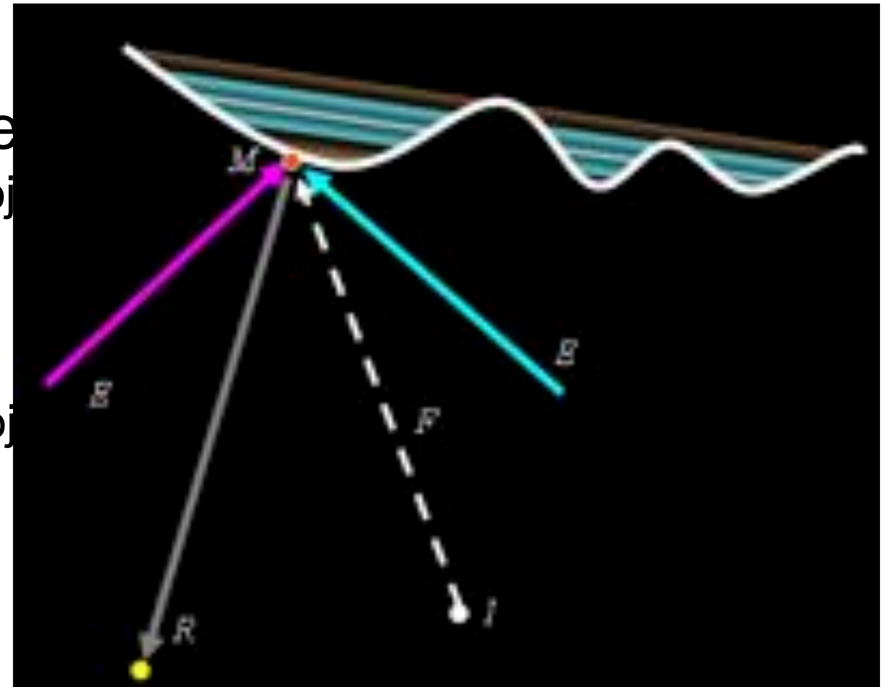
Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

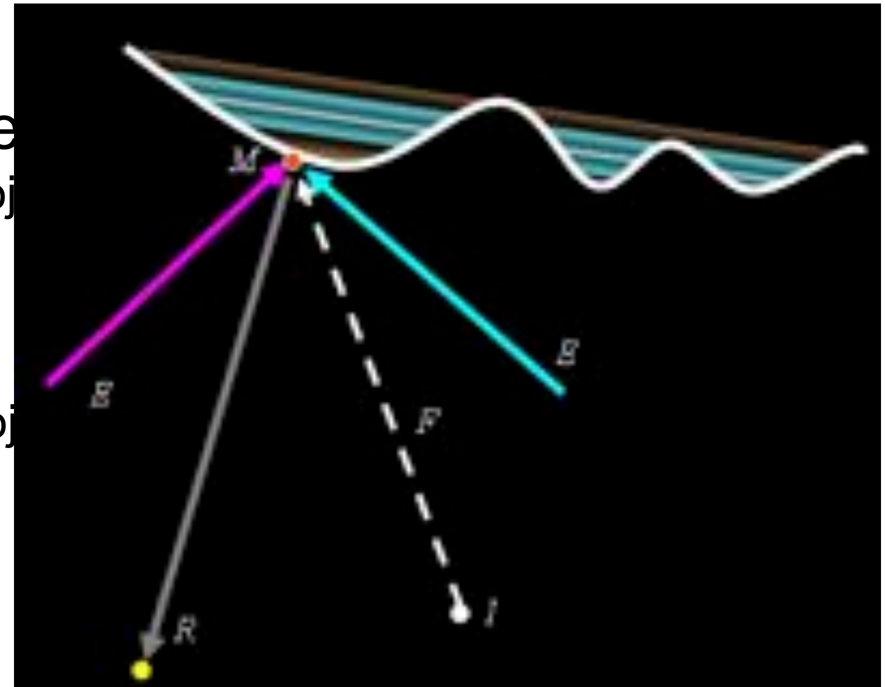
determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

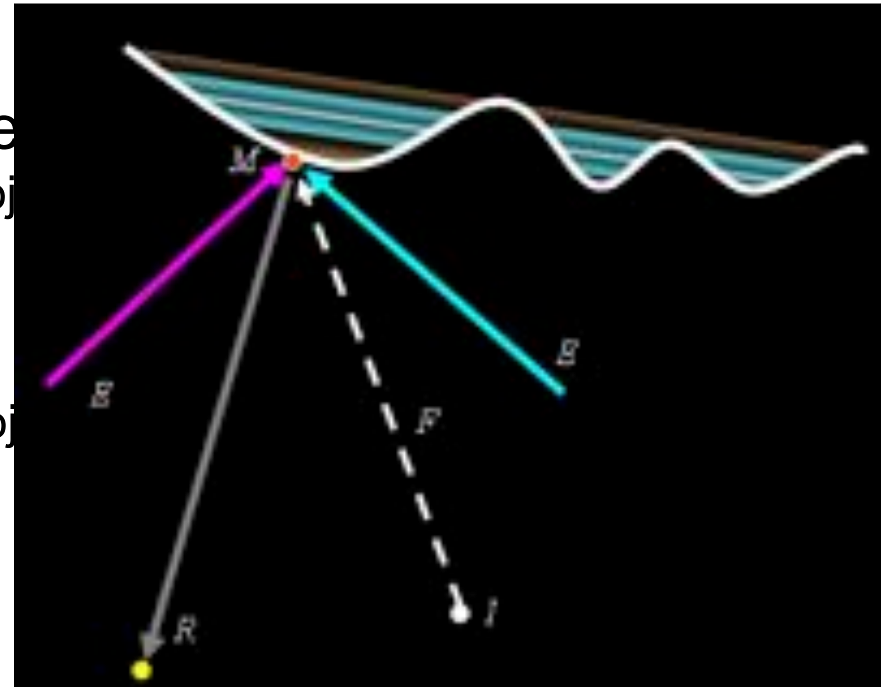
(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

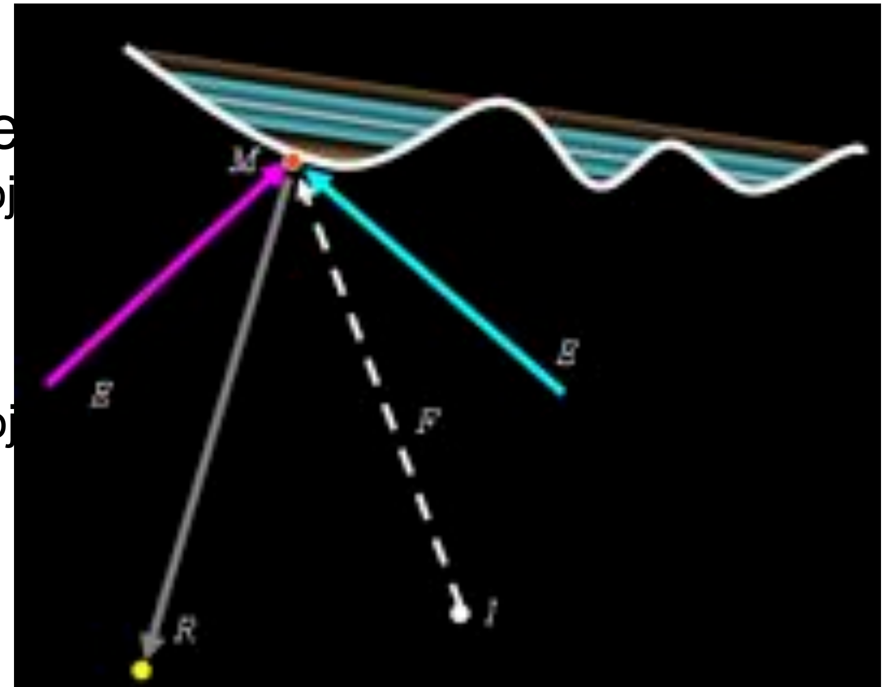
(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and
project white flood image



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

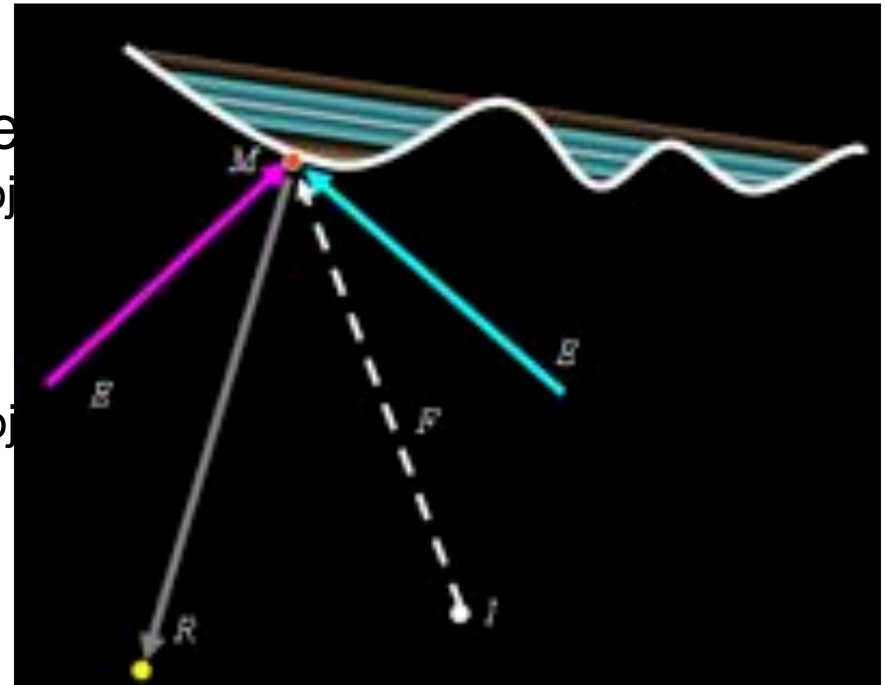
I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and
project white flood image

I=1,E=0 → FM (incl. **BFM !**)



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

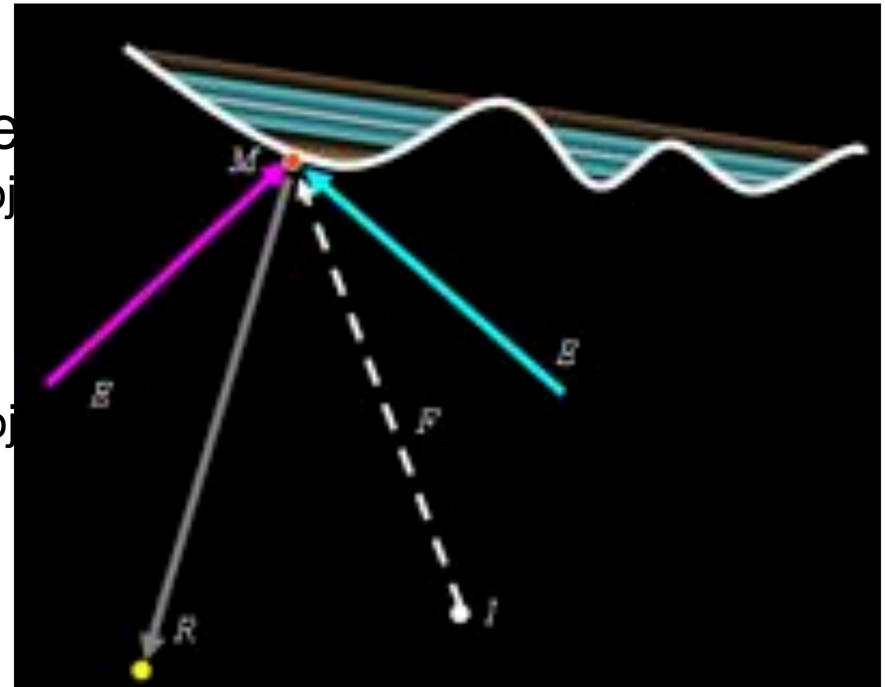
(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and
project white flood image

I=1,E=0 → FM (incl. **BFM !**)

→ FM=FM-BFM



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

(2) turn on environment light and proj
black flood image

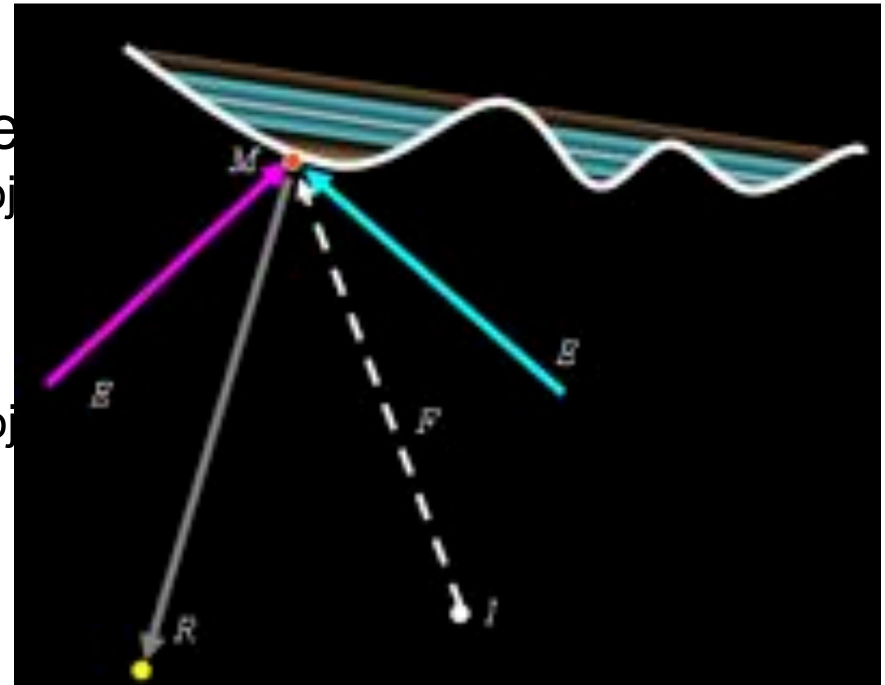
I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and
project white flood image

I=1,E=0 → FM (incl. **BFM !**)

→ FM=FM-BFM

compensation (per pixel):



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

Bimber et al, IEEE Computer 2005

Single Projector

determining parameters (texture

(1) turn off environment light and proj
black flood image

I=0,E=0 → BFM

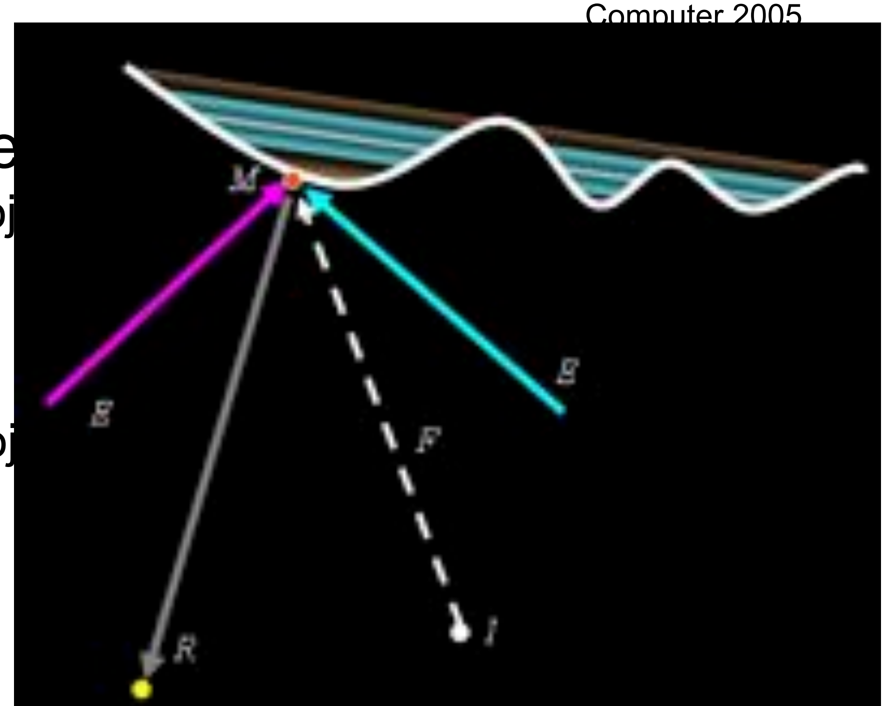
(2) turn on environment light and proj
black flood image

I=0,E=1 → EM (incl. **BFM !**)

(3) turn off environment light and
project white flood image

I=1,E=0 → FM (incl. **BFM !**)

→ FM=FM-BFM



R=IFM+EM

I → projected image
B → black-level
F → projector-2-surface form factor
E → environment light
M → surface reflectance (diffuse)

compensation (per pixel):

I=(R-EM)/(FM)

Color Mixing

Color Mixing

Nayar et al, CVPR 2004

red in red | green in red | blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

R=V*I

I → projected image

V → color mixing matrix (projector/camera/reflectance)

Color Mixing

Nayar et al, CVPR 2004

red in red   green in red   blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix
(projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

red in red | green in red | blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix
(projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

red in red   green in red   blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix
(projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images → least squares

red in red   green in red   blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

- for un-normalized matrix: (camera and projector response must be known and linearized):
  - capture 9+ images → least squares
- for normalized matrix (camera response must be known, projector response can be unknown):

(pe

red in red | green in red | blue in red

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

- for un-normalized matrix: (camera and projector response must be known and linearized):
  - capture 9+ images → least squares
- for normalized matrix (camera response must be known, projector response can be unknown):
  - diagonals are 1 (unknown scaling)

(pe

red in red — green in red — blue in red

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

- for un-normalized matrix: (camera and projector response must be known and linearized):
  - capture 9+ images → least squares
- for normalized matrix (camera response must be known, projector response can be unknown):
  - diagonals are 1 (unknown scaling)
  - off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$

red in red   green in red   blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

- capture 9+ images → least squares

for normalized matrix (camera response must be known, projector response can be unknown):

- diagonals are 1 (unknown scaling)
- off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$
  (since $\mathbf{V_{ii}}$=1, $\mathbf{\Delta I_i=\Delta C_i}$)

red in red — green in red — blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images → least squares

for normalized matrix (camera response must be known, projector response can be unknown):

diagonals are 1 (unknown scaling)

off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$

(since $\mathbf{V_{ii}}=1$, $\mathbf{\Delta I_i=\Delta C_i}$)

capture 6 images **C** (2 per color channel

(pe

red in red   green in red   blue in red

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

- for un-normalized matrix: (camera and projector response must be known and linearized):
  - capture 9+ images → least squares
- for normalized matrix (camera response must be known, projector response can be unknown):
  - diagonals are 1 (unknown scaling)
  - off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$ (since $\mathbf{V_{ii}}=1$, $\mathbf{\Delta I_i=\Delta C_i}$)
  - capture 6 images **C** (2 per color channel to determine deltas)

red in red — green in red — blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images → least squares

for normalized matrix (camera response must be known, projector response can be unknown):

diagonals are 1 (unknown scaling)

off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$

(since $\mathbf{V_{ii}}=1$, $\Delta\mathbf{I_i}=\Delta\mathbf{C_i}$)

capture 6 images **C** (2 per color channel to determine deltas)

red in red | green in red | blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images → least squares

for normalized matrix (camera response must be known, projector response can be unknown):

diagonals are 1 (unknown scaling)

off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$

(since $\mathbf{V_{ii}}=1$, $\mathbf{\Delta I_i=\Delta C_i}$)

capture 6 images **C** (2 per color channel to determine deltas)

(pe

red in red | green in red | blue in red

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

compensation (per pixel):

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

- for un-normalized matrix: (camera and projector response must be known and linearized):
  - capture 9+ images → least squares
- for normalized matrix (camera response must be known, projector response can be unknown):
  - diagonals are 1 (unknown scaling)
  - off-diagonals are $\mathbf{V_{ij}}=\Delta \mathbf{C_j}/\Delta \mathbf{I_i}=\Delta \mathbf{C_j}/\Delta \mathbf{R_i}$ (since $\mathbf{V_{ii}}=1$, $\Delta \mathbf{I_i}=\Delta \mathbf{C_i}$)
  - capture 6 images **C** (2 per color channel to determine deltas)

red in red — green in red — blue in red

(pe

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

→ FM (in un-normalized matrix)

compensation (per pixel):

$\mathbf{I}=\mathbf{V}^{-1}*\mathbf{R}$ (does not consider

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

Nayar et al, CVPR 2004

Color Mixing

determining color mixing matrix V:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images → least squares

for normalized matrix (camera response must be known, projector response can be unknown):

diagonals are 1 (unknown scaling)

off-diagonals are $\mathbf{V_{ij}=\Delta C_j/\Delta I_i=\Delta C_j/\Delta R_i}$

(since $\mathbf{V_{ii}}=1$, $\Delta \mathbf{I_i}=\Delta \mathbf{C_i}$)

capture 6 images **C** (2 per color channel to determine deltas)

red in red   green in red   blue in red

$$V=\begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

(pe

→ FM (in un-normalized matrix)

R=V*I

I → projected image
V → color mixing matrix (projector/camera/reflectance)

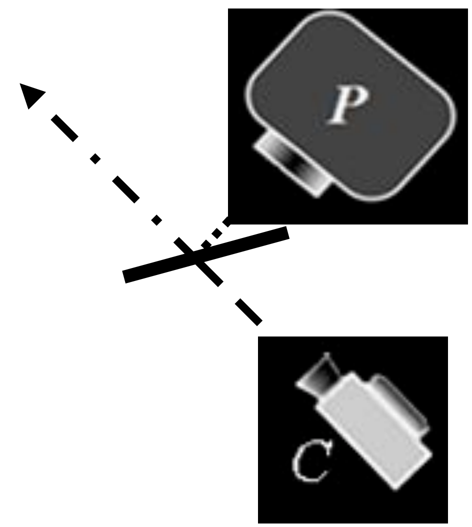
compensation (per pixel):

$\mathbf{I=V^{-1}*R}$ (does not consider environment light!)

Dynamic Adaptation

Dynamic Adaptation

Fujii et al, CVPR 2005



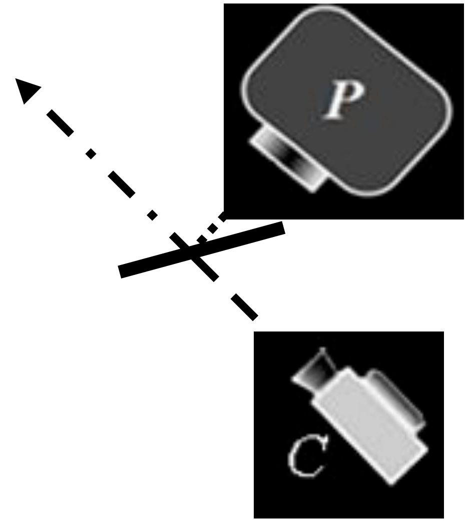
$$R_t=M_t/M_0*(E_t*M_0+V_0*I_t)$$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

Fujii et al, CVPR 2005

Dynamic Adaptation

determining color mixing matrix V_0:



$$R_t=M_t/M_0*(E_t*M_0+V_0*I_t)$$

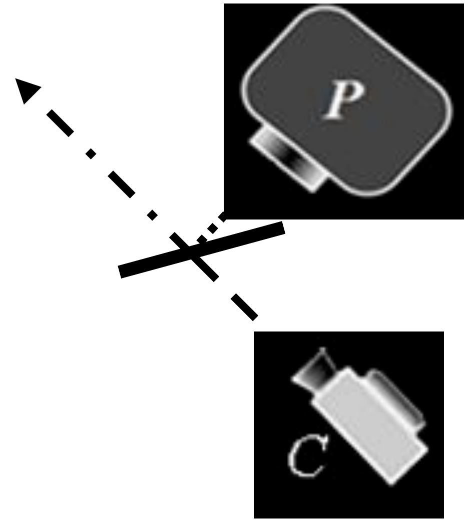
- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

Fujii et al, CVPR 2005

Dynamic Adaptation

determining color mixing matrix V_0:

similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$



$$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

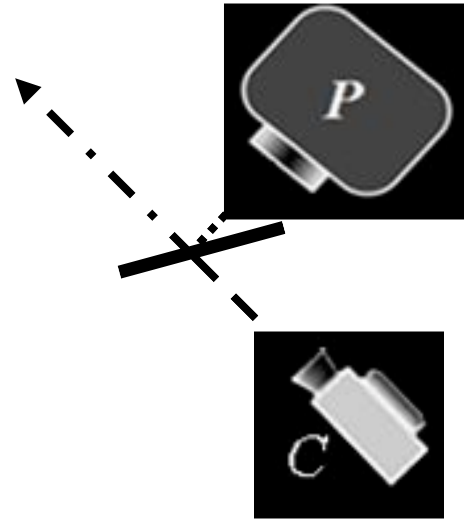
Fujii et al, CVPR 2005

Dynamic Adaptation

determining color mixing matrix V_0:

similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$

(un-normalized!)



