# Building Illumination Coherent 3D Models of Large Scale Outdoor Scenes

Alejandro Troccoli
Peter K. Allen
Dept. of Computer Science
Columbia University

Columbia Vision + Graphics Center

# The problem

3D Model

# The problem

# Previous approaches

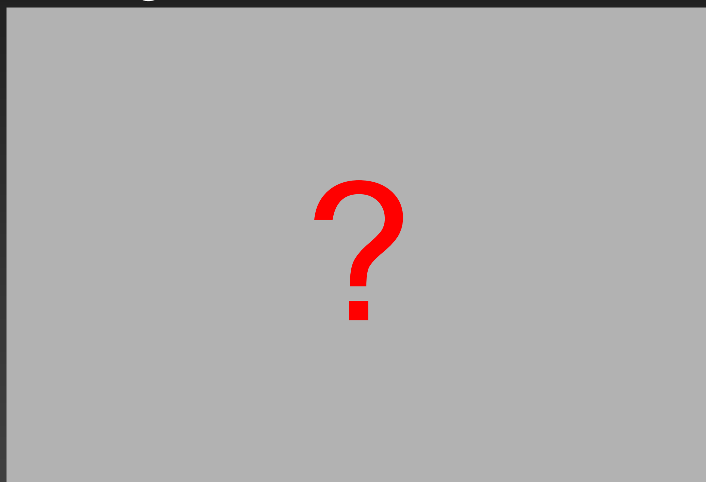
- Weighted blending
  - Pictures acquired under same illumination
- Color correction and relighting
  - Relighting faces [Roy 03]
  - Color correcting small models [Agathos 03]
- Inverse rendering
  - Estimate reflectance property from images with known/measured lighting [Debevec 04]

# Our Method

- Relighting method
  - Outdoor scenes
  - Can be used to perform de-shadowing
- Texture and shading factorization
  - No need to measure illumination
  - Compute diffuse reflectance