$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

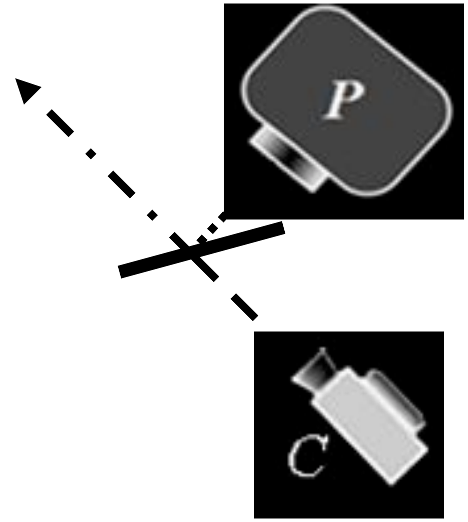
Fujii et al, CVPR 2005

Dynamic Adaptation

determining color mixing matrix V_0:

similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$

(un-normalized!)



determine reflected environment

$$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

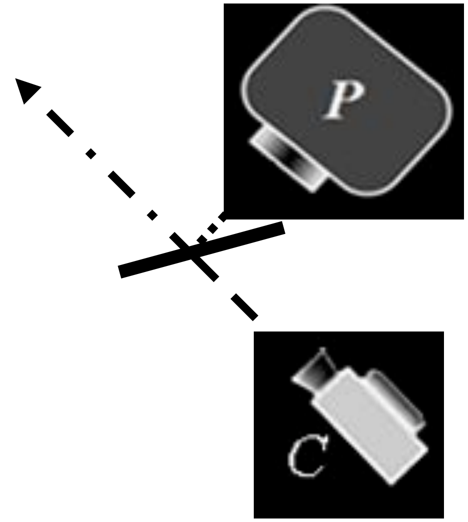
Fujii et al, CVPR 2005

Dynamic Adaptation

determining color mixing matrix V_0:

similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$

(un-normalized!)



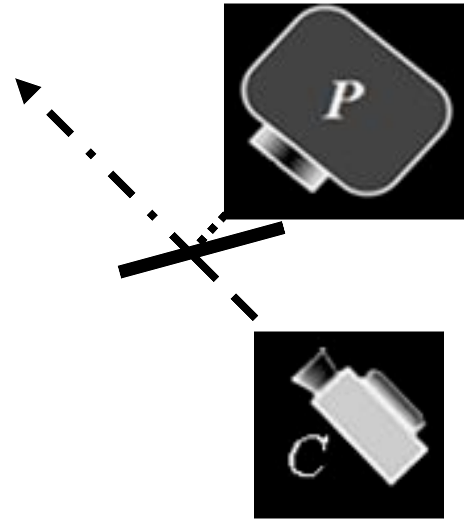
determine reflected environment light $E_0 * M_0$ at t=0:

$$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

Fujii et al, CVPR 2005

Dynamic Adaptation



determining color mixing matrix V_0:

similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$ (un-normalized!)

determine reflected environment light E_0*M_0 at t=0:

$\mathbf{E_0*M_0=C-V_0*I}$ (project

$$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$$

- t → time index
- I_t → projected image at t
- V_0 → un-normalized color mixing matrix at t=0 (const.)
- M_t → material at t
- M_0 → material at t=0
- E_t → environment light at t=0

Fujii et al, CVPR 2005

Dynamic Adaptation

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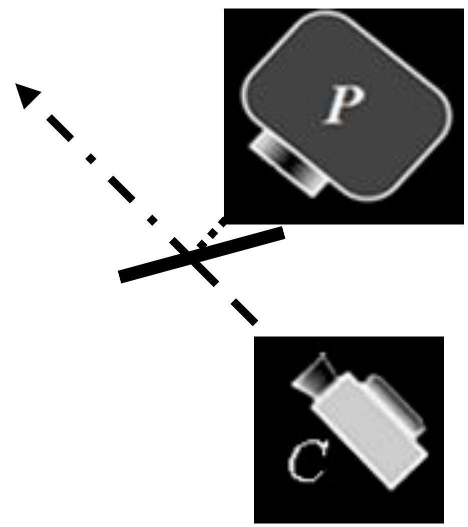

determine reflected environment light E_0*M_0 at t=0:

$\mathbf{E_0*M_0=C-V_0*I}$ (project arbitrary I and capture C)

$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$

- t → time index
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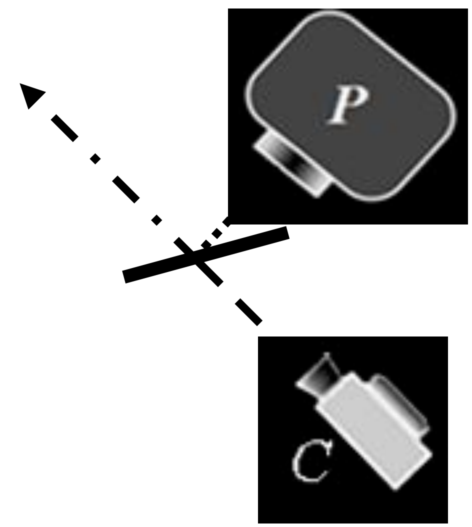
Fujii et al, CVPR 2005

Dynamic Adaptation



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compensation (per pixel at t):

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- t → time index
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Dynamic Adaptation

Fujii et al, CVPR 2005

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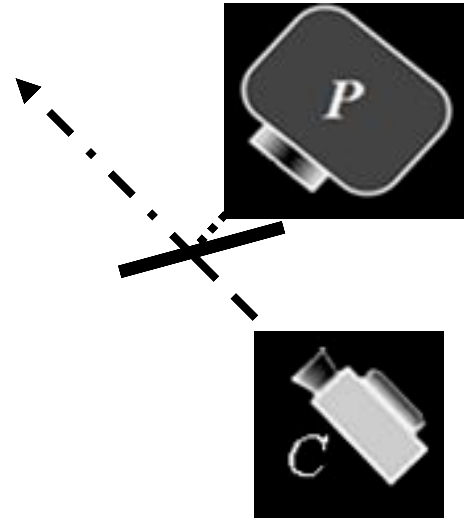

determine reflected environment light $E_0{*}M_0$ at t=0:

$\mathbf{E_0{*}M_0=C-V_0{*}I}$ (project arbitrary I and capture C)

compensation (per pixel at t):

$\mathbf{I_t=V_0^{-1}{*}(R{*}M_0/M_{t-1}-E_{t-1}{*}M_0)}$

$\mathbf{R_t=M_t/M_0{*}(E_t{*}M_0+V_0{*}I_t)}$

- t → time index
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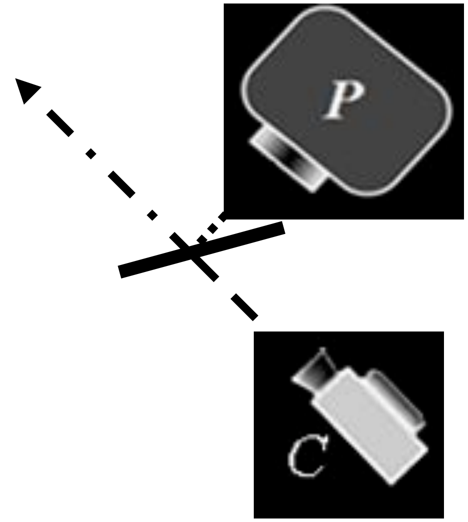
Fujii et al, CVPR 2005

Dynamic Adaptation



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similar as before: $\mathbf{V_{ij}=\Delta C_j/\Delta I_i}$ (un-normalized!)

determine reflected environment light E_0*M_0 at t=0:

$\mathbf{E_0*M_0=C-V_0*I}$ (project arbitrary I and capture C)

compensation (per pixel at t):

$\mathbf{I_t=V_0^{-1}*(R*M_0/M_{t-1}-E_{t-1}*M_0)}$

$\rightarrow \mathbf{E_{t-1}*M_0}$ **approx.** $\mathbf{E_0*M_0}$

$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$

- t → time index
- I_t → projected image at t
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Fujii et al, CVPR 2005

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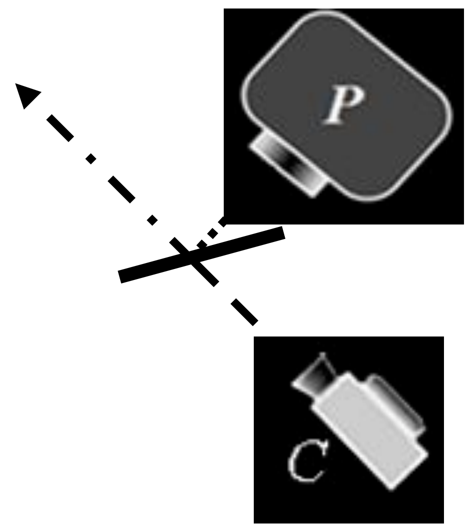

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→ $\mathbf{E_{t-1}*M_0}$ **approx.** $\mathbf{E_0*M_0}$

→ $\mathbf{M_0/M_{t-1}= C_0/C_{t-1}}$

$\mathbf{R_t=M_t/M_0*(E_t*M_0+V_0*I_t)}$

- t → time index
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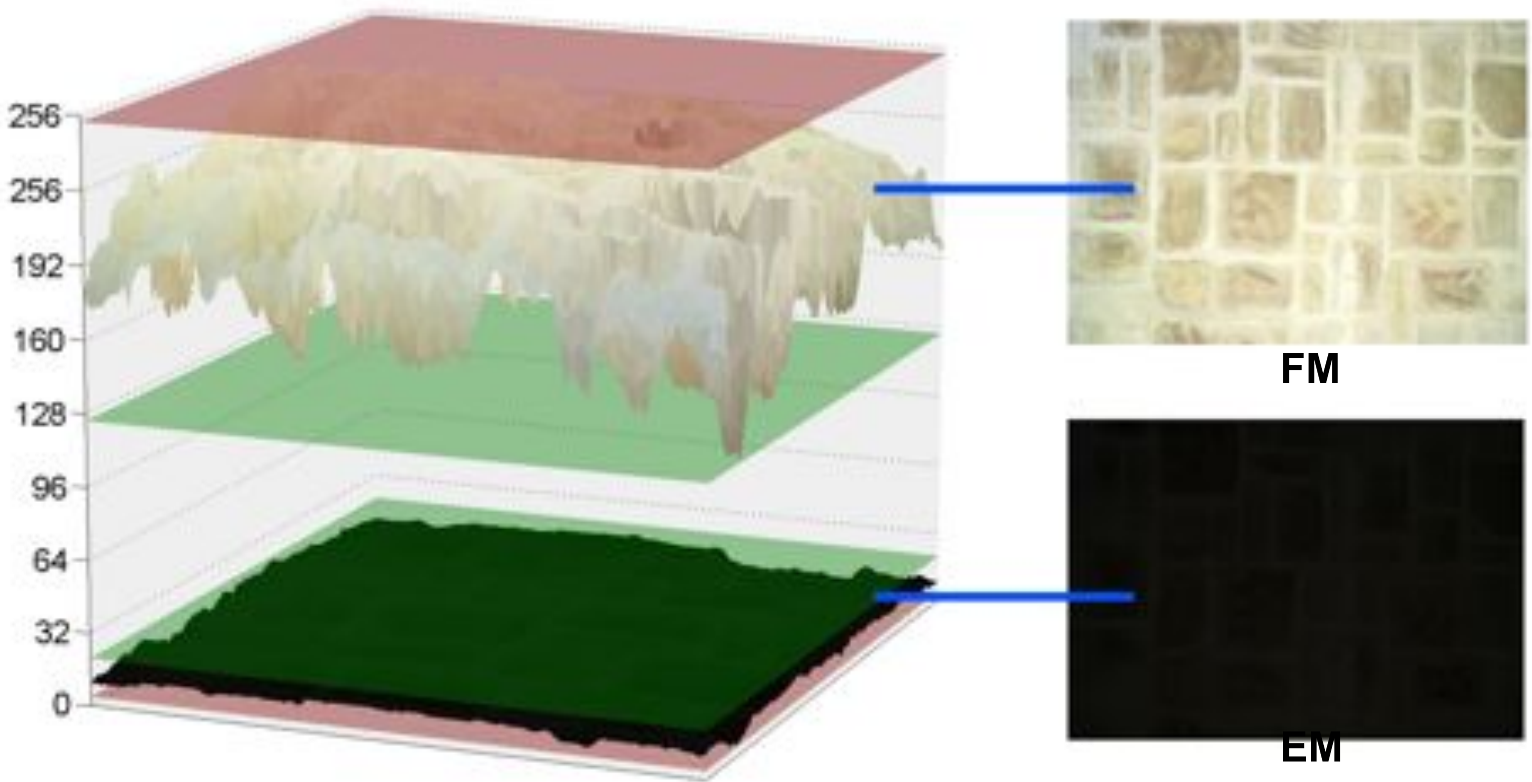
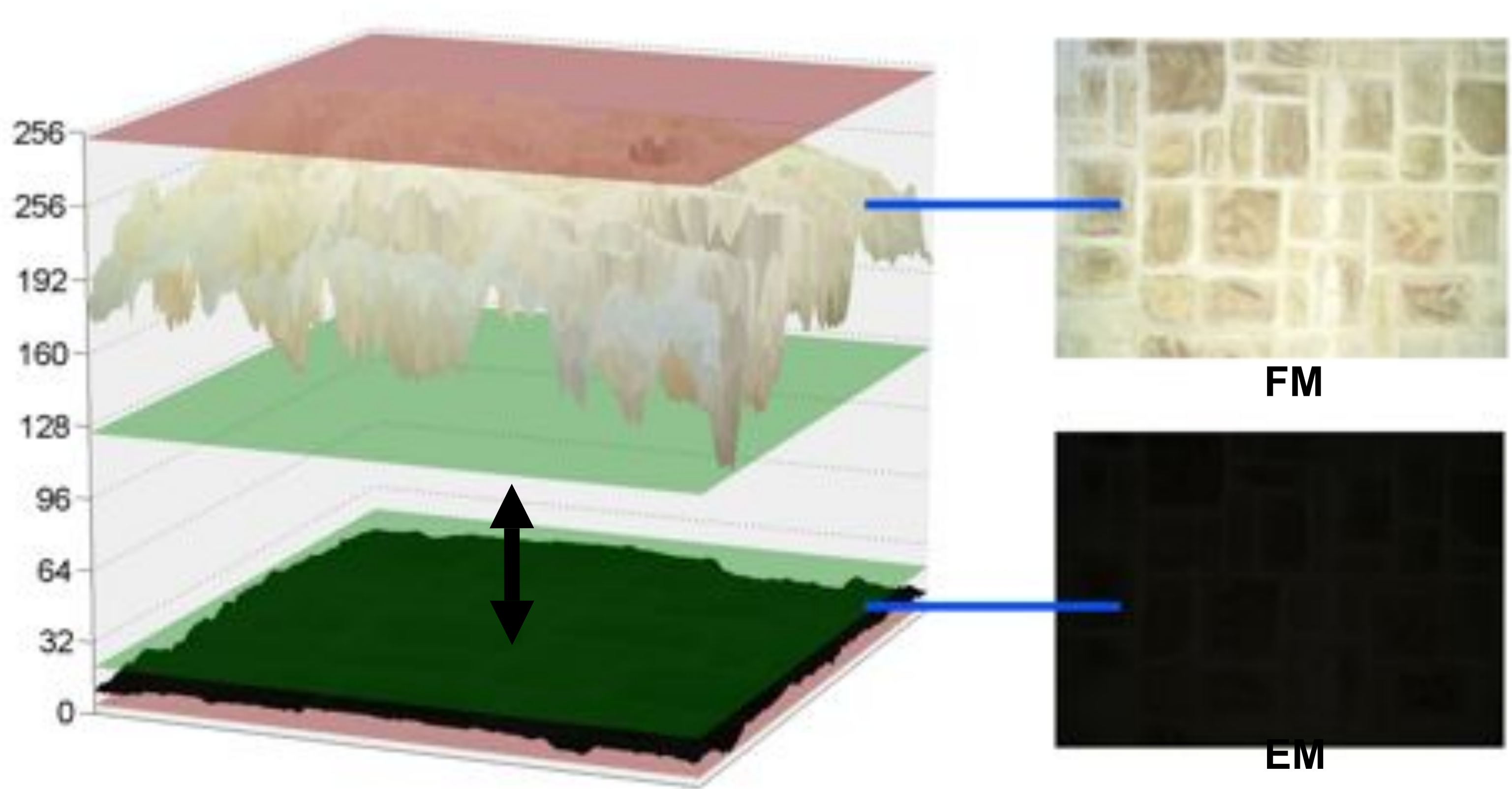
Limited Dynamic Range and Brightness

Limited Dynamic Range and Brightness

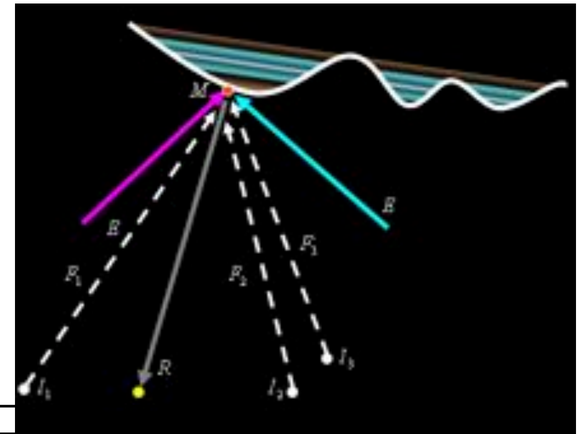


Limited Dynamic Range and Brightness



Multiple Projectors

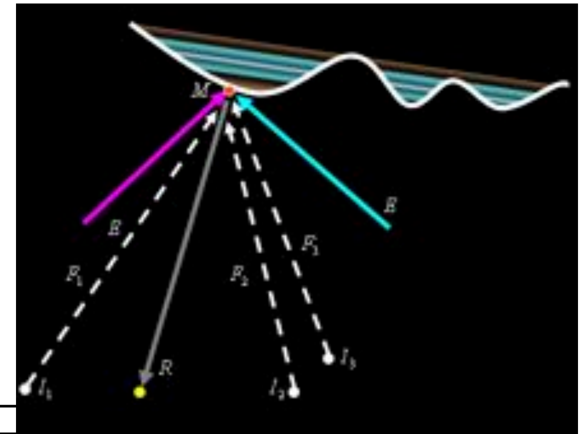
Multiple Projectors



$$R = EM + I_1F_1M + I_2F_2M + \; + I_NF_NM$$

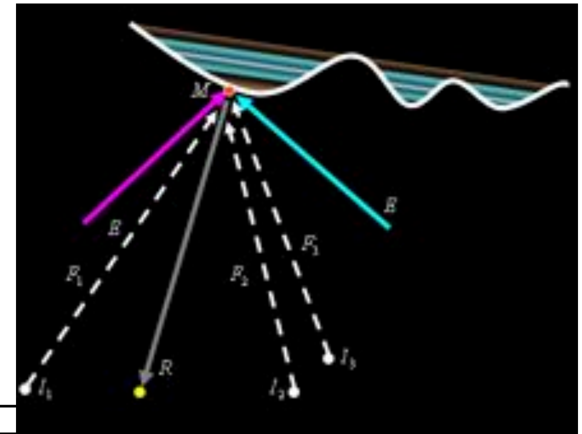
Multiple Projectors

strategy: balance intensity load



$$R = EM + I_1F_1M + I_2F_2M + \dots + I_NF_NM$$

Multiple Projectors



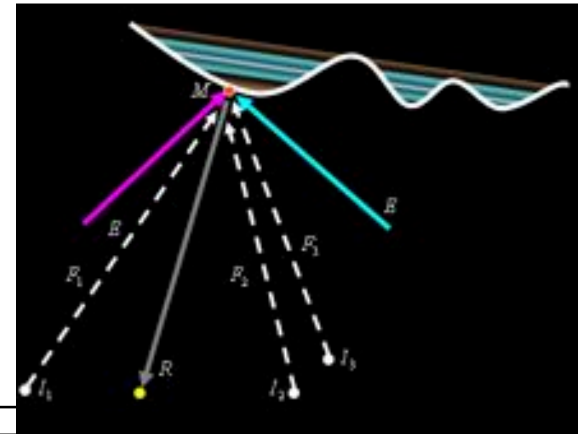
strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units

$$I_i = I_1 = I_2 = \ldots = I_N$$

$$R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM$$

Multiple Projectors



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$$I_i = I_1 = I_2 = \ldots = I_N$$

$$R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM$$

$$R = EM + I_i(F_1M + F_2M + \ldots + F_NM)$$

$$\rightarrow EM + I(F_1 + F_2 + \ldots F_N)M$$

Multiple Projectors

strategy: balance intensity load

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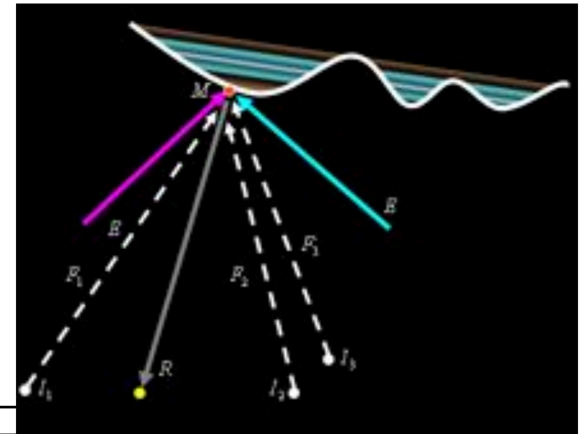

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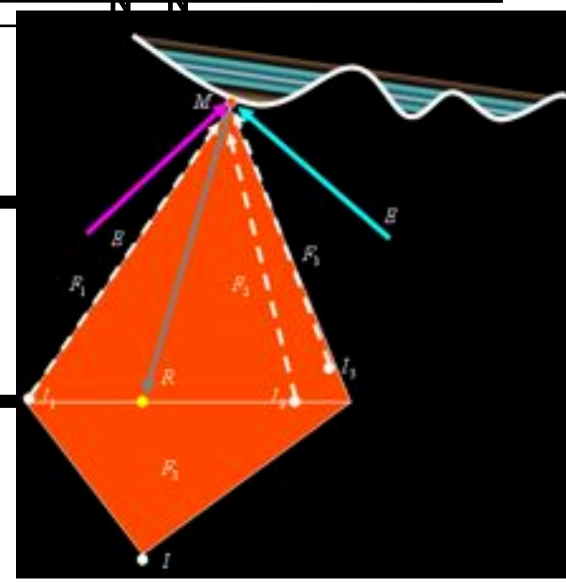


Multiple Projectors

strategy: balance intensity load

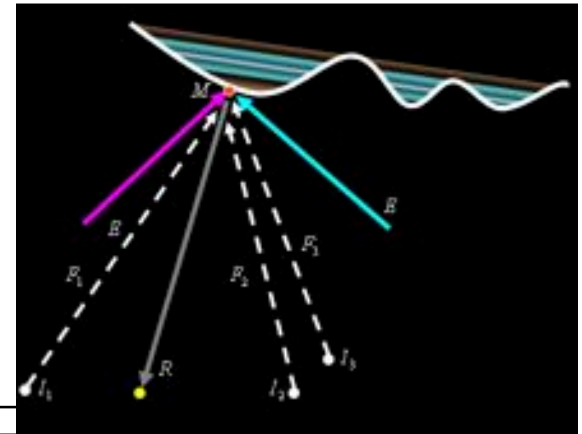
- assume: total intensity is equally balanced among multiple low-capacity units

  $I_i = I_1 = I_2 = \ldots = I_N$

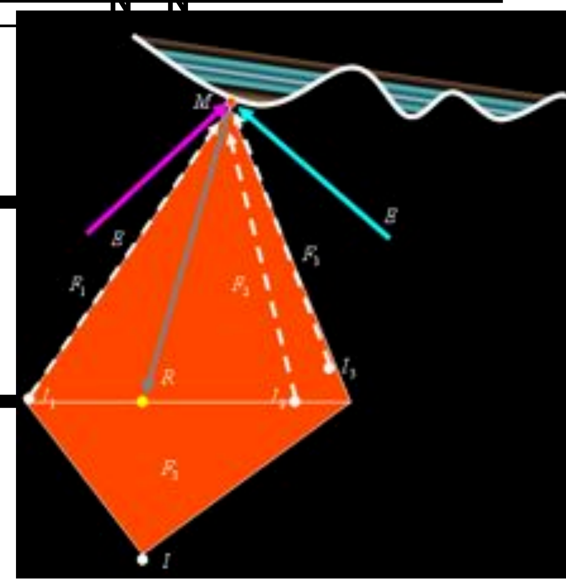
- this is equivalent to the assumption that a single high capacity projector produces the total intensity arriving on the surface virtually

  $R = EM + I_i(F_1M + F_2M + \ldots + F_NM)$

  $\rightarrow EM+I(F_1+F_2+\ldots F_N)M$



$R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM$



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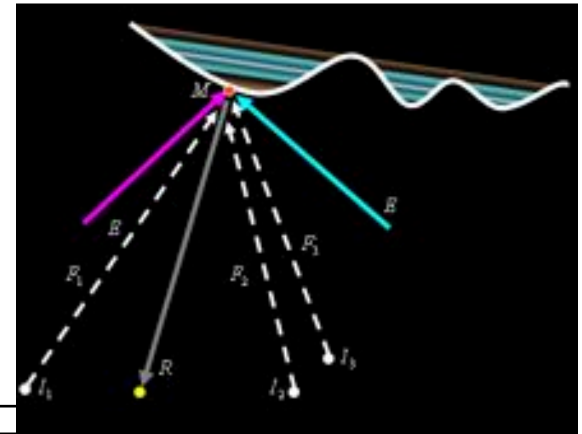

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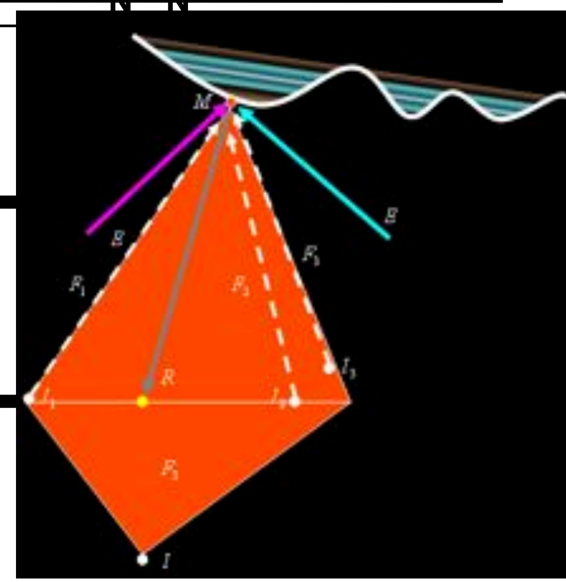

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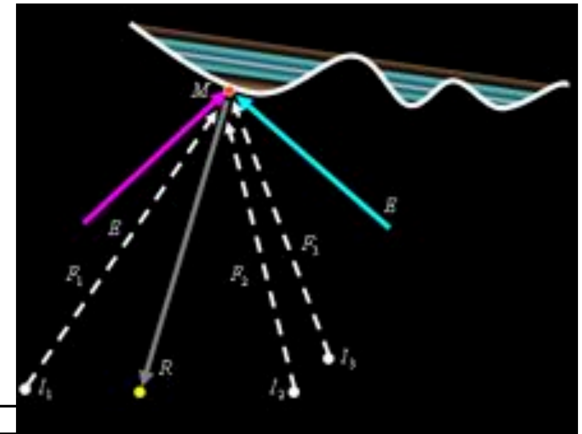

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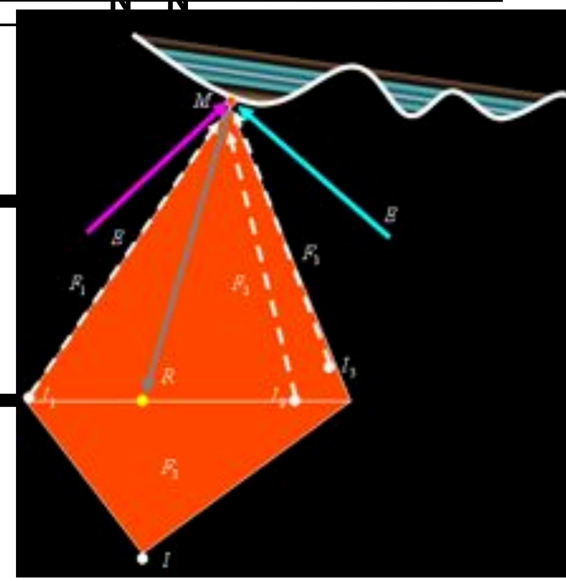

compensation (per pixel):

Multiple Projectors

strategy: balance intensity load

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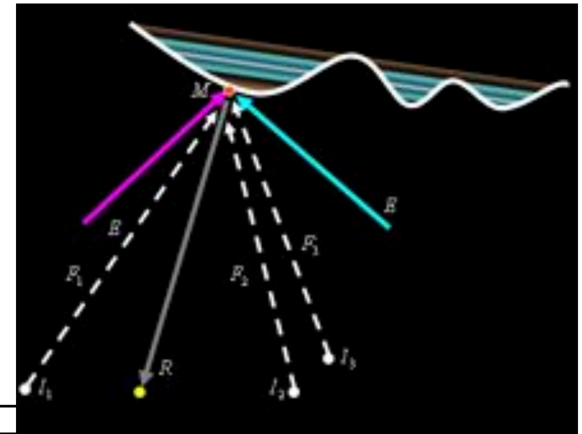

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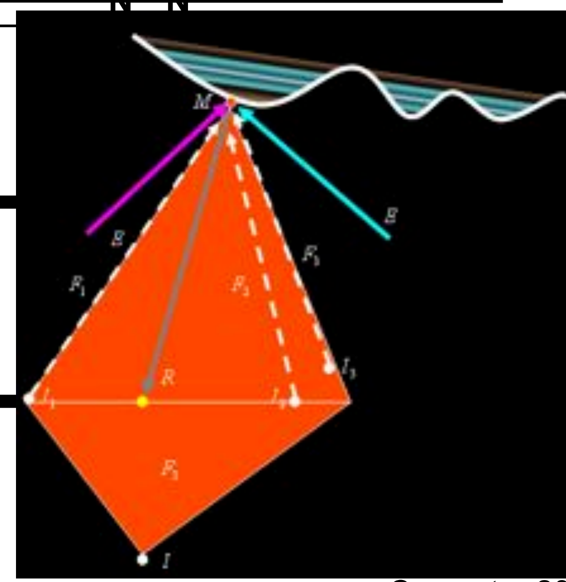


compensation (per pixel):

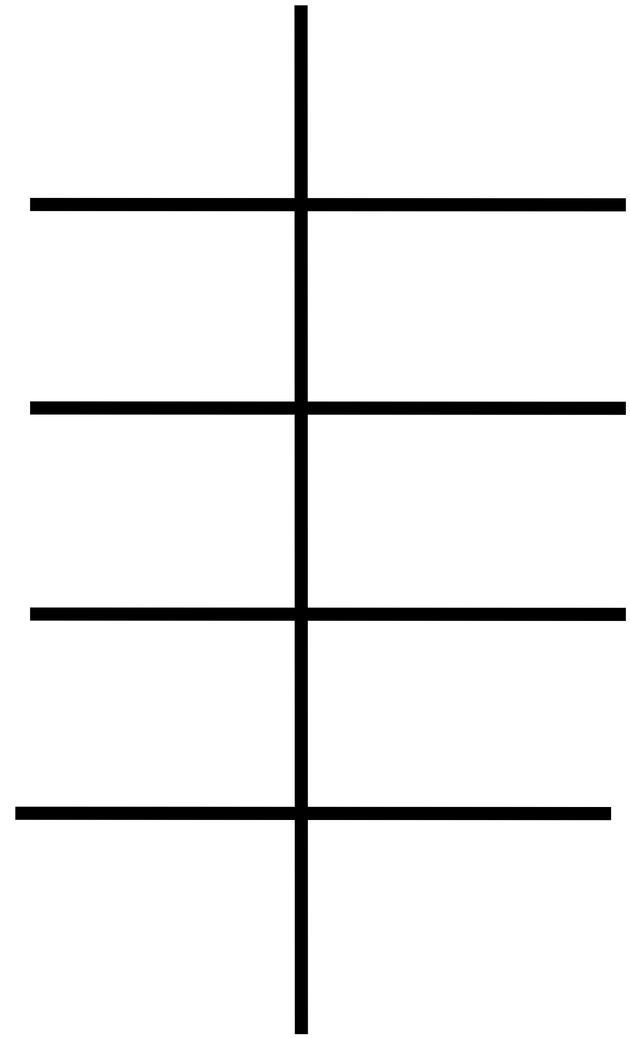
$I_i = (R\text{-}EM)/(F_1M + F_2M + \ldots + F_NM)$

remember: $F_iM=F_iM\text{-}B_iF_iM$!

or $BFM=B_1F_1M+\ldots+B_iF_iM$

IEEE Computer 2005

Considering Human Visual Perception



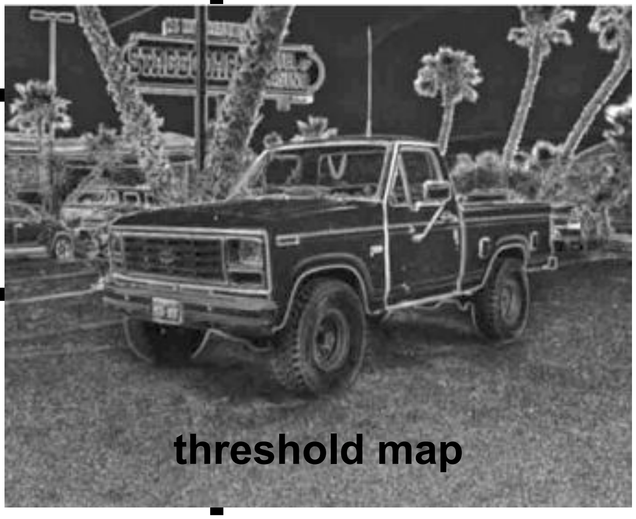
Considering Human Visual Perception

threshold map (Ramasubramanian et al. Siggraph'99)

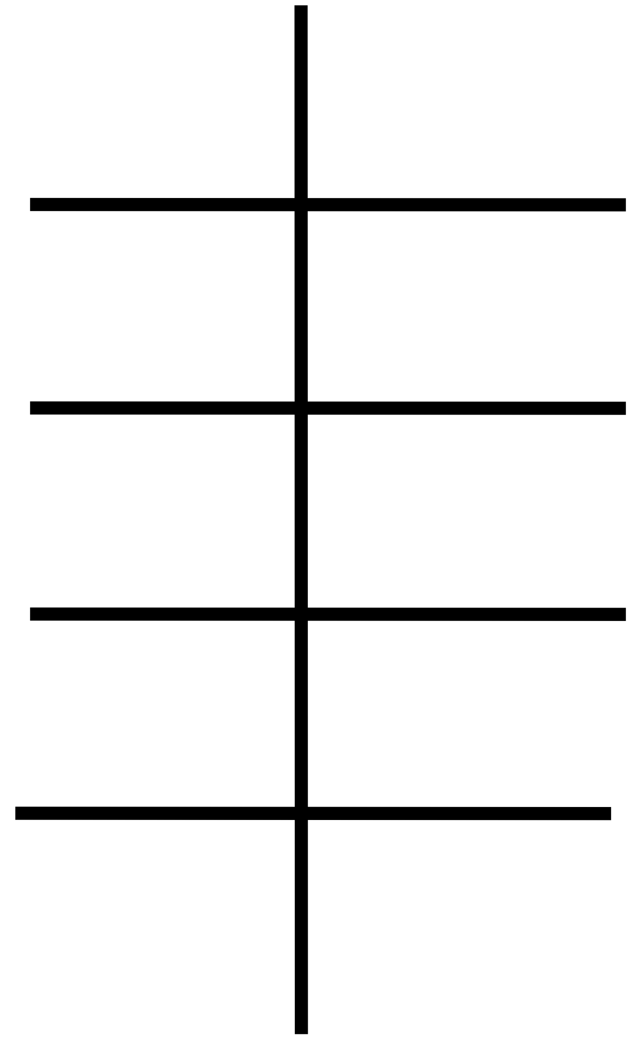
- computes for every pixel of an image **R** the amount of luminance difference that is imperceptible
- considers ***contrast***, ***luminance*** and ***spatial frequency*** in local neighborhood

adaptation of un-compensated (original) image R:

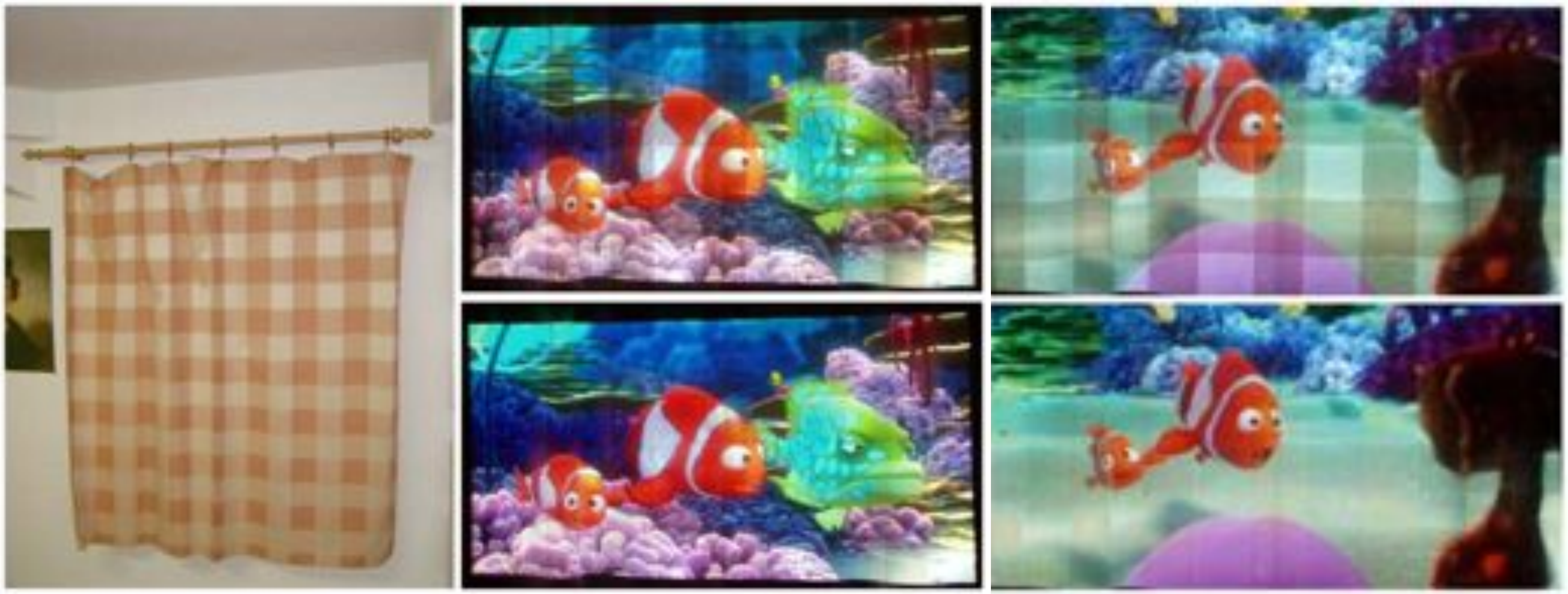
- compute and apply a single (global) scaling factor **R'=R***α that minimizes the perceived error (Wang, et al. 2005, only monochrome, not real-time, single projector)
- coming soon: color, real-time, global and local adaptation, potentially multiple projectors



Example: Curtain



Example: Curtain



Bimber et al, IEEE
Computer 2005

Example: Fossil

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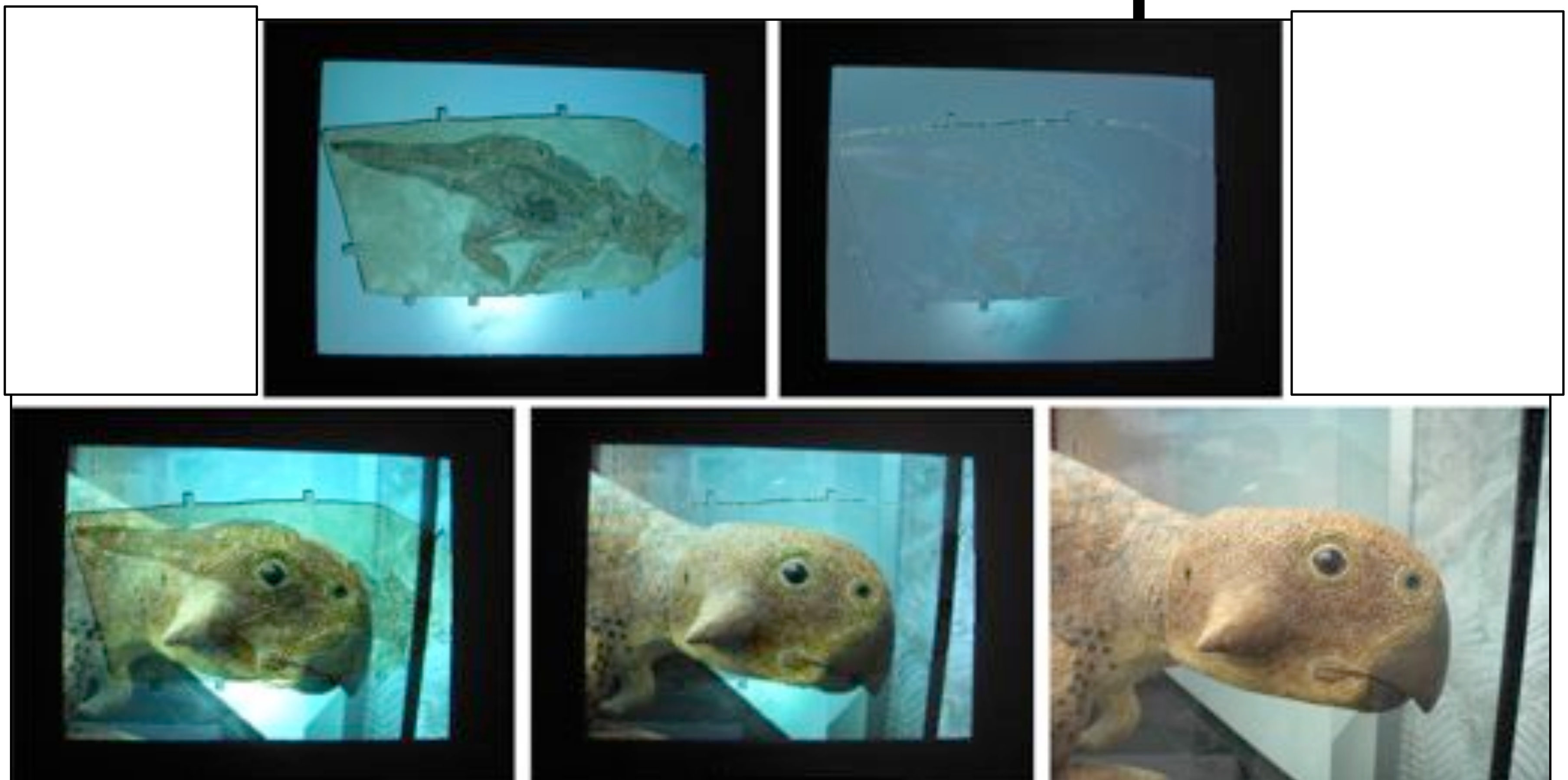
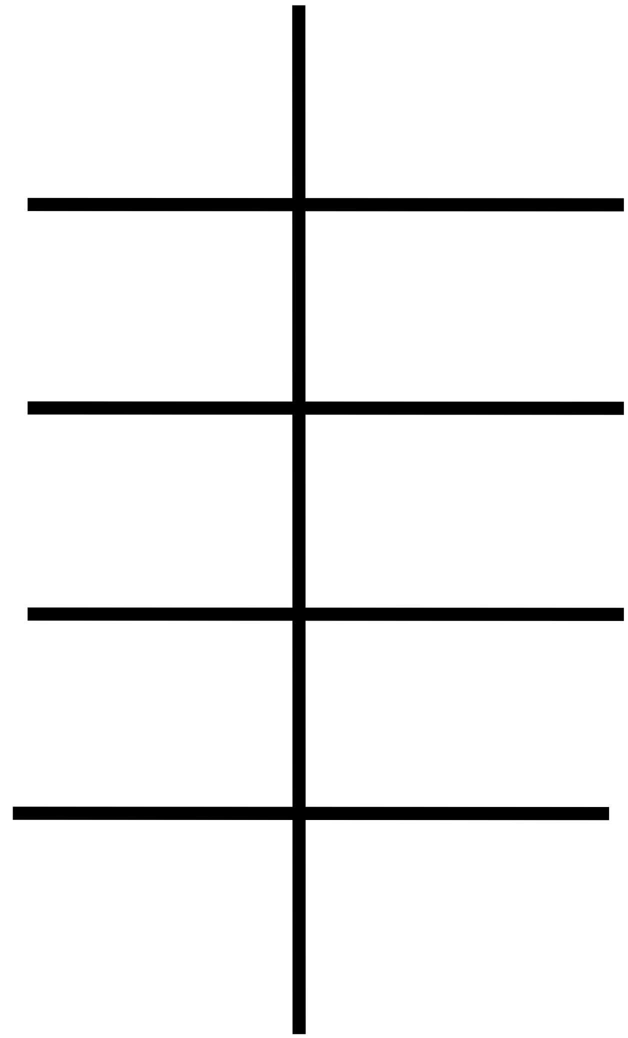
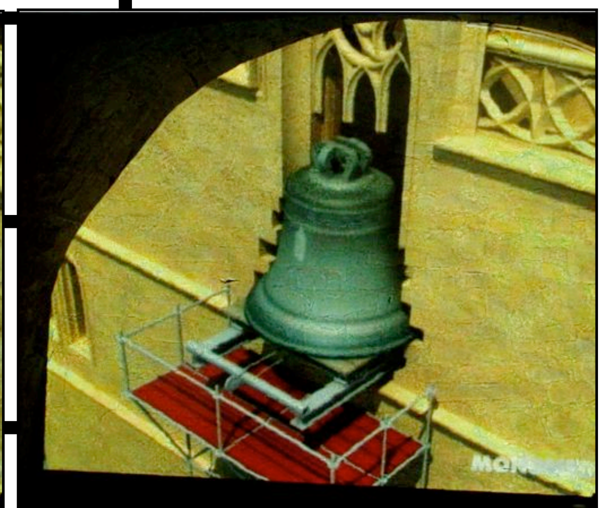


In coop. with Senckenberg Museum

Example: Natural Stone Wall



Example: Natural Stone Wall



Bimber et al, IEEE Computer 2005
In coop. with Bennert Group

Example: Wallpaper

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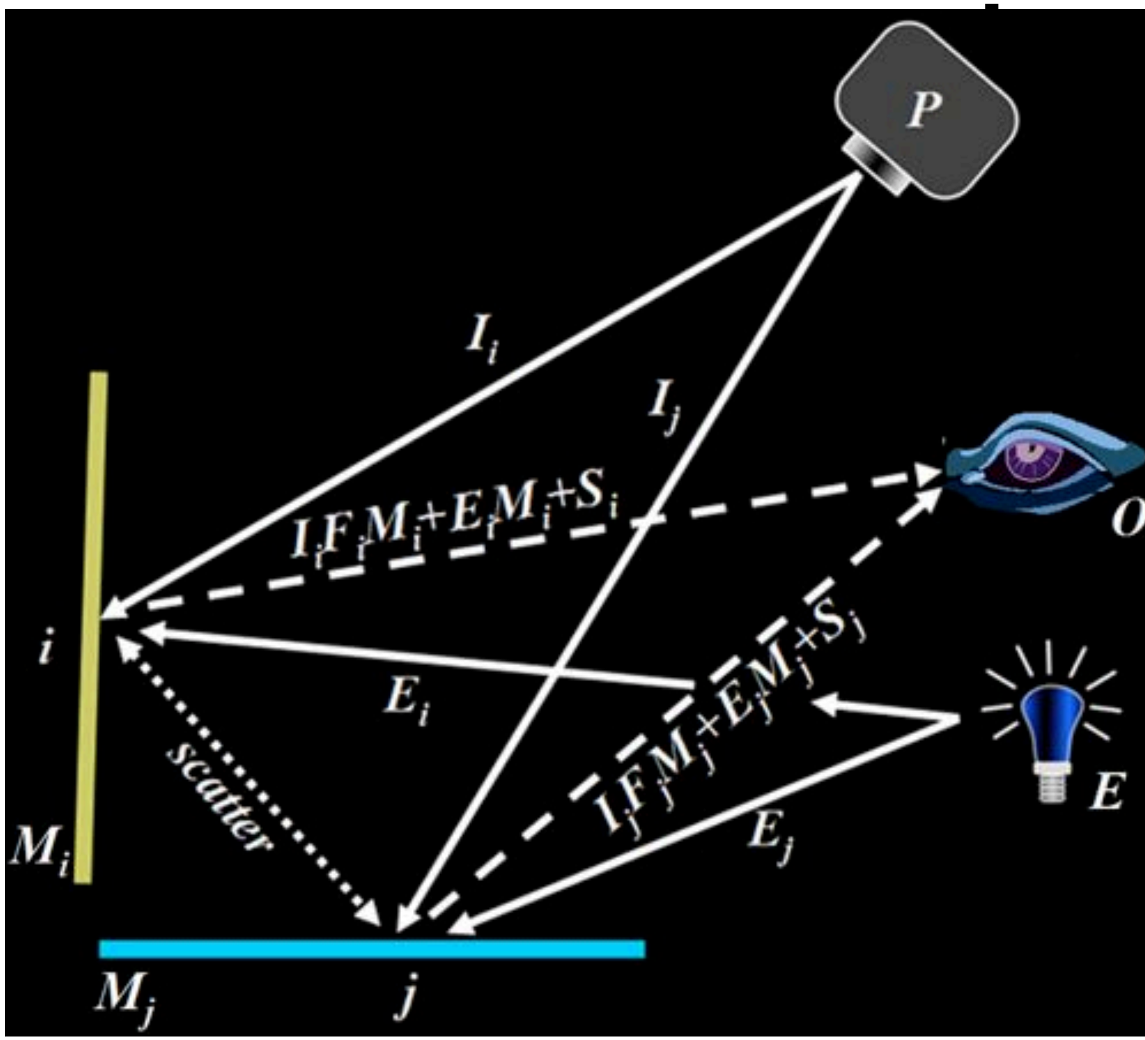
Bimber et al,
IEEE Computer
2005