# Relighting

Images




Illumination

Relight

Sky images courtesy of Stumpfel and Debevec

# Irradiance ratio

Irradiance changed

Intensity = albedo * irradiance

Distant illumination – no shadows nor interreflections

# Irradiance ratio

$I_1 = \rho * Irr_1$

$I_2 = I_1 * ratio_{2-1}$

$ratio_{2-1} = Irr_2/Irr_1$

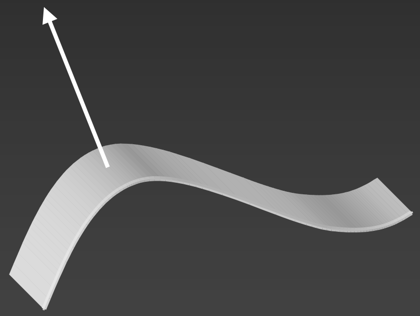
# The solution

1. Compute irradiance ratio from overlap region

2. Relight

# Irradiance ratio map

Per surface normal

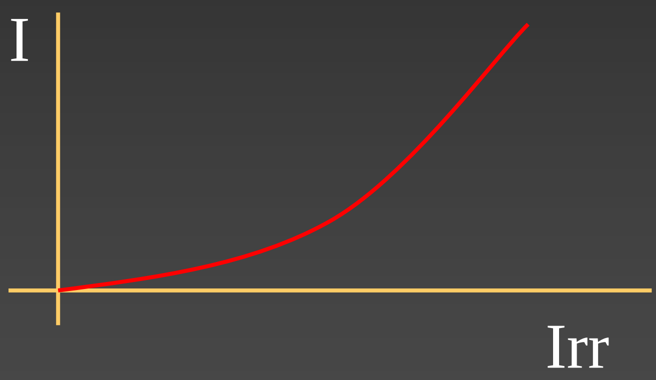


$(\theta, \phi) \rightarrow$ ratio

# Irradiance ratio map

Compute from HDR images

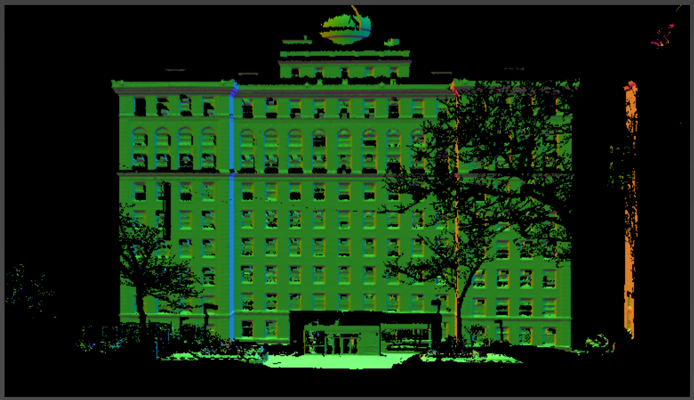
1. Linearize camera




2. Compute

$$\text{ratio}_{2\text{-}1} = Irr_2 / Irr_1 = I_2 / I_1$$

Must look up normals



Color encoded normals

# Relighting

Per pixel

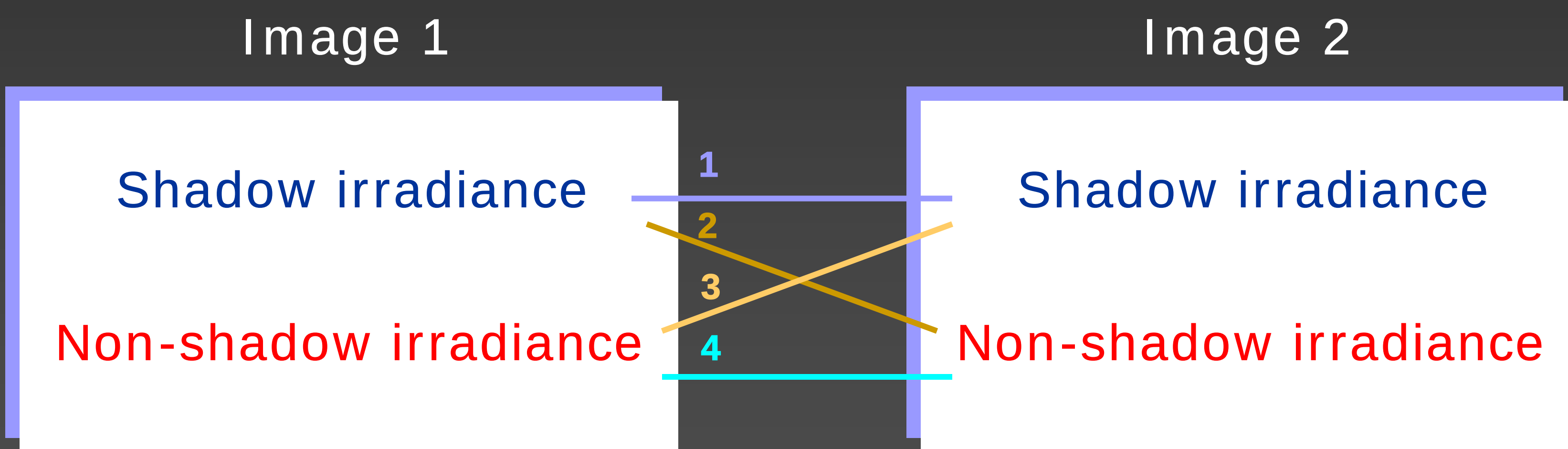
1. Lookup normal
2. Lookup irradiance ratio
3. Multiply