Compensating Global Light Effects

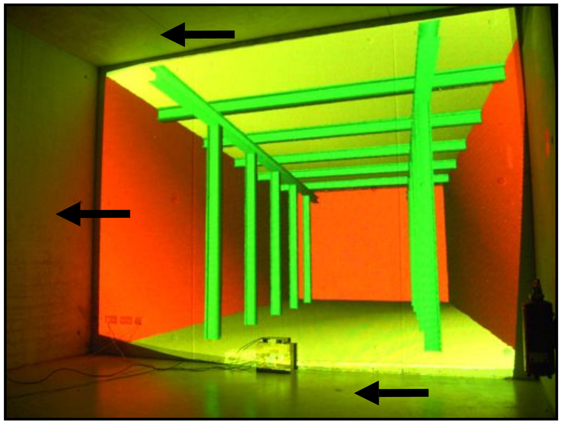
Compensating Global Light Effects

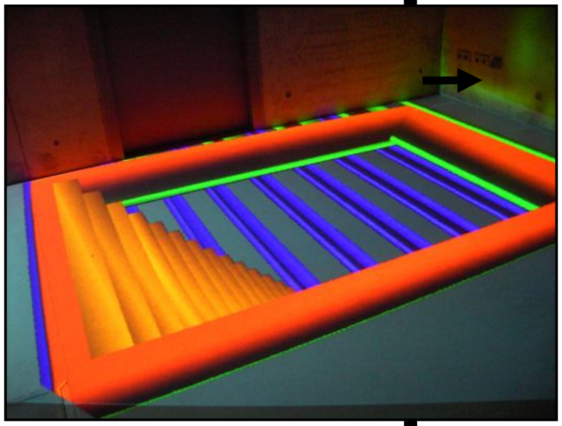


Compensating Diffuse Scattering

Compensating Diffuse Scattering

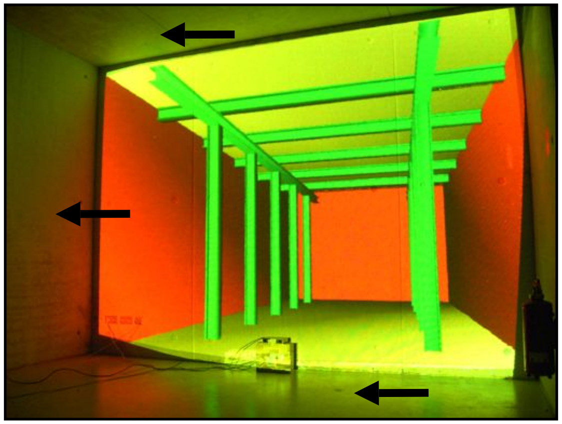
Bimber et al,
IEEE/ACM
ISMAR 2005

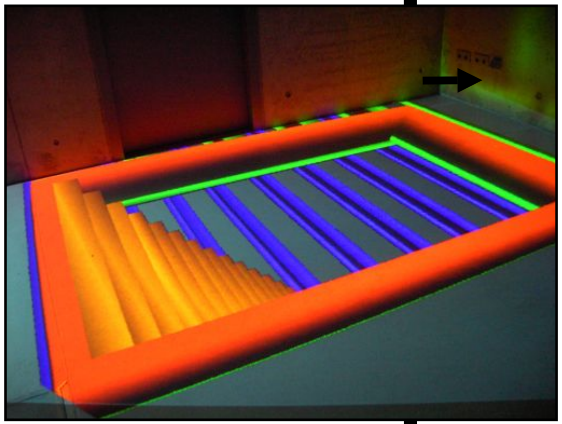




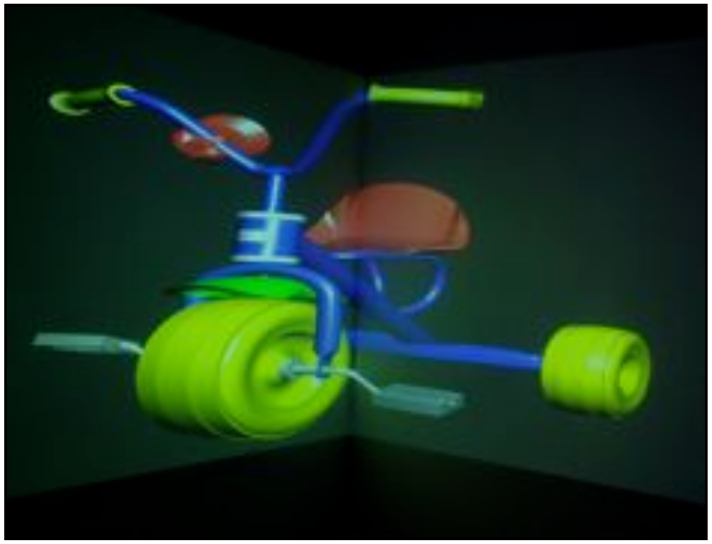
Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005



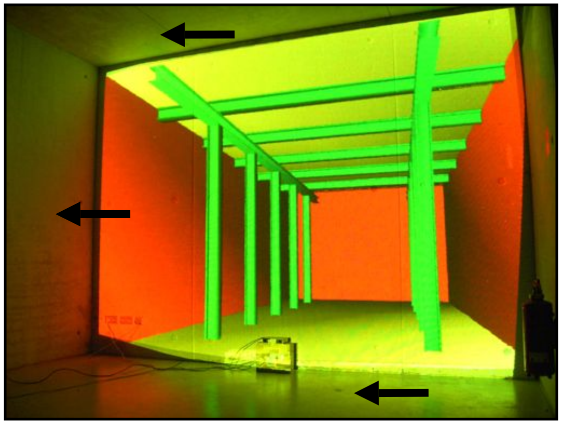


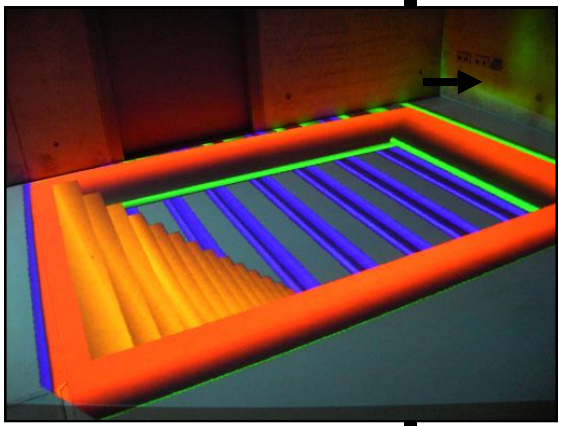
Bimber et al, IEEE VR, 2006



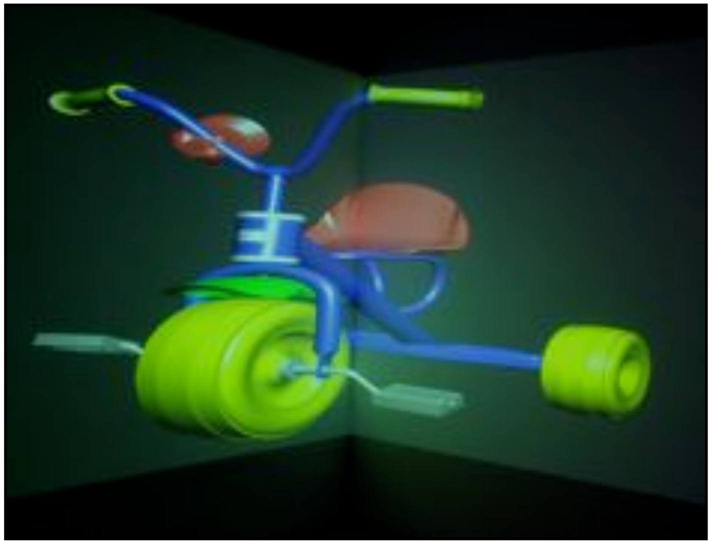
Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005



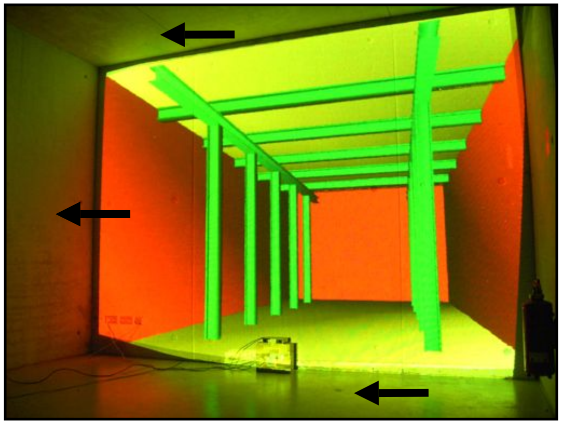


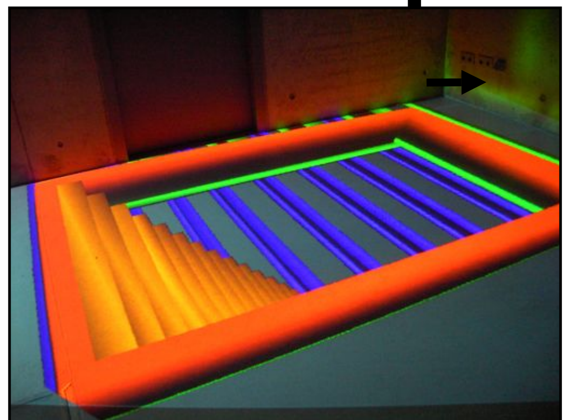
Bimber et al, IEEE VR, 2006



Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005





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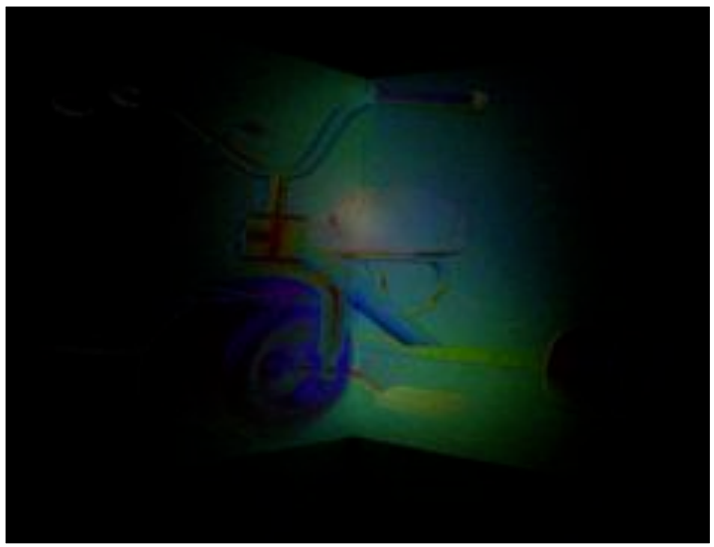


details:
IEEE VR talk on Wednesday morning (8:30am), session on tracking and projection displays

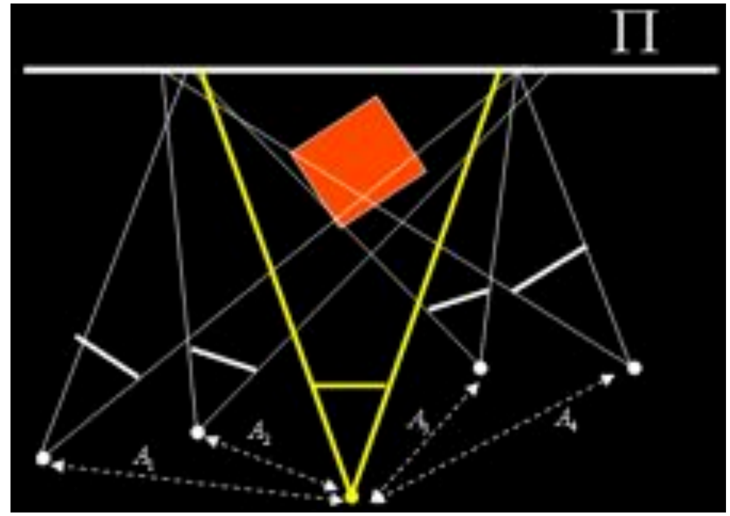
see demo!

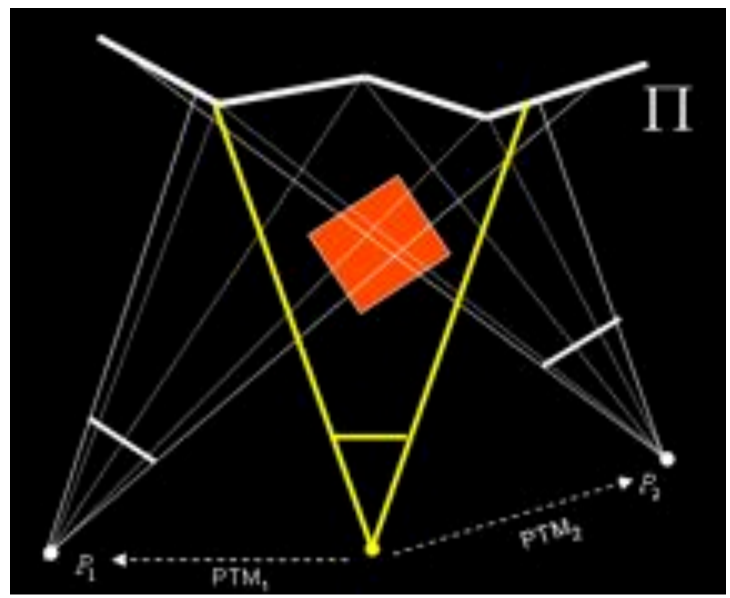
Advanced Techniques
View-Dependence

Non-Complex Surfaces

Non-Complex Surfaces

- view-dependent geometry correction can be compute if geometry is known
- for example:
  - **planar/multi-plane:** off-axis projection
  - **parametric:** warping via parametric description
  - **scanned/modelled:** projective texture mapping





Example: Life-Sized Projector-Based Dioramas

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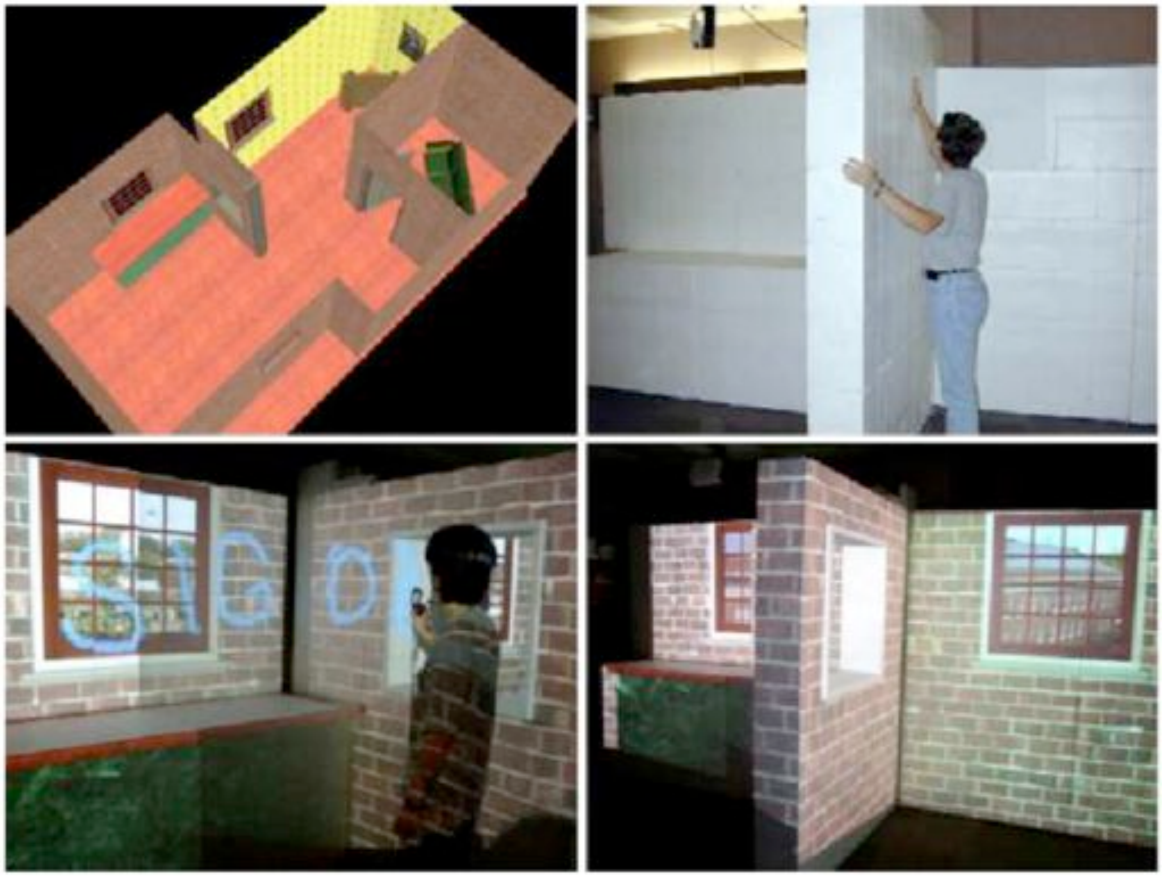


Courtesy: Low, et al., 2001

Complex Surfaces

Complex Surfaces

- if geometry is unknown image-based rendering helps
- sample geometric and radiometric parameters from multiple (source) camera (perspective)
- for novel (destination) camera
  - compute weighted penalties:

$$p_j = \alpha a_j + (1-\alpha) b_j$$

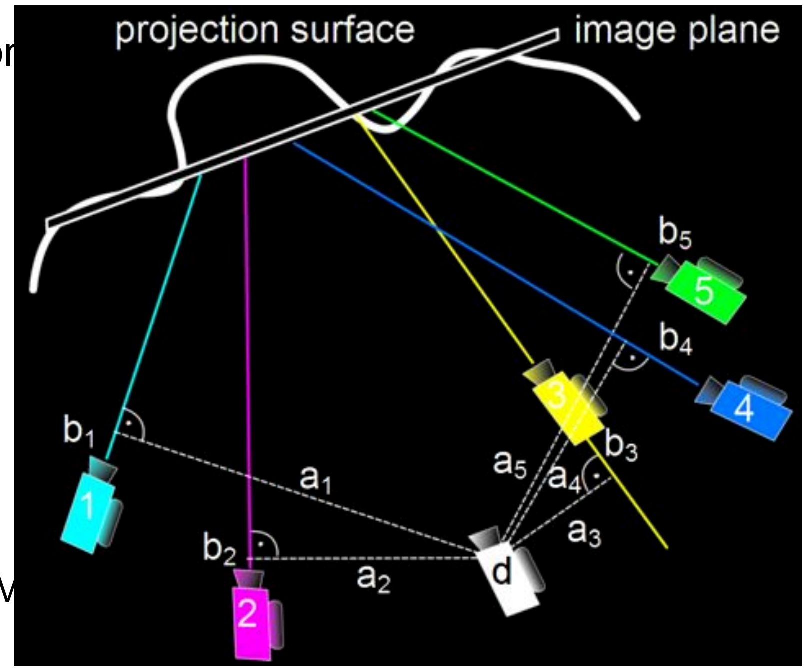
  - select k best perspectives (lowest penalties) and normalize them:

$$w_j = \left(1 - \frac{p_j}{\max_{pk}}\right)\frac{1}{p_j}$$

  - interpolate n… $_i2C_j$, $F_{ij}M$, $E_{ij}M$ and direction vector for destination perspective to render new IP:

$$t_d = \sum_j^k w_j t_j$$

  - lookups in $F_{ij}M$, $E_{ij}M$ with non-interpolated P_i2C_j
  - lookups in IP with interpolated P_i2C_j



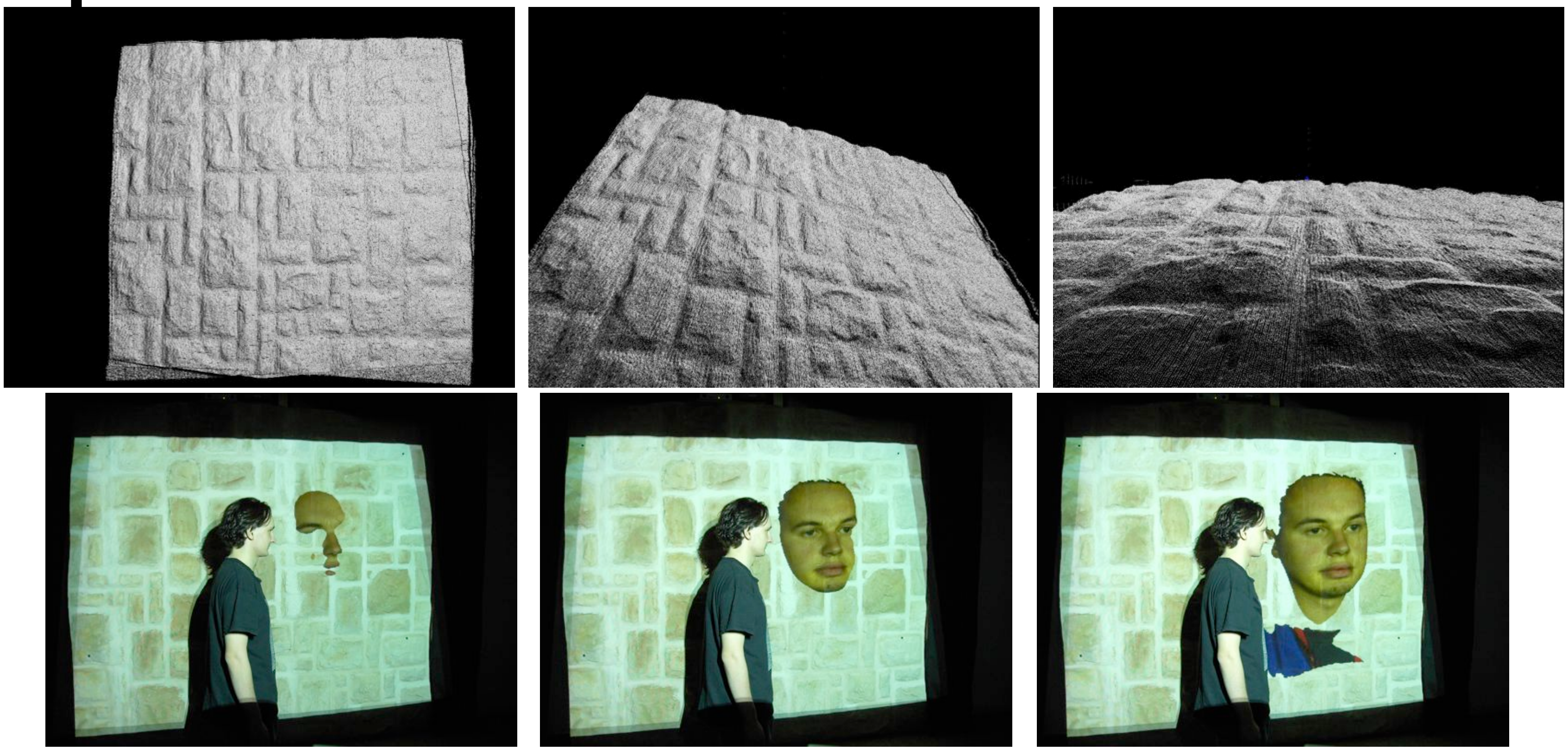
Example: Tracking and Stereo

Example: Tracking and Stereo

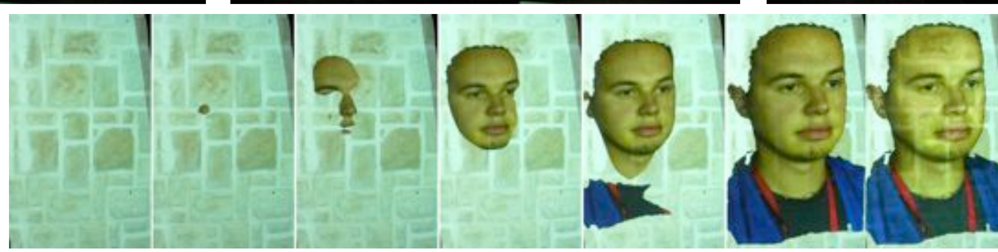
Bimber et al, IEEE/ACM ISMAR 2005

Depth and Occlusion

Depth and Occlusion



Bimber et al,
IEEE/ACM
ISMAR 2005



Example: Stereo on Wallpaper

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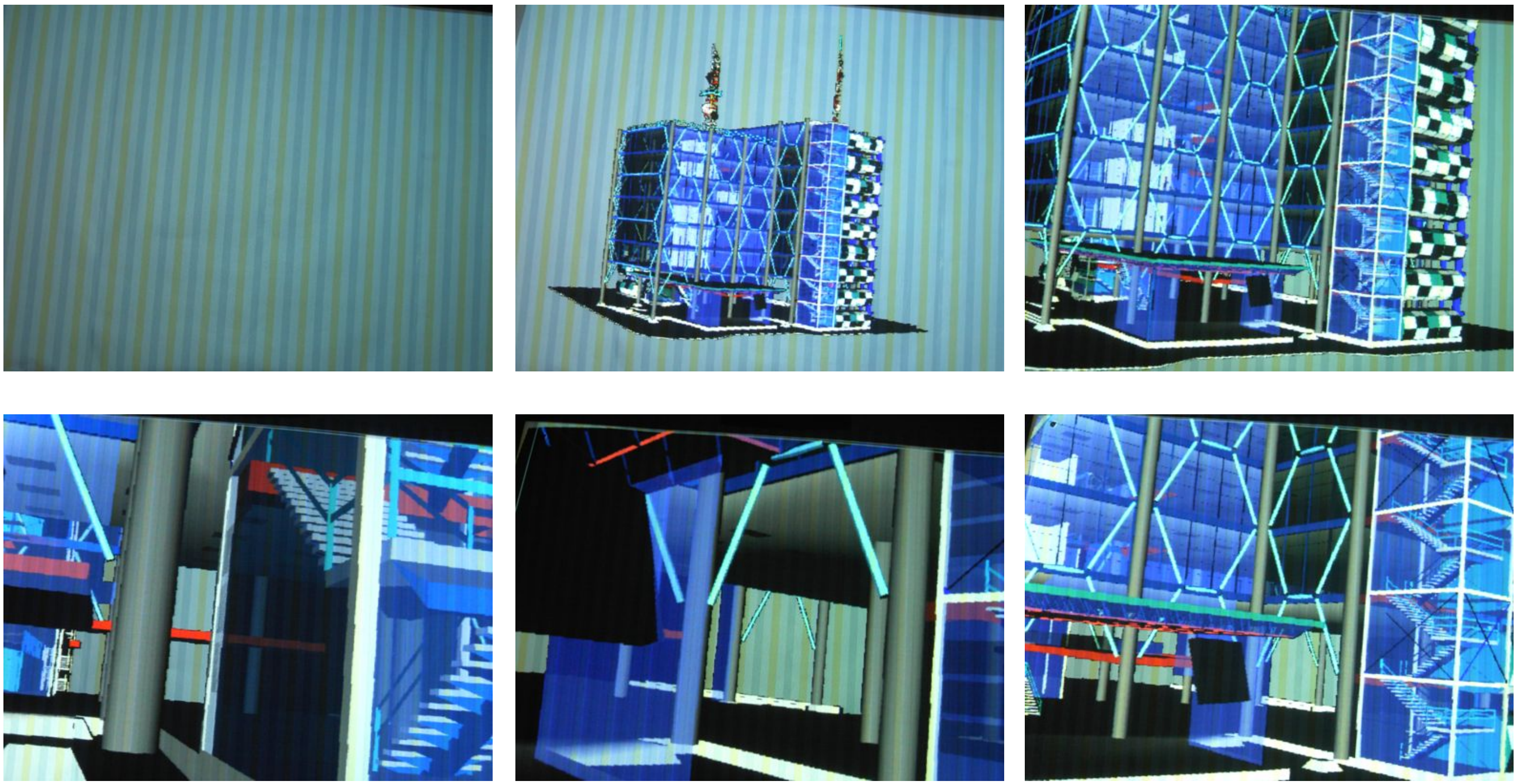
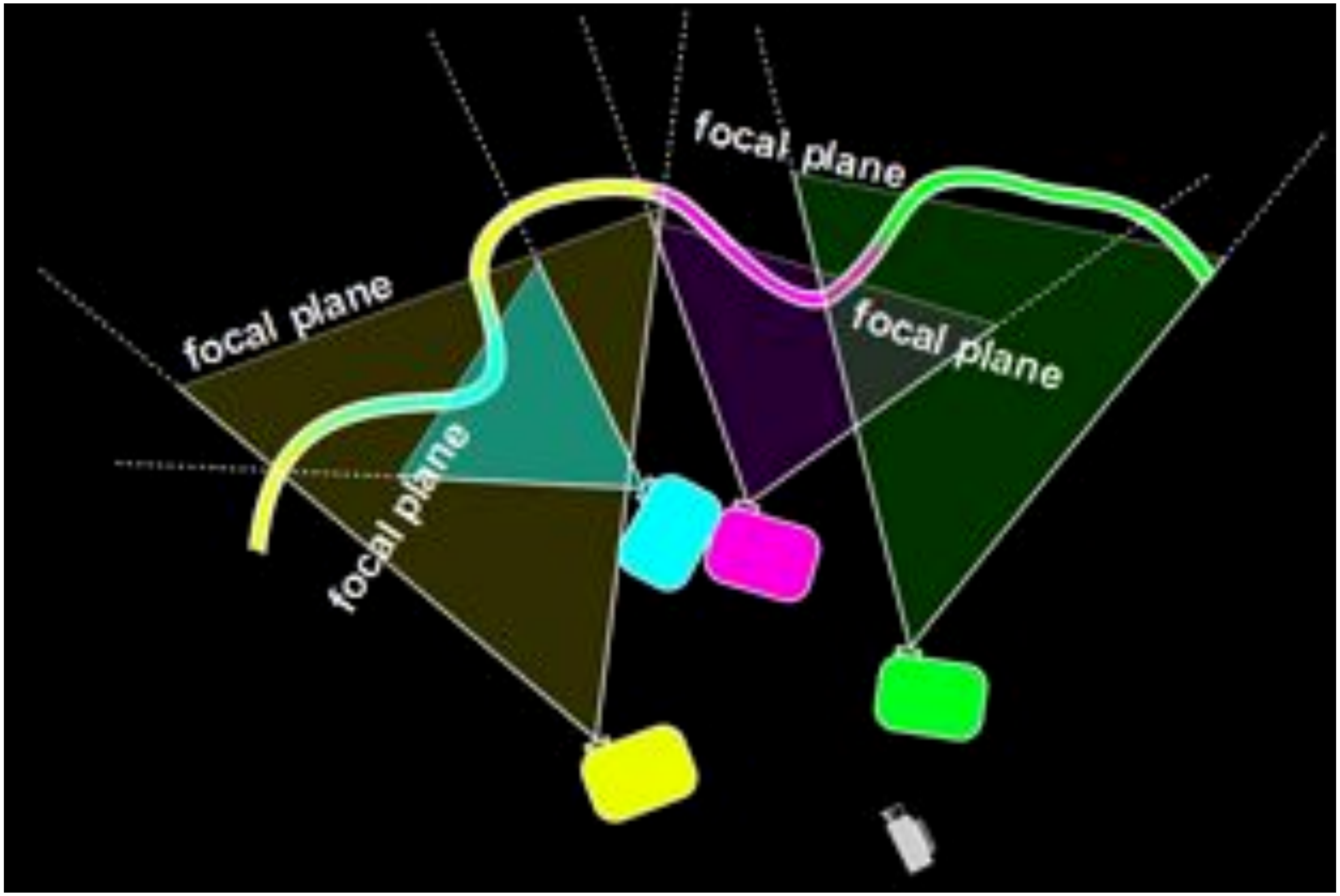


Bimber et al, IEEE/ACM
ISMAR 2005

Advanced Techniques
Multi-Focal Projection

Multi-Projector-Camera Technique that Increases Focal Depth



Determining Defocus

Determining Defocus

- structured light projection of grid point samples (2- dimensional phase shift)
  - **pre-correction:** geometric and radiometric correction (corrected grid points must be observed in camera)

$$I_{x,y} = (R_{x,y} - EM_{x,y}) / FM_{x,y}$$

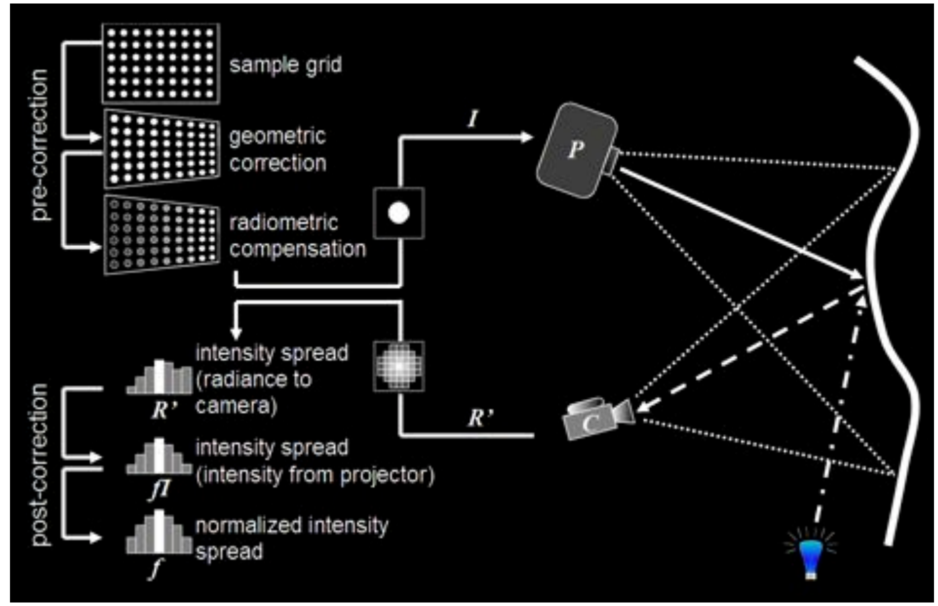
  - **post-correction:**

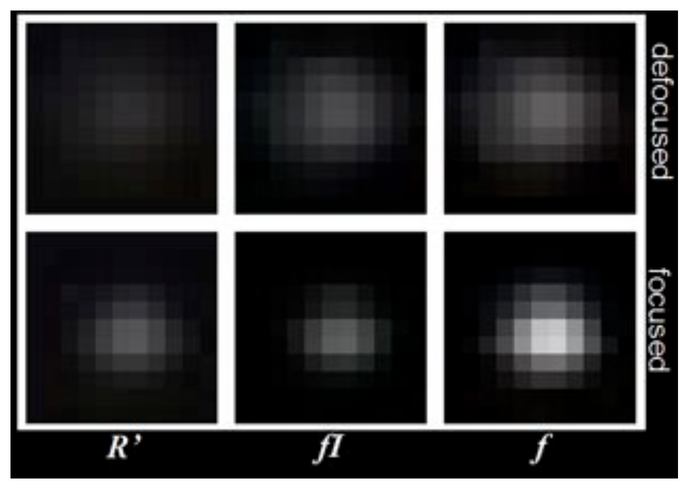
$$R'_{x',y'} = fI_{x,y} FM_{x',y'} + EM_{x',y'}$$

$$fI_{x,y} = \frac{(R'_{x',y'} - EM_{x',y'})}{FM_{x',y'}}$$

$$f = \frac{fI_{x,y}}{I_{x,y}}$$

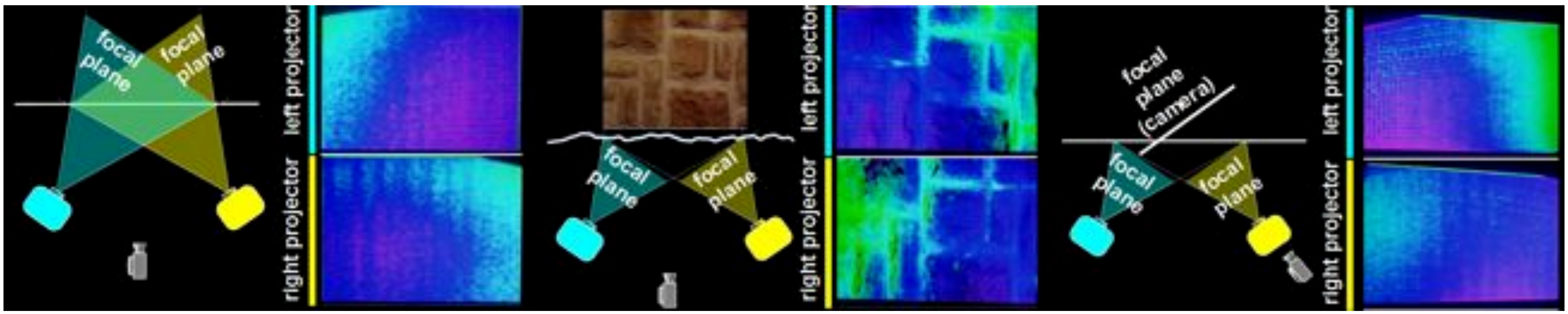
  - the texture f serves as basis to estimate focus measures (e.g., via FFT/DCT, intensity loss, point spread, etc.)





Example: Different Configurations

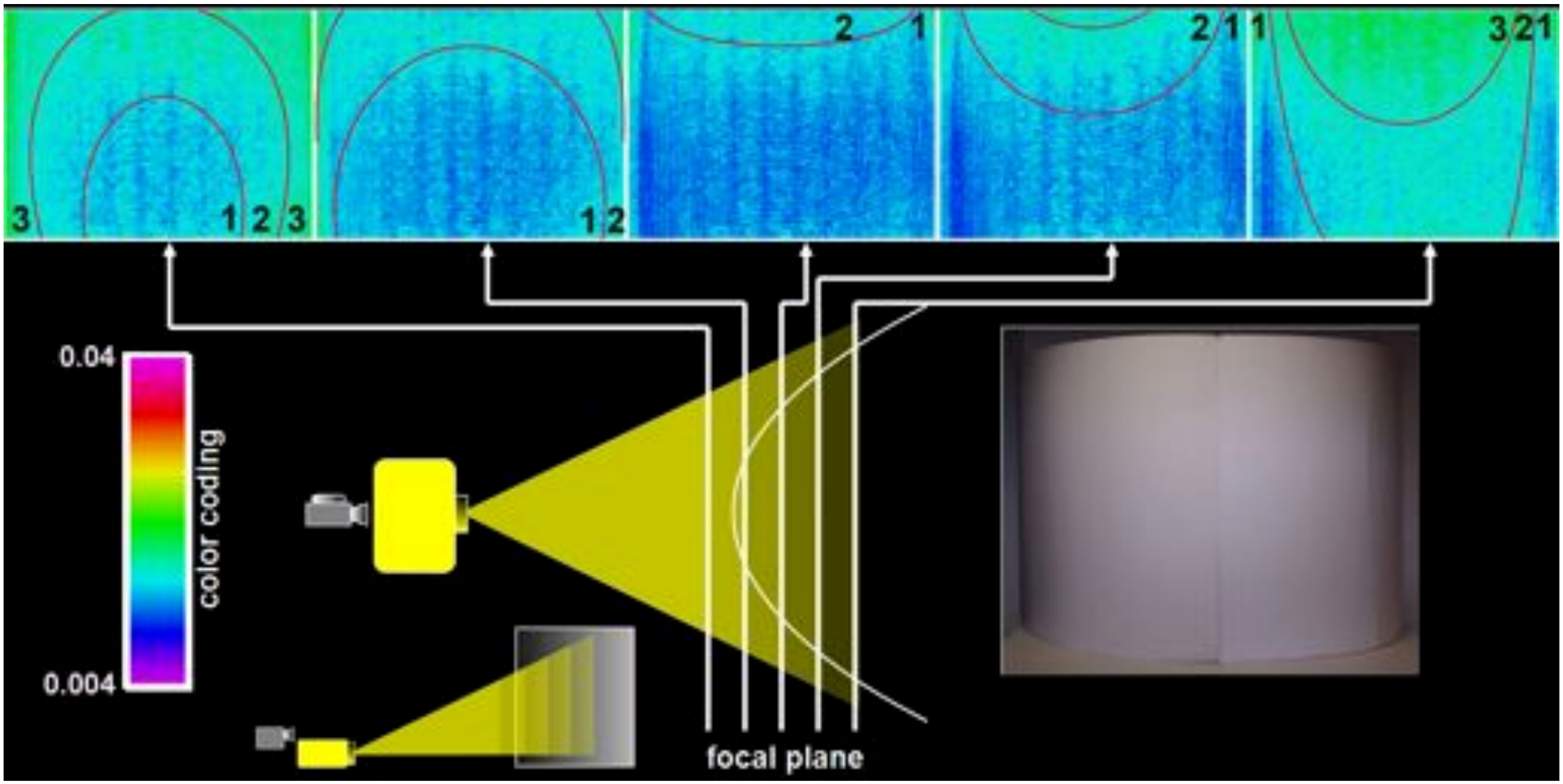
Example: Different Configurations



Bimber et al, IEEE TVCG 2006

Example: Shifting Focal Plane

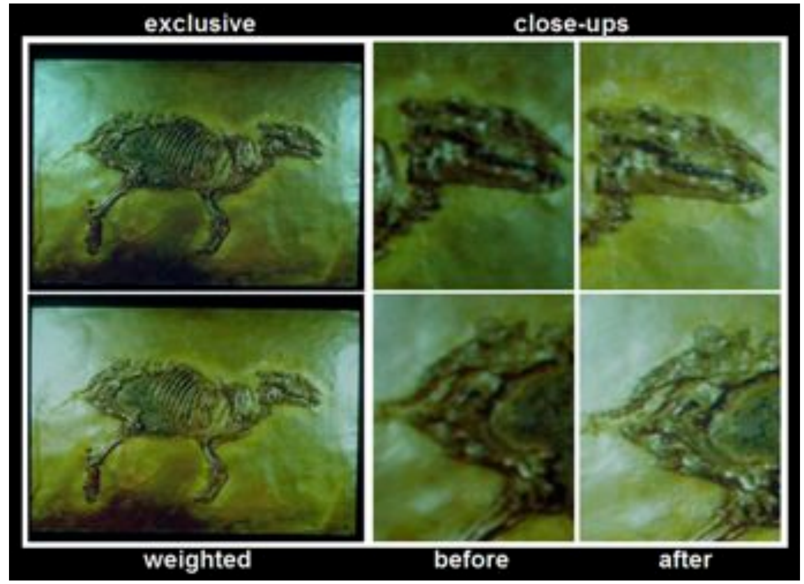
Example: Shifting Focal Plane



Bimber et al, IEEE TVCG 2006

Image Composition

Image Composition



- using the focus values of each projector's pixels ($\Phi_{i,x,y}$), compose an image with minimal total defocus
  - **excusive composition:** surface point is covered by a single projector pixel (the one with highest $\Phi_{i,x,y}$)

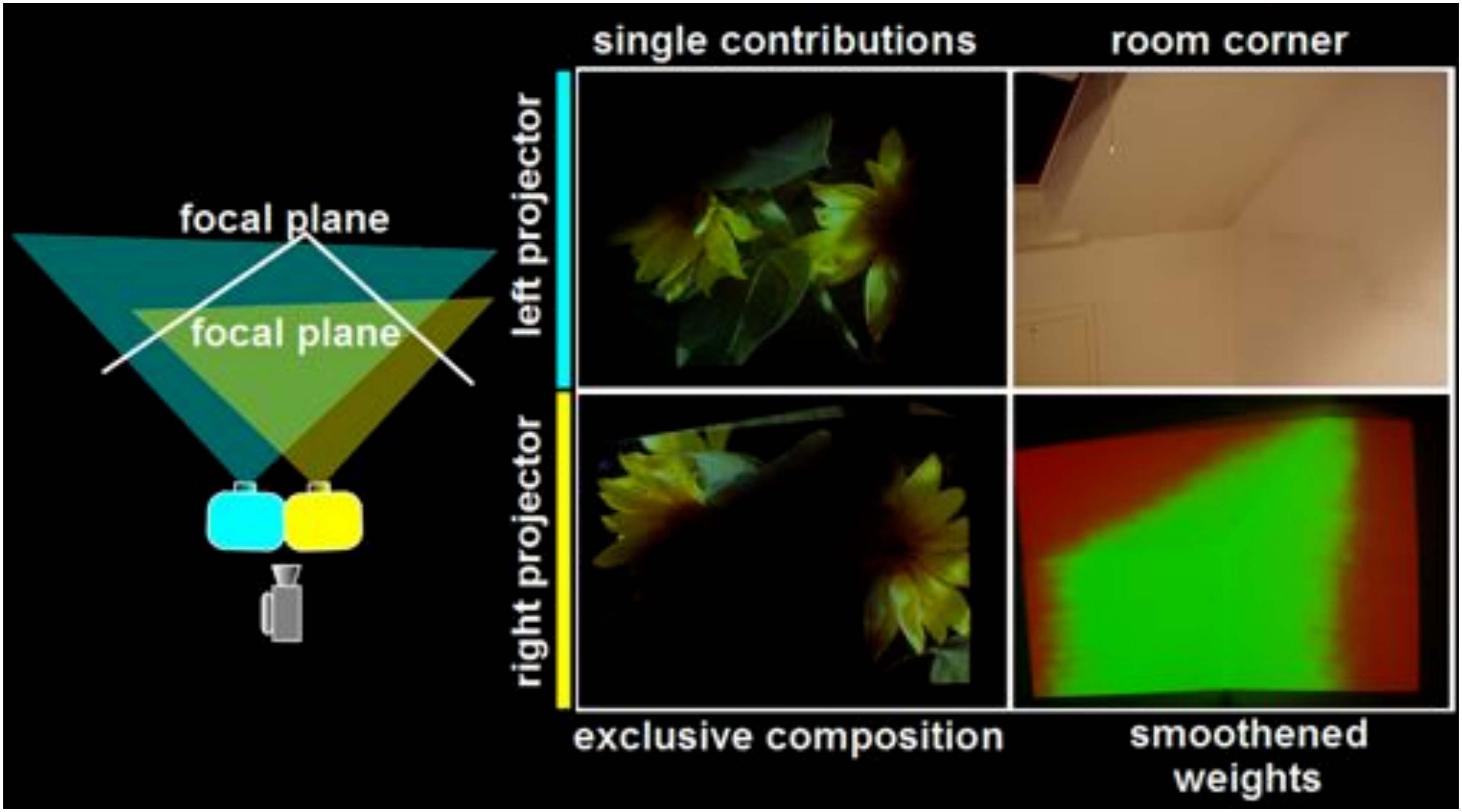
$$I_i = \frac{w_i(R-EM)}{\sum_j^N w_j FM_j} \qquad w_{i,x,y} = \frac{\Phi_{i,x,y}}{\sum_j^N \Phi_{j,x,y}}$$

  - **weighted composition:** compute normalized weight and multiply it with *FM* and *I*

$$I_i = w_i(R-EM)/FM_i, \quad w_i = \begin{cases} 1 & \Phi_{i,x,y} \geq \Phi_{j,x,y} \\ 0 & else \end{cases}$$

Example: Room Corner

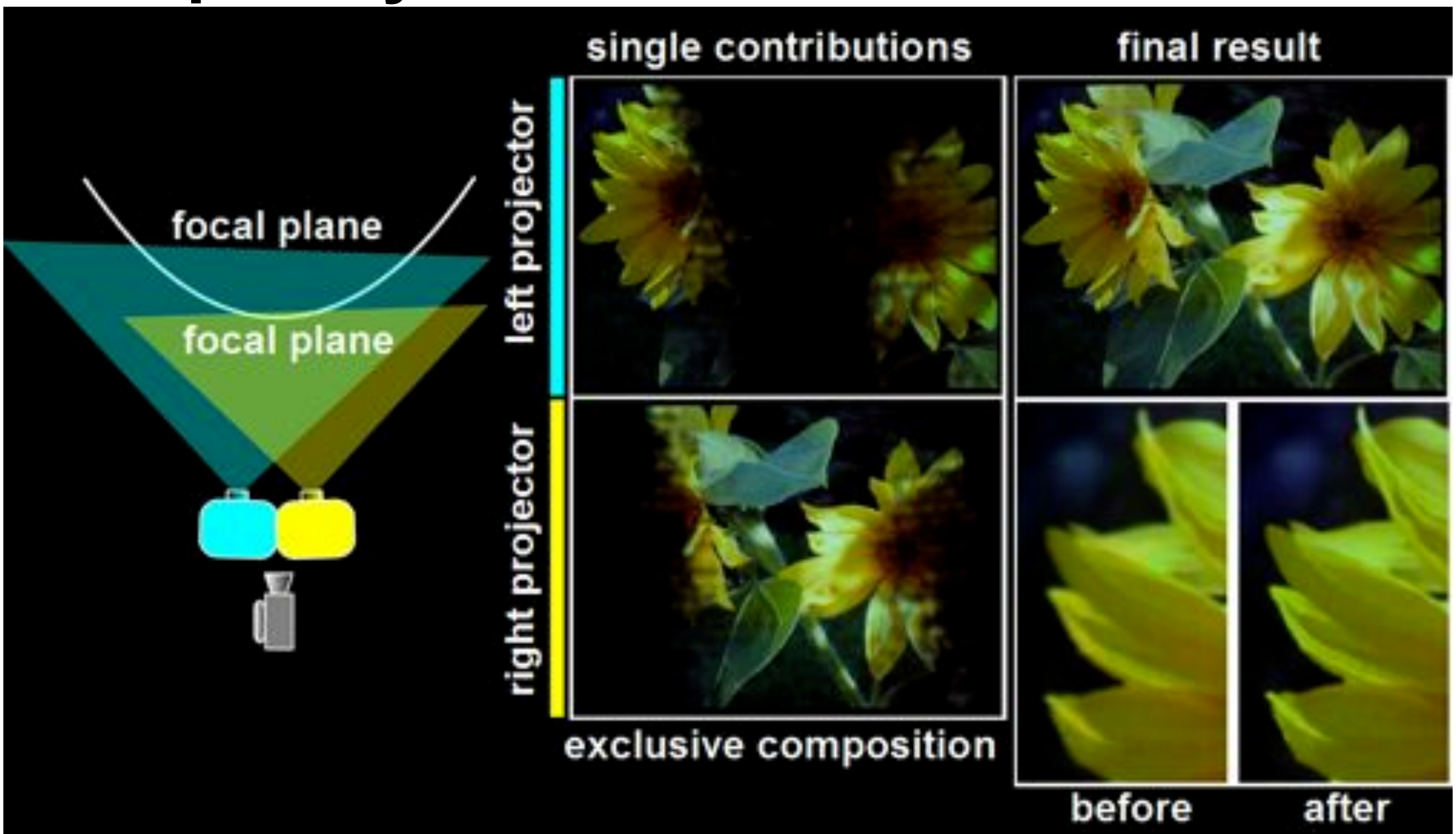
Example: Room Corner



Bimber et al, IEEE TVCG 2006

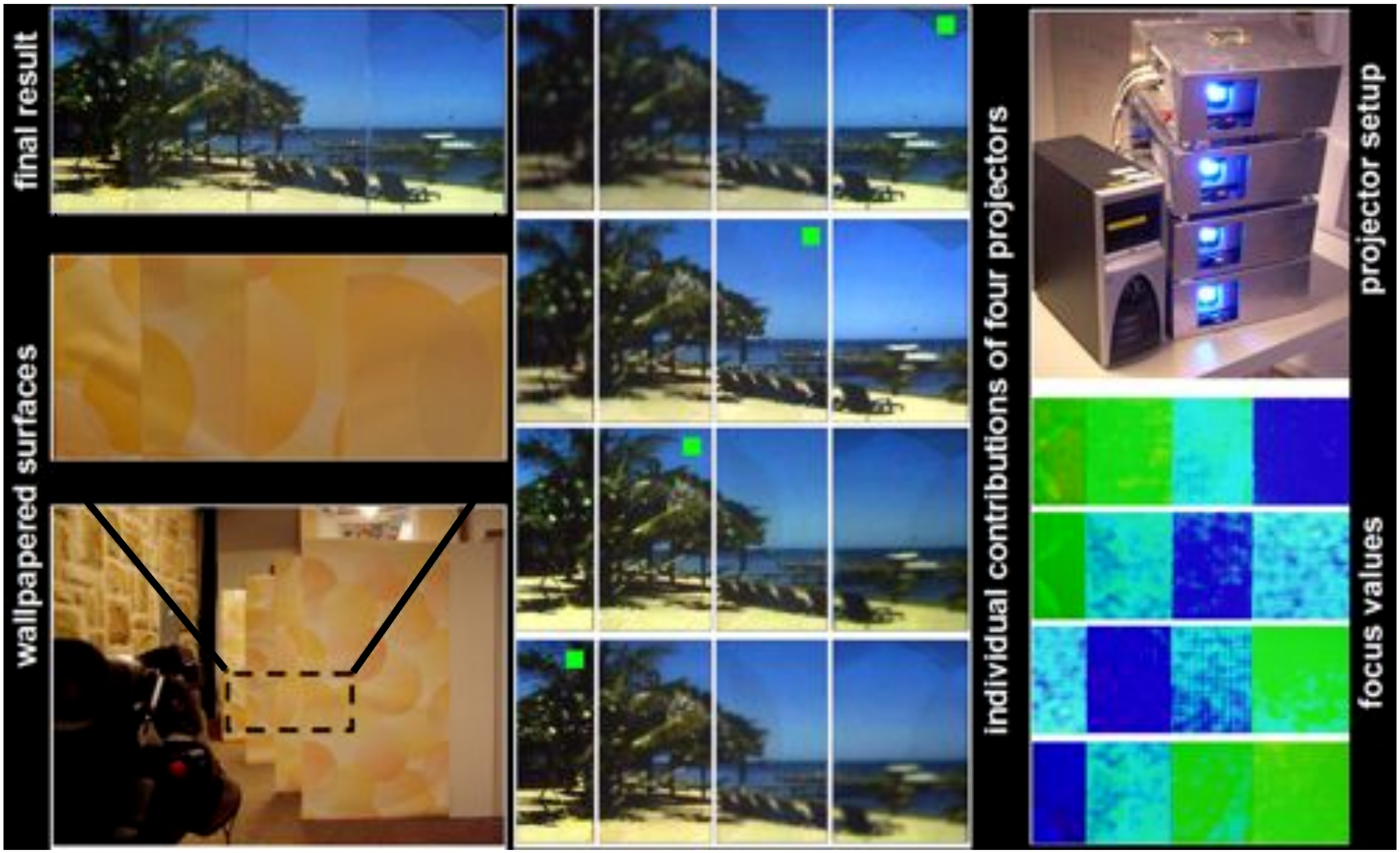
Example: Cylindrical Surface

Example: Cylindrical Surface



Example: Large Focal Depth

Example: Large Focal Depth



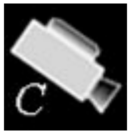
Bimber et al, IEEE TVCG 2006

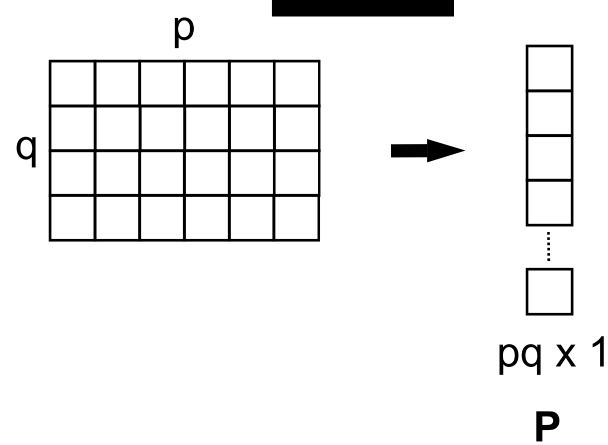
Advanced Techniques
Light Transport

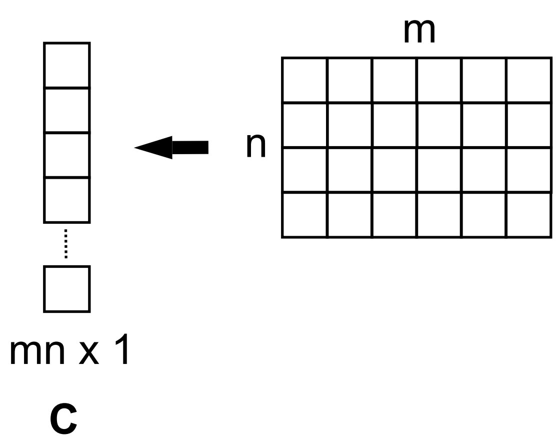
Acquisition

Acquisition

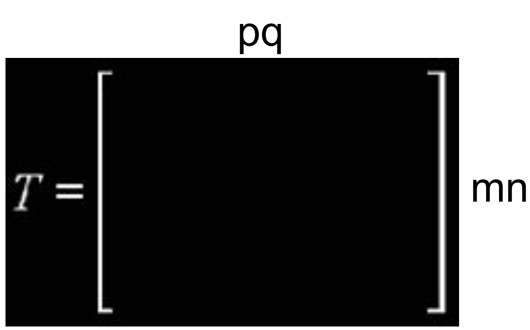
single camera & projector capture 4D slice of 8D reflectance field



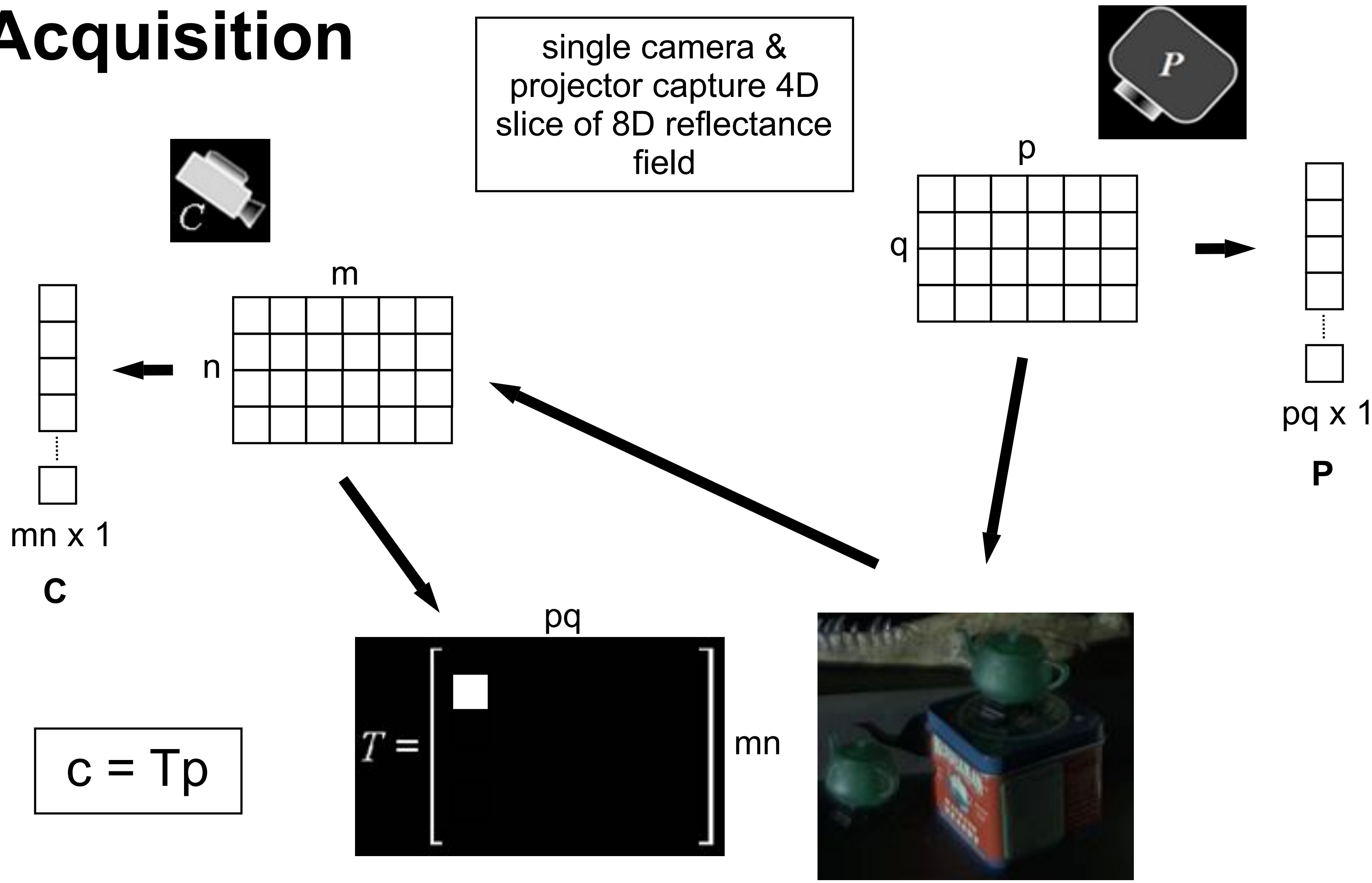




c = Tp



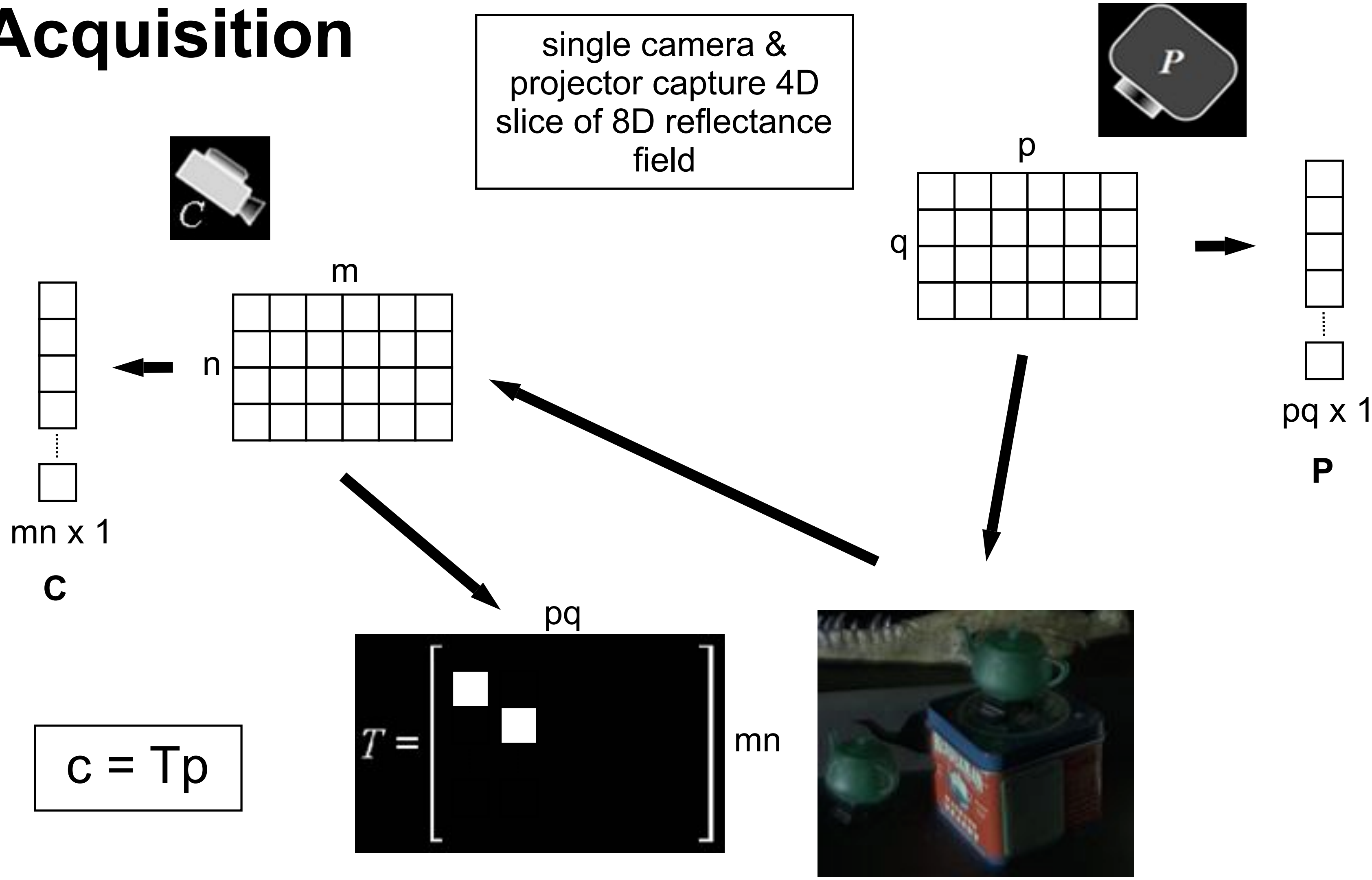
Acquisition



$$c = Tp$$

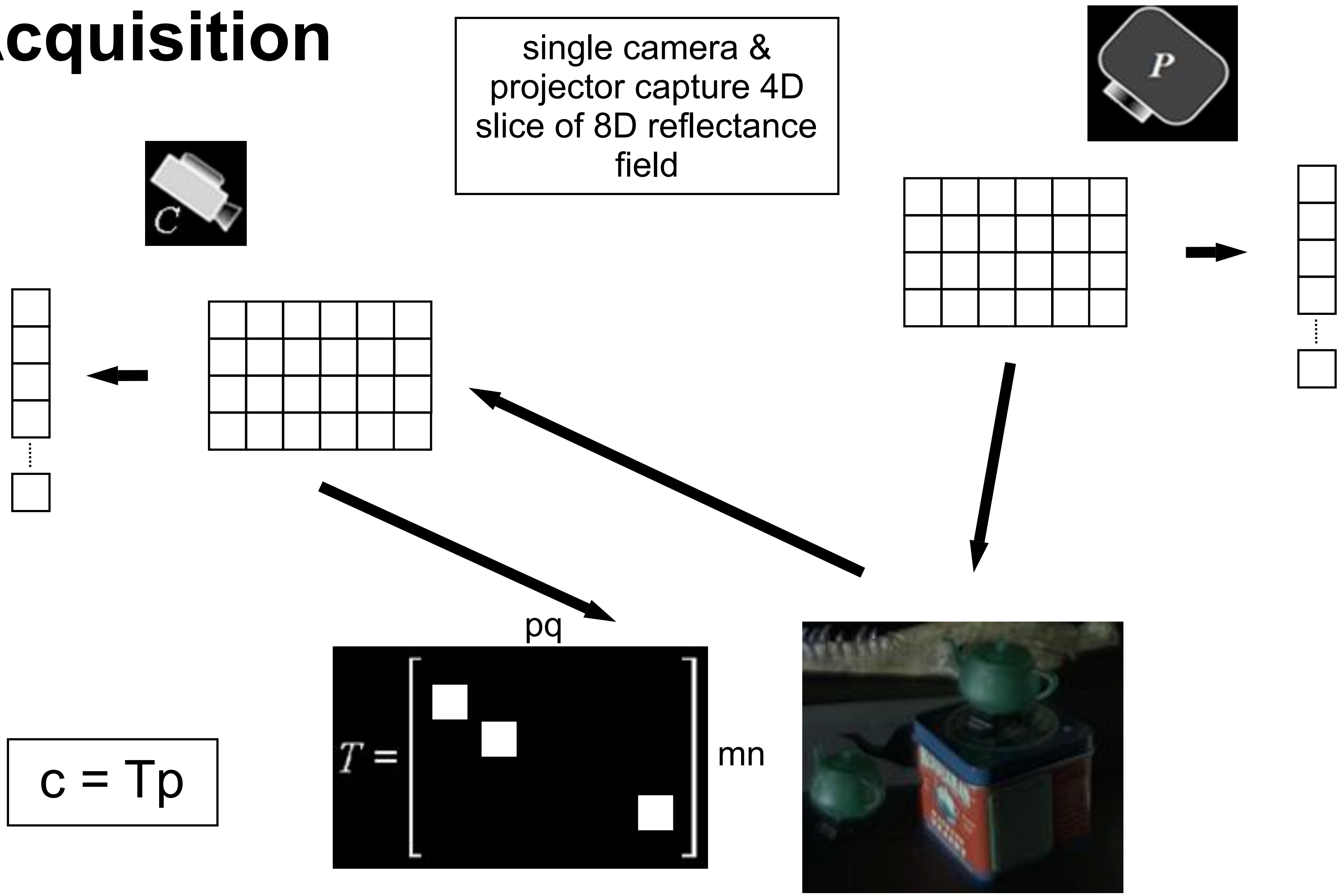
Acquisition

single camera & projector capture 4D slice of 8D reflectance field



$$c = Tp$$

Acquisition



Acquisition

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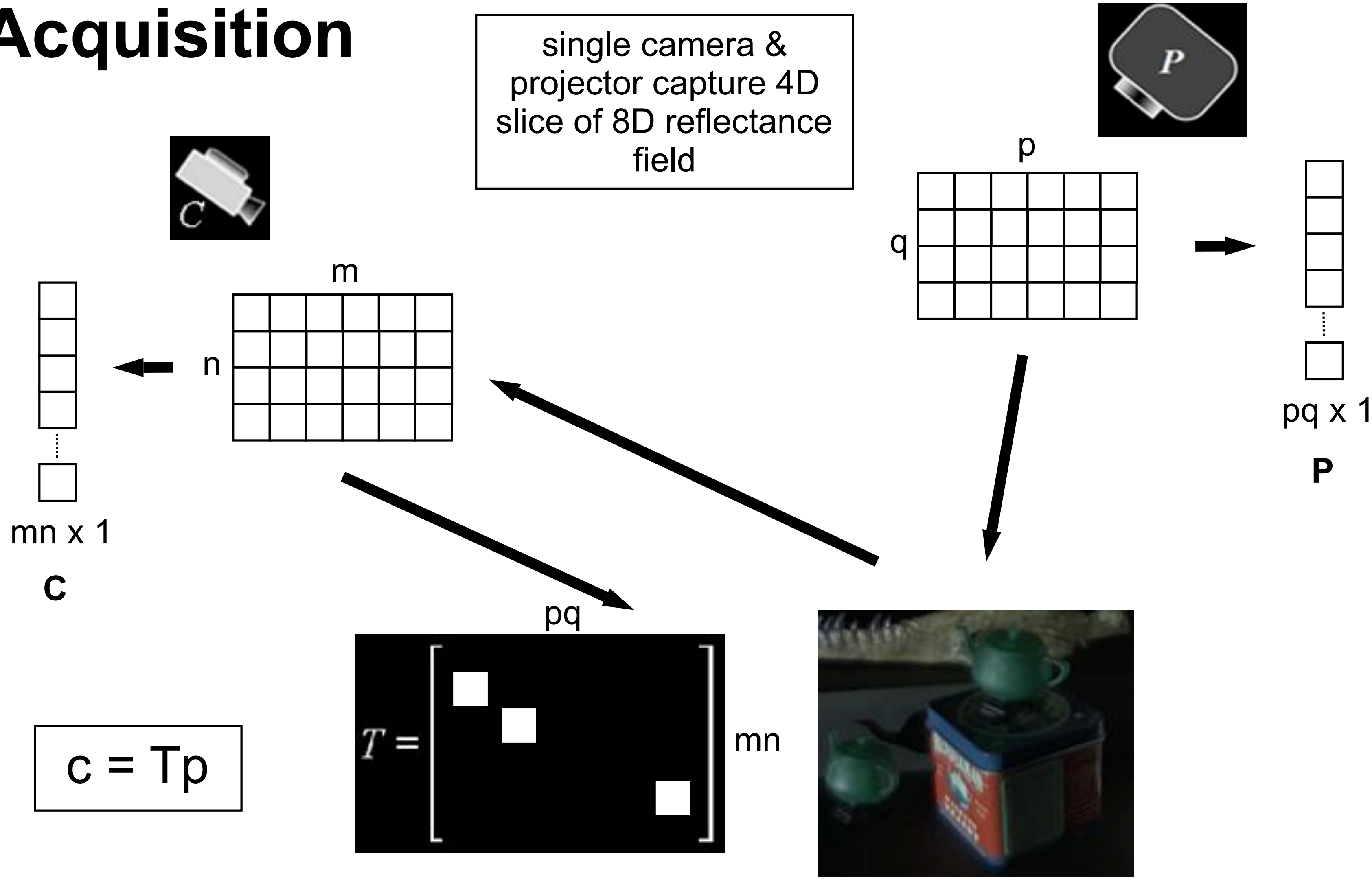

$$c = Tp$$

Acquisition

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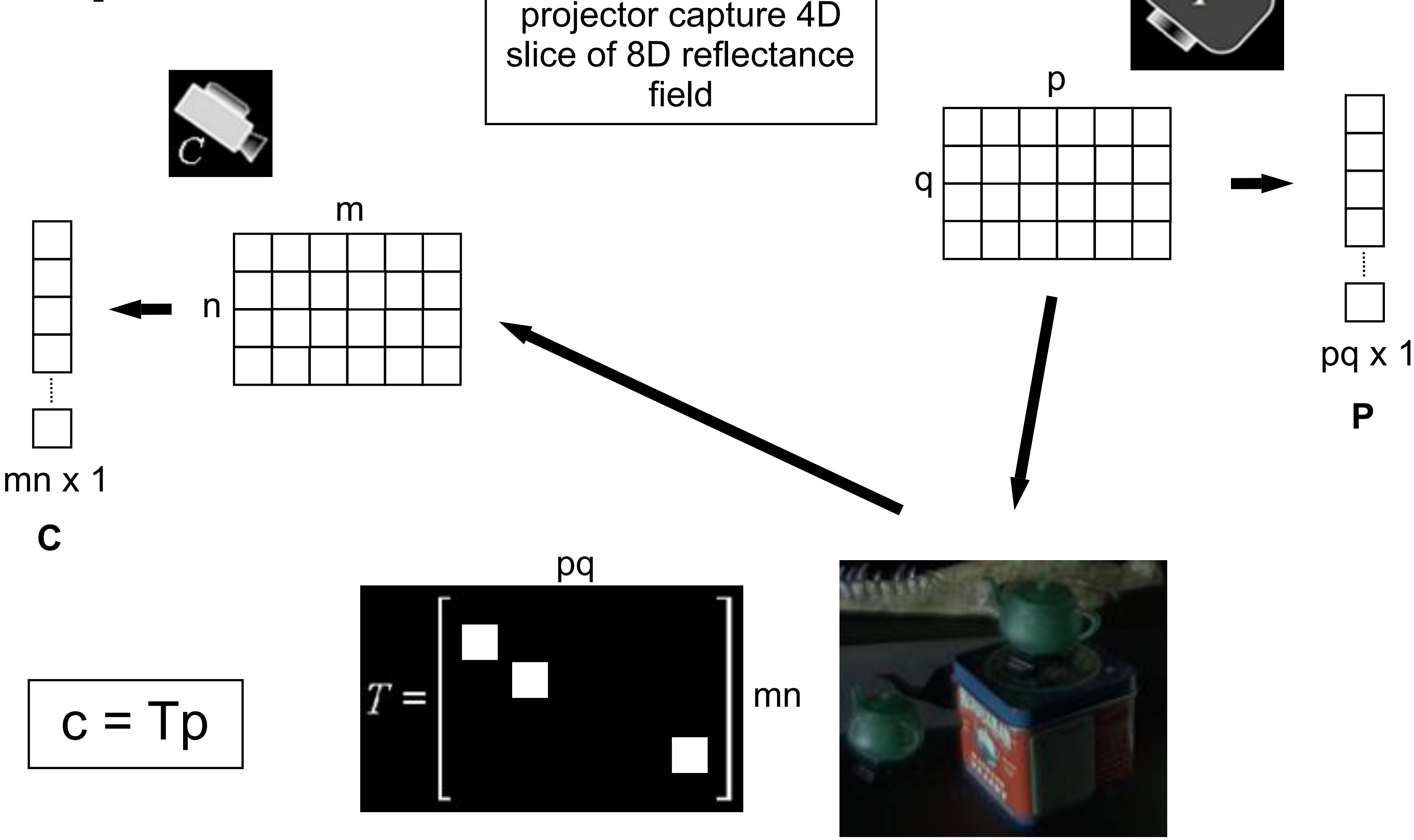
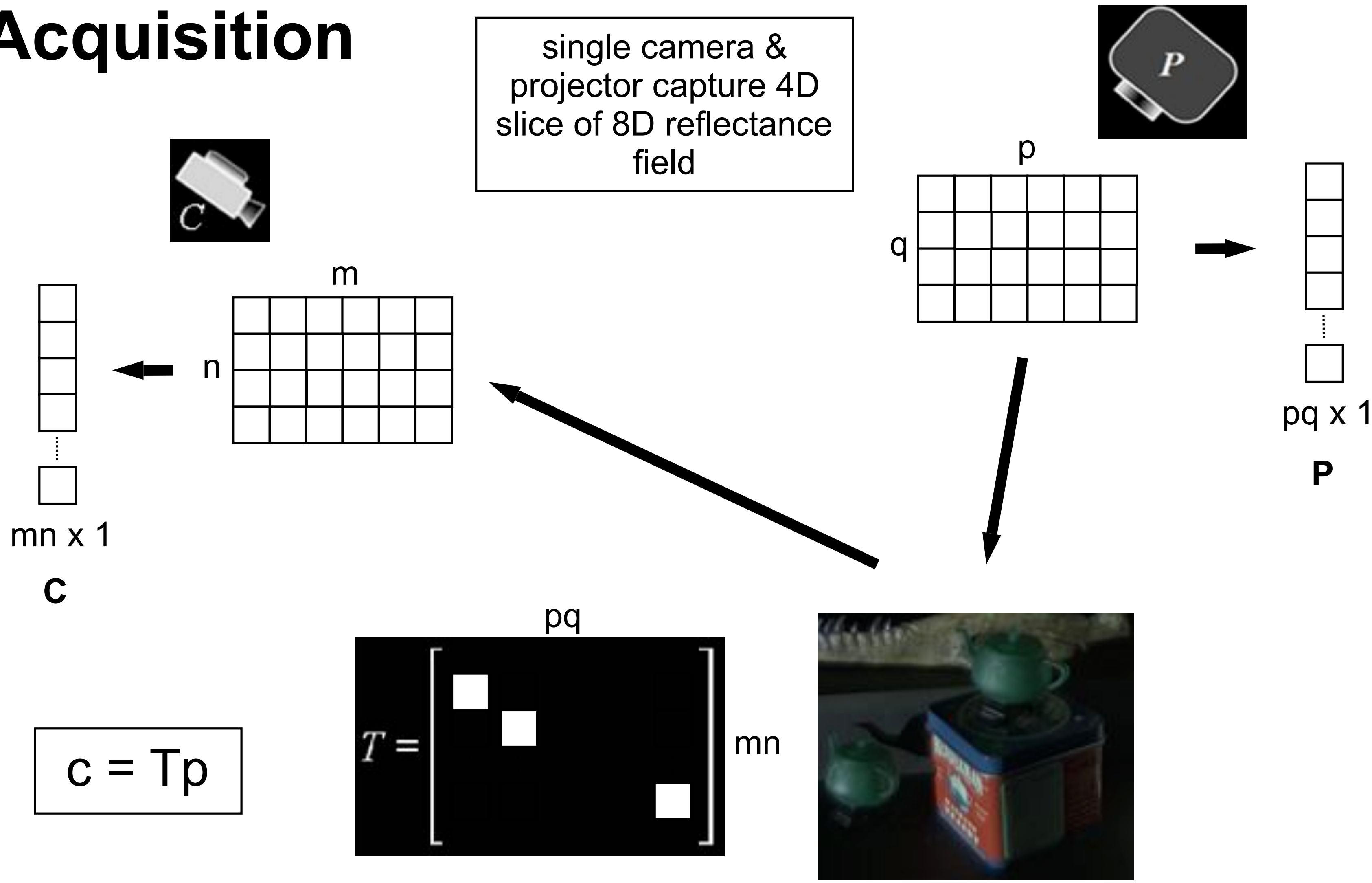


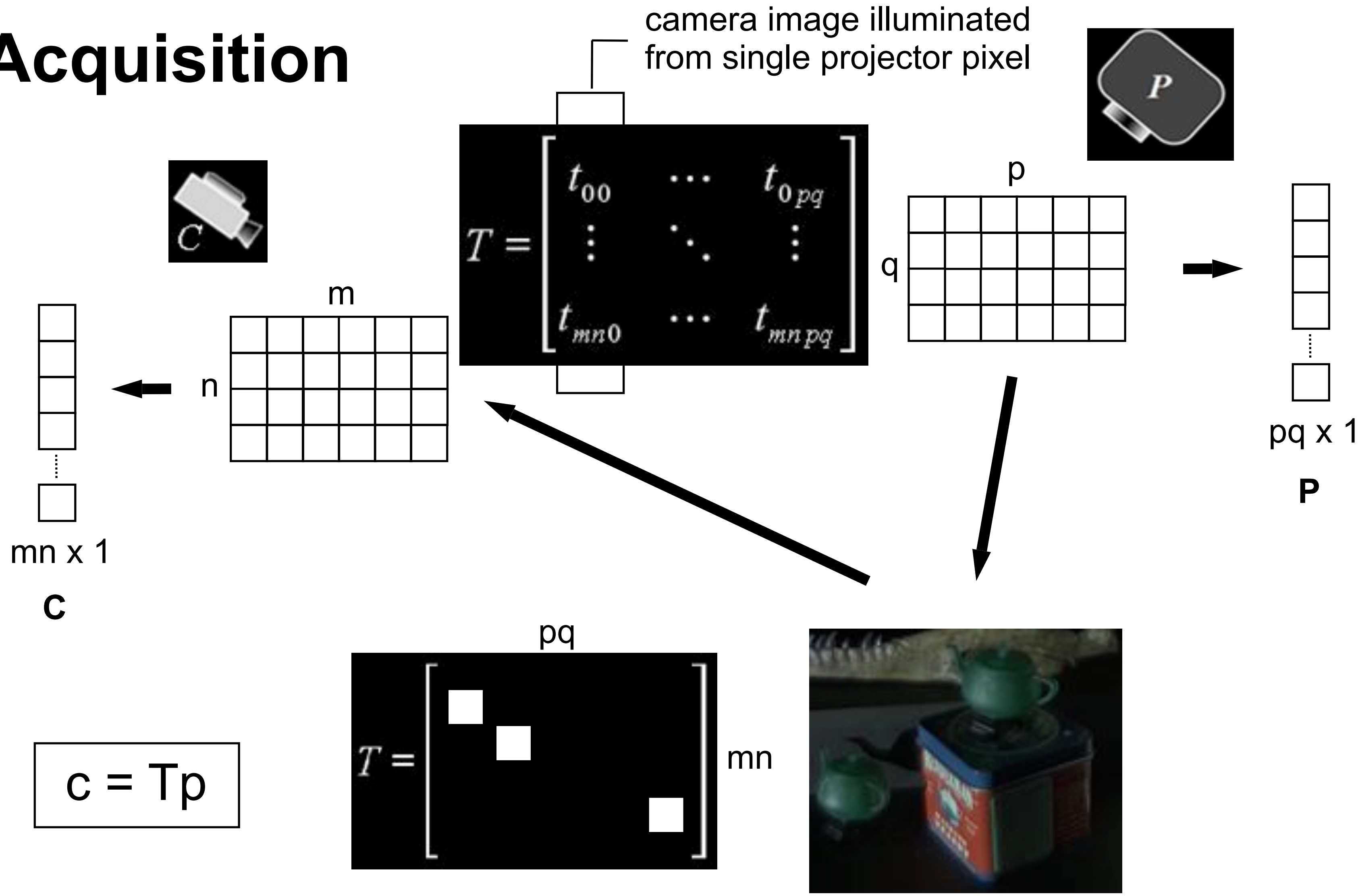
$$c = Tp$$

Acquisition

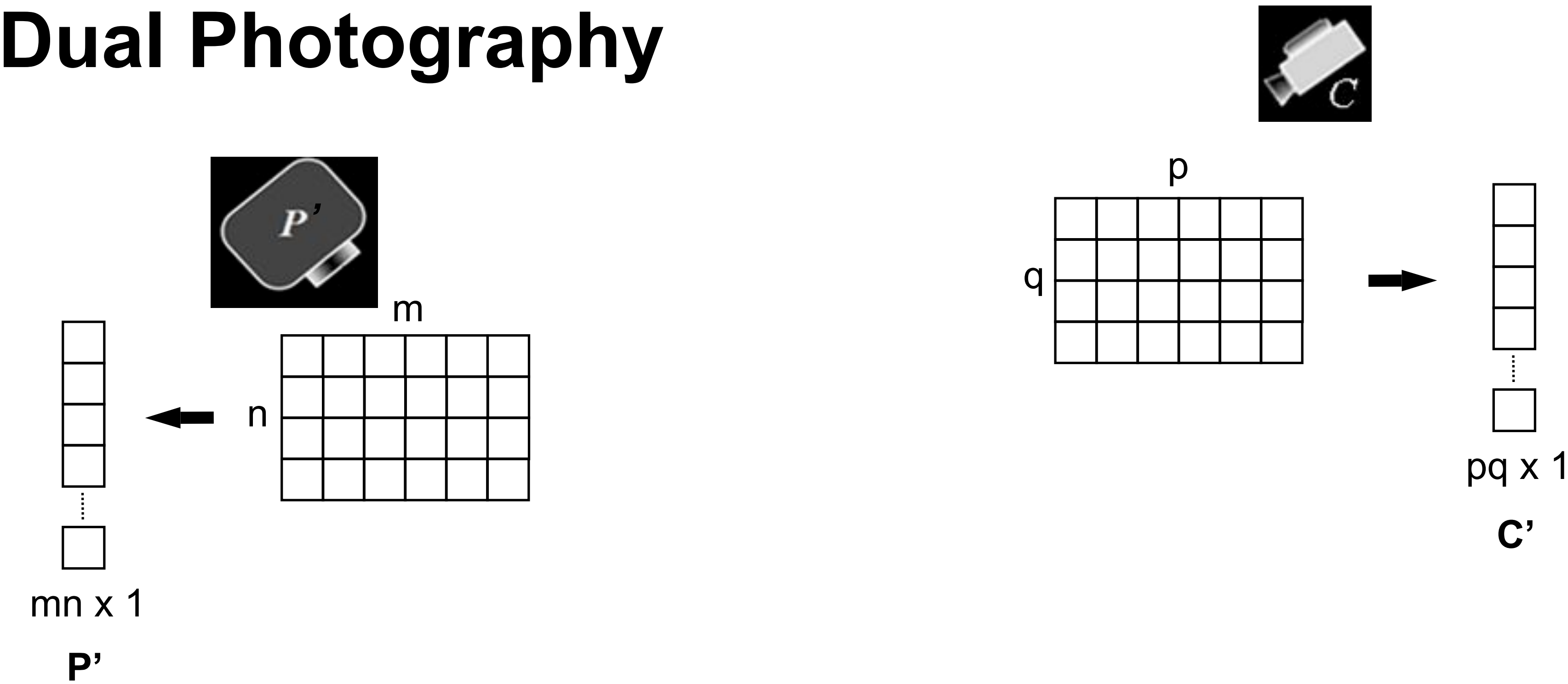
single camera & projector capture 4D slice of 8D reflectance field



Acquisition

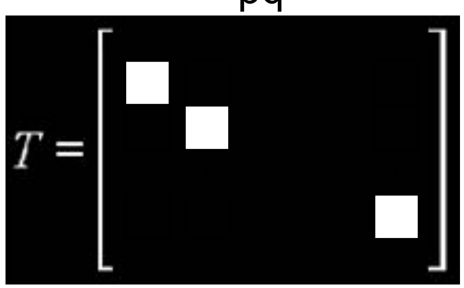


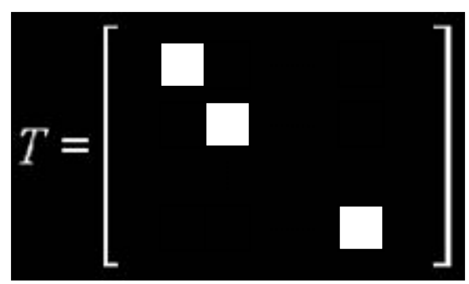
Dual Photography



$$c = Tp$$

$$c' = T^T p'$$

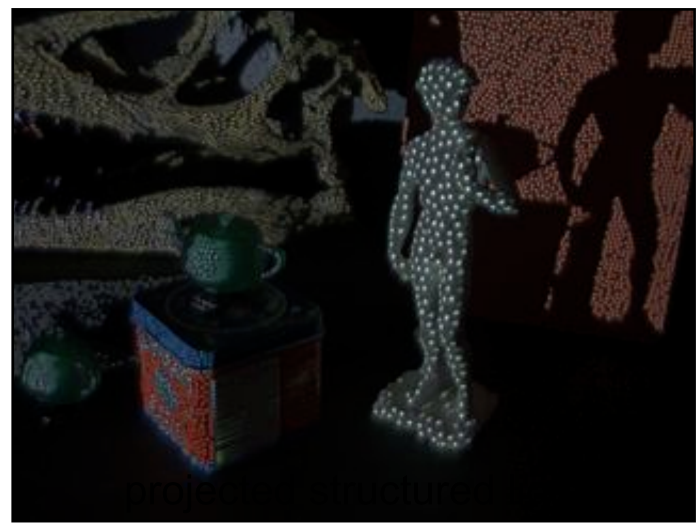




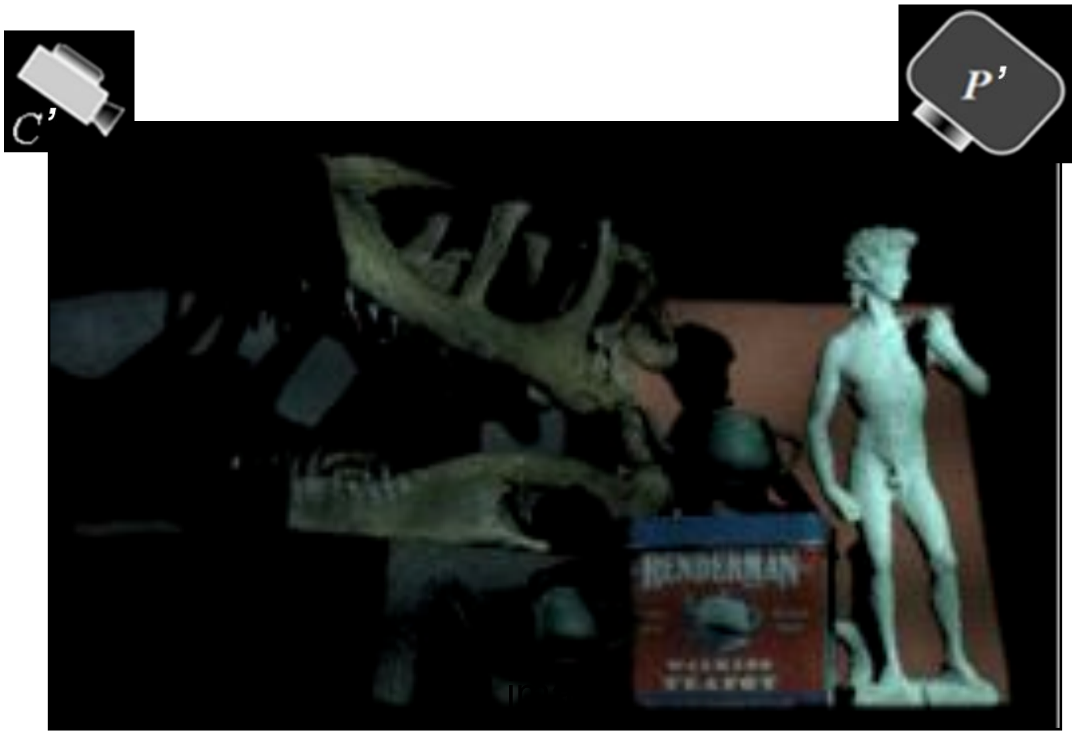
Dual Photography

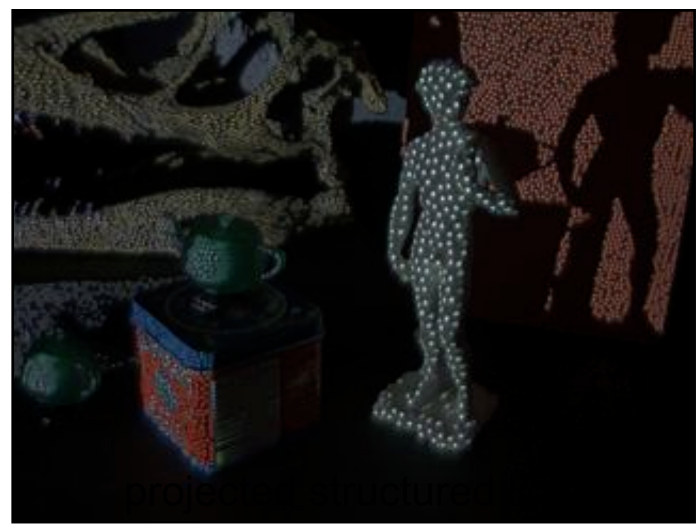
Dual Photography

Dual Photography



Dual Photography

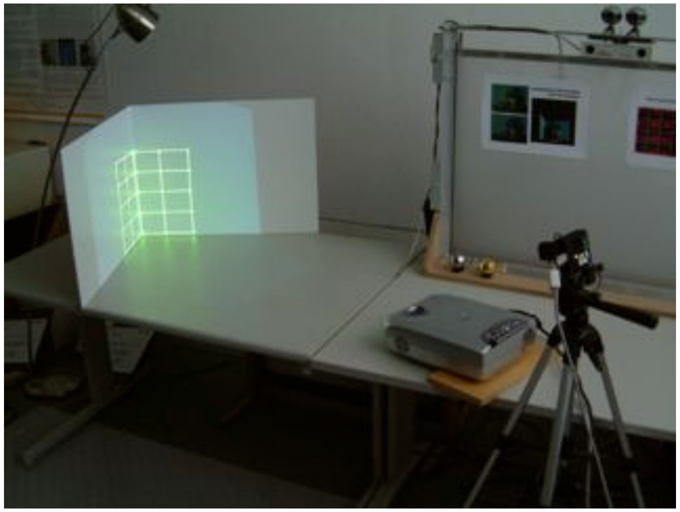




more information on
dual photography:
Sen,et al.,
Siggraph'05

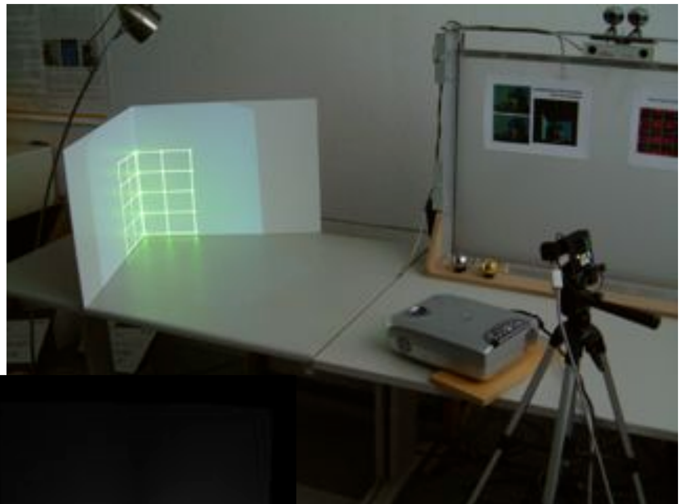
Form-Factors from Light Transport Matrix

Form-Factors from Light Transport Matrix

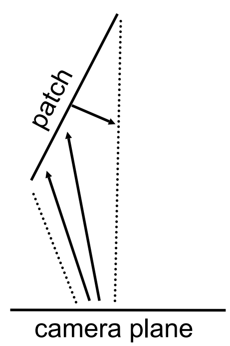


experimental setup

Form-Factors from Light Transport Matrix

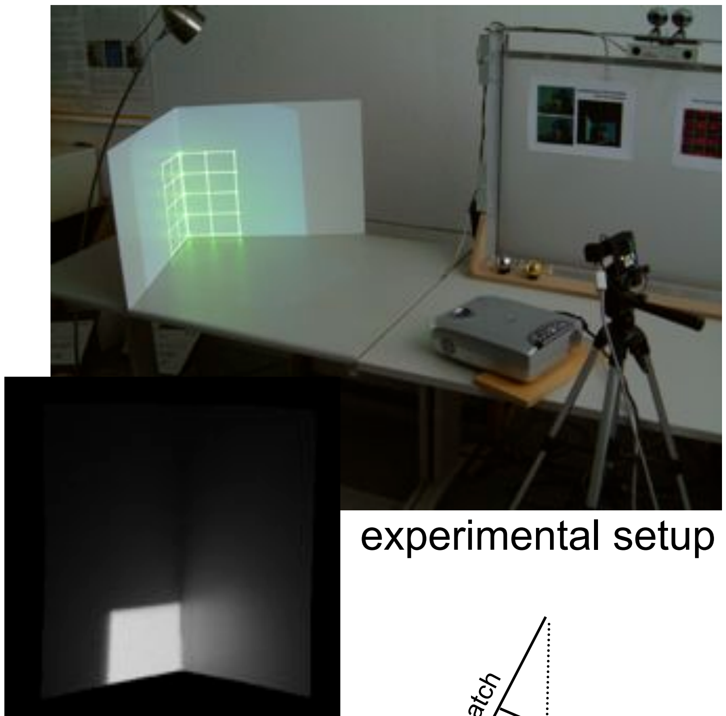


experimental setup



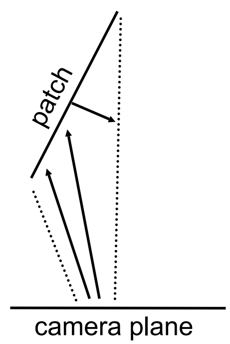
$$M_e = \frac{d^2}{\cos\alpha} L_e$$

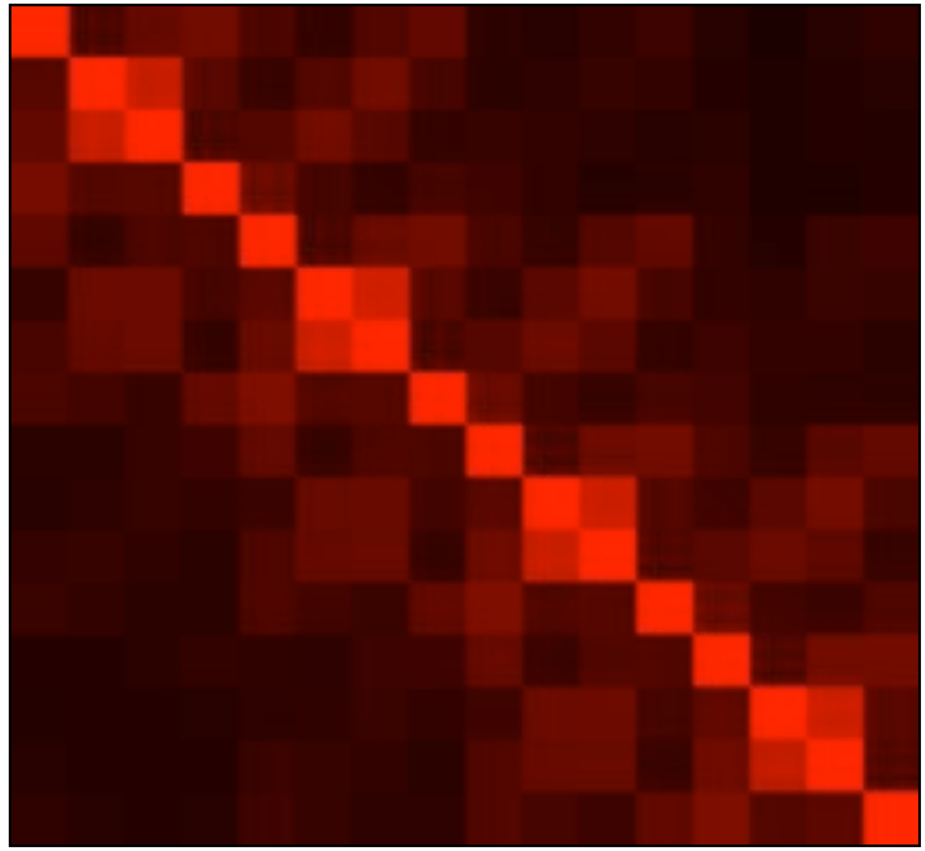
Form-Factors from Light Transport Matrix



experimental setup

$$M_e = \frac{d^2}{\cos\alpha} L_e$$





measured 16x16 form-factor matrix
(computed from light transport matrix)

Global Radiometric Compensation

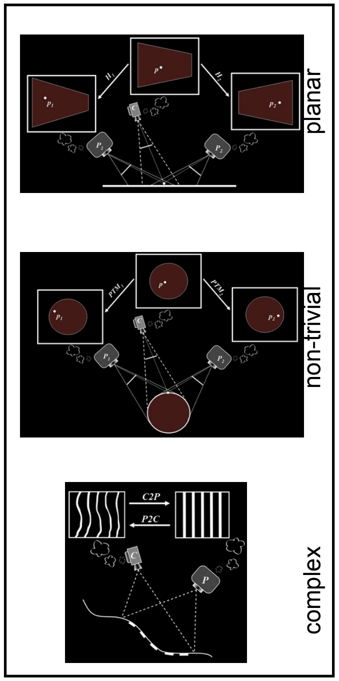
Global Radiometric Compensation

- traditional radiometric compensation requires direct projector-camera pixel correspondence
- include arbitrary global illumination effects using T
- apply inverse light transport $T^{-1}C=P$
- since T is huge, decompose it into clusters and solve in real-time on GPU

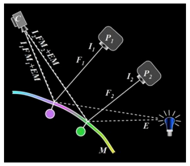
$$C = T\,P:\quad \begin{bmatrix} c_{10} \\ c_{11} \\ c_{12} \\ c_{13} \\ c_{14} \end{bmatrix} = \begin{bmatrix} t^4_{10} & t^3_{10} \\ t^4_{11} & t^3_{11} \\ t^4_{12} & t^3_{12} \\ t^4_{13} & t^3_{13} \\ t^4_{14} & t^3_{14} \end{bmatrix} \begin{bmatrix} p_4 \\ p_3 \end{bmatrix}$$

$$T^{-1}\,C = P:\quad \begin{bmatrix} t^4_{10} & t^4_{11} & t^4_{12} & t^4_{13} & t^4_{14} \\ t^3_{10} & t^3_{11} & t^3_{12} & t^3_{13} & t^3_{14} \end{bmatrix}^{-1} \begin{bmatrix} c_{10} \\ c_{11} \\ c_{12} \\ c_{13} \\ c_{14} \end{bmatrix} = \begin{bmatrix} p_4 \\ p_3 \end{bmatrix}$$

Outlook

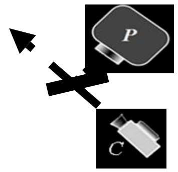


geometric warping

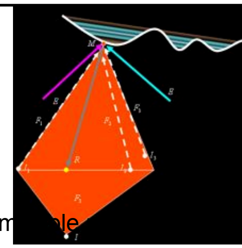

single projector

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

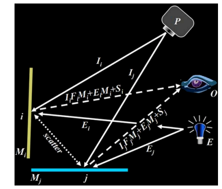
color mixing



dynamic adaptation

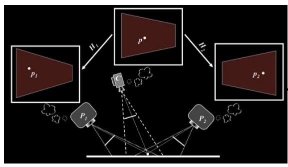

m le

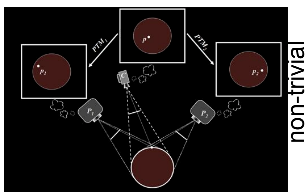

perception

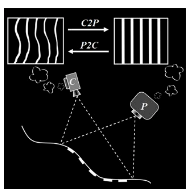

global effects

radiometric compensation

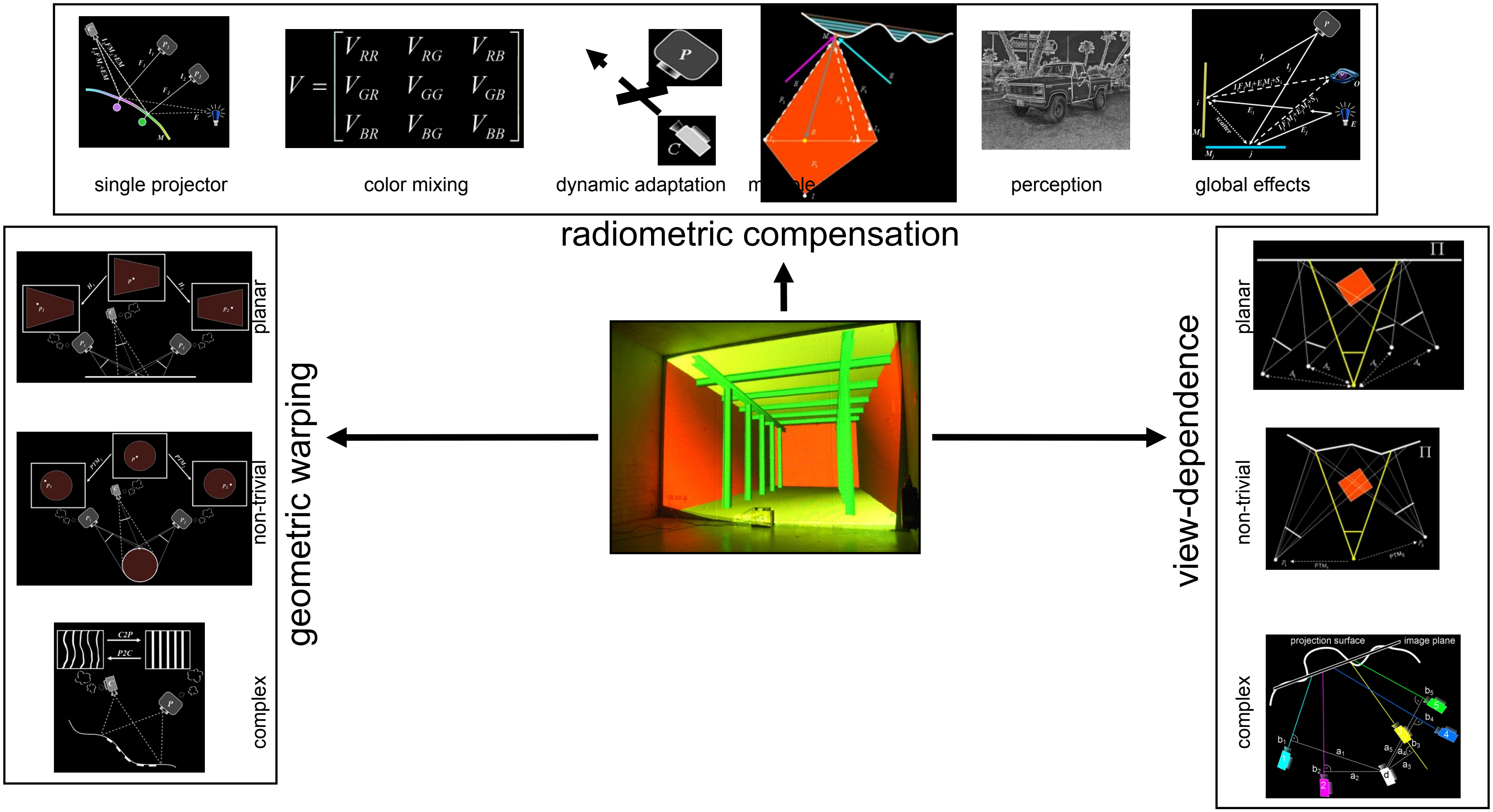
geometric warping

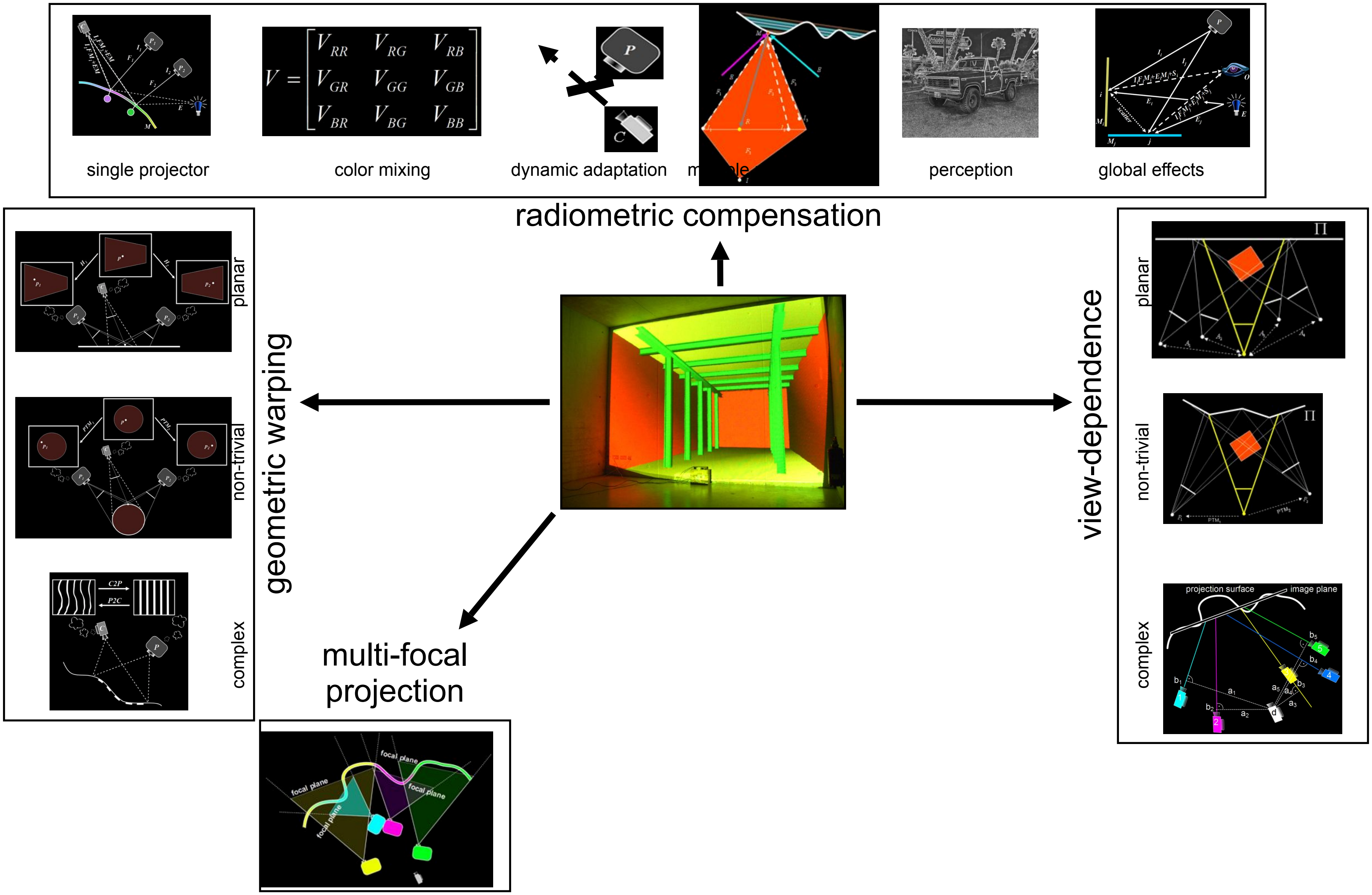

planar

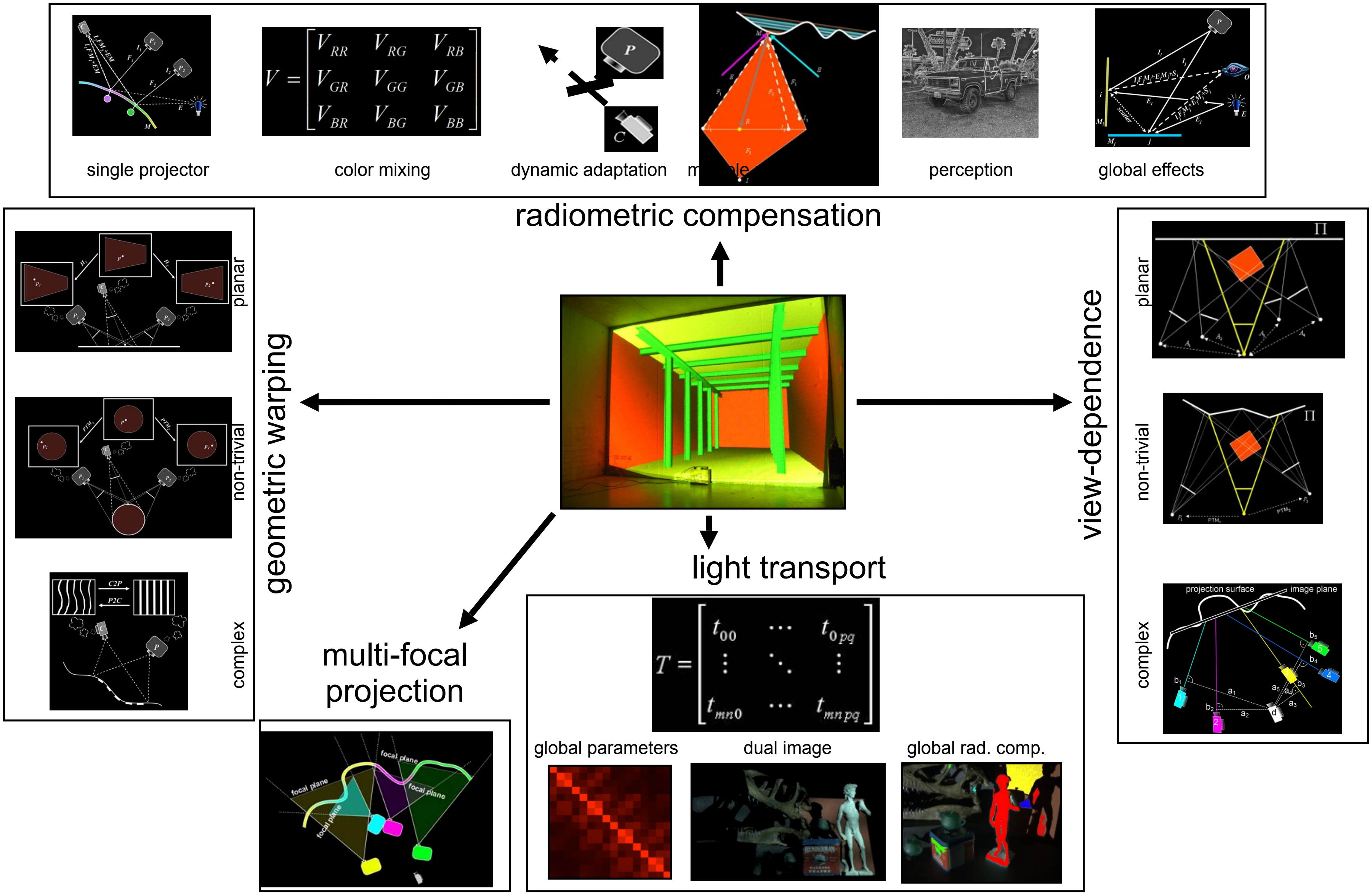

non-trivial



complex


single projector
color mixing
dynamic adaptation
perception
global effects
radiometric compensation
geometric warping
planar
non-trivial
complex
view-dependence
planar
non-trivial
complex
projection surface
image plane


single projector
color mixing
dynamic adaptation
perception
global effects
radiometric compensation
geometric warping
planar
non-trivial
complex
view-dependence
planar
non-trivial
complex
projection surface
image plane
multi-focal projection
focal plane
focal plane
focal plane
focal plane


single projector
color mixing
dynamic adaptation
perception
global effects
radiometric compensation
geometric warping
planar
non-trivial
complex
view-dependence
planar
non-trivial
complex
projection surface
image plane
light transport
multi-focal projection
focal plane
global parameters
dual image
global rad. comp.

Limitations

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- technological limitations of projectors:
  - brightness, resolution, focal depth

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  - brightness, resolution, focal depth → can be solved by using multiple projectors (or wait for better ones)
  - black-level and dynamic range

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  - black-level and dynamic range → wait for HDR light-valve or laser projectors
  - size, cost, portability

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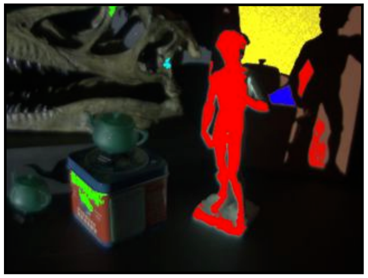
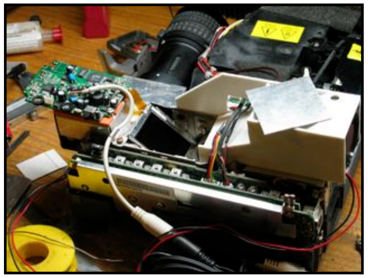
- technological limitations of projectors:
  - brightness, resolution, focal depth → can be solved by using multiple projectors (or wait for better ones)
  - black-level and dynamic range → wait for HDR light-valve or laser projectors
  - size, cost, portability → wait for (good enough) pocket projectors
- technological limitations of cameras:

Future Work

Future Work

- new techniques:
  - consider human visual perception
    - spent computational power only on overcoming limitations that can actually be perceived
  - consider global effects
    - inter-reflections, scattering, etc.





Selected Papers on Geometric Correction

Selected Papers on Geometric Correction

Bimber, O., Wetzstein, G., Emmerling, A., & Nitschke, C. (2005). Enabling View-Dependent Stereoscopic Projection in Real Environments. *Proc. of IEEE/ACM International Symposium on Mixed and Augmented Reality (ISMAR'05)*, 14-23.

Low, K-L., Welch, G., Lastra, A., & Fuchs, H. (2001). Life-Sized Projector-Based Dioramas, *Proc. Symp. Virtual Reality Software and Technology (VRST'01)*, 93-101.

Raskar, R. (1999). Oblique Projector Rendering on Planar Surfaces for a Tracked User. *Proc. of ACM Siggraph'99*, sketch.

Raskar, R., Brown, M.S., Yang, R., Chen, W., Welch, G., Towles, H., Seales, B., & Fuchs, H. (1999b). Multi-projector displays using camera-based registration, *Proc. of IEEE Visualization* (IEEE Viz'99), 161-168.

Raskar, R., Welch, G., Low, K.L. & Bandyopadhyay, D. (2001). Shader Lamps: Animating real objects with image-based illumination. *Proc. of Eurographics Rendering Workshop*, 89-102.

Selected Papers on Radiometric Compensation

Selected Papers on Radiometric Compensation

Bell, I.E. (2003). Neutralizing Paintings with a Projector. *Proc. of SPIE/IS&T*, 5008, 560-568.

Bimber, O., Coriand, F., Kleppe, A., Bruns, E., Zollmann, S., & Langlotz, T. (2005). Superimposing Pictorial Artwork with Projected Imagery. *IEEE MultiMedia*. 12(1), 16-26.

Bimber, O., Grundhöfer, A., Zeidler, T., Danch, D., & Kapakos, P. (2006). Compensating Indirect Scattering for Immersive and Semi-Immersive Projection Displays. *Proc. of IEEE Virtual Reality (IEEE VR'06)*.

Fujii, K., Grossberg, M.D., & Nayar, S.K. (2005). A projector-camera system with real-time photometric adaptation for dynamic environments. *Proc. of Computer Vision and Pattern Recognition (CVPR'05)*, 2, 20-25.

Grossberg, M.D., Peri, H., Nayar, S.K., & Bulhumeur, P. (2004). Making One Object Look Like Another: Controlling Appearance Using a Projector-Camera System. *Proc. of IEEE Conference on Computer Vision and Pattern Recognition (CVPR'04)*, 1, 452-459.

Nayar, S.K., Peri, H., Grossberg, M.D., & Belhumeur, P.N. (2003). A Projection System with Radiometric Compensation for Screen Imperfections. *Proc. of International Workshop on Projector-Camera Systems (ProCams'03)*.

Wang, D., Sato, I., Okabe, T., & Sato, Y. (2005). Radiometric Compensation in a Projector-Camera System Based on the Properties of Human Vision System. *In Proc. of IEEE International Workshop on Projector-Camera Systems (ProCams'05)*.

Yoshida, T., Horii, C. & Sato, K. (2003). A Virtual Color reconstruction System for Real Heritage with Light Projection. *Proc. of Virtual Systems and Multimedia*, 158-164.

Selected Papers Other and Related Techniques

Selected Papers Other and Related Techniques

Bimber, O. & Emmerling, A. (2006). Multi-Focal Projection: A Multi-Projector Technique for Increasing Focal Depth. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*.

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Thank you!

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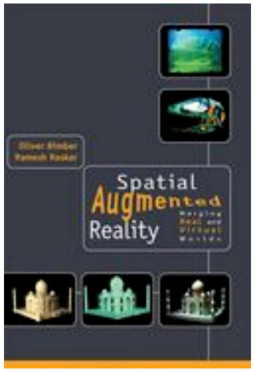

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Thank you!

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