Shadows are a problem

# Handling shadows

Shadow irradiance $\neq$ Non-shadow irradiance

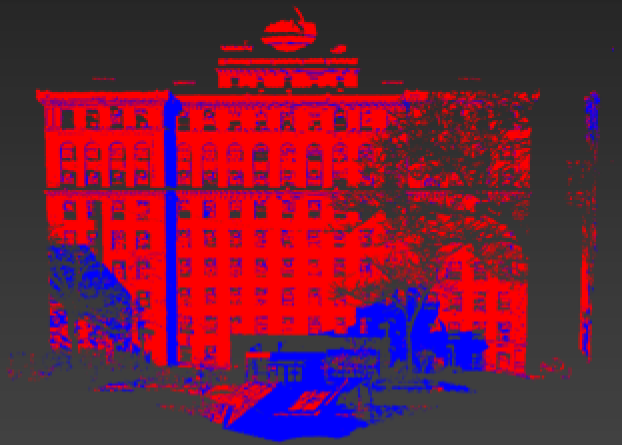
Treat them separately

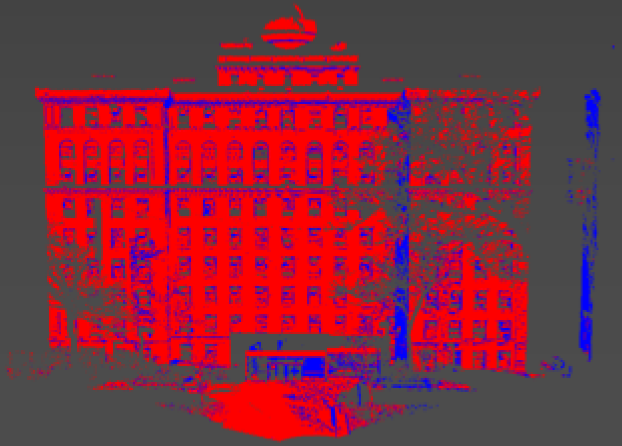



Compute 4 irradiance ratio maps

# Handling shadows

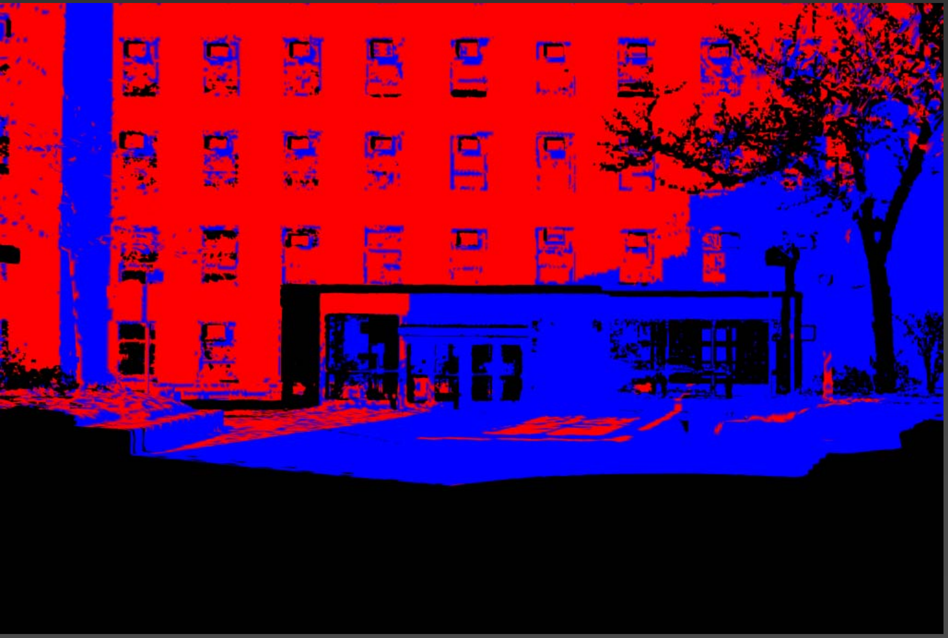
Create shadow map





# Shadow detection

- Penumbras can be a problem



Geometry based shadow map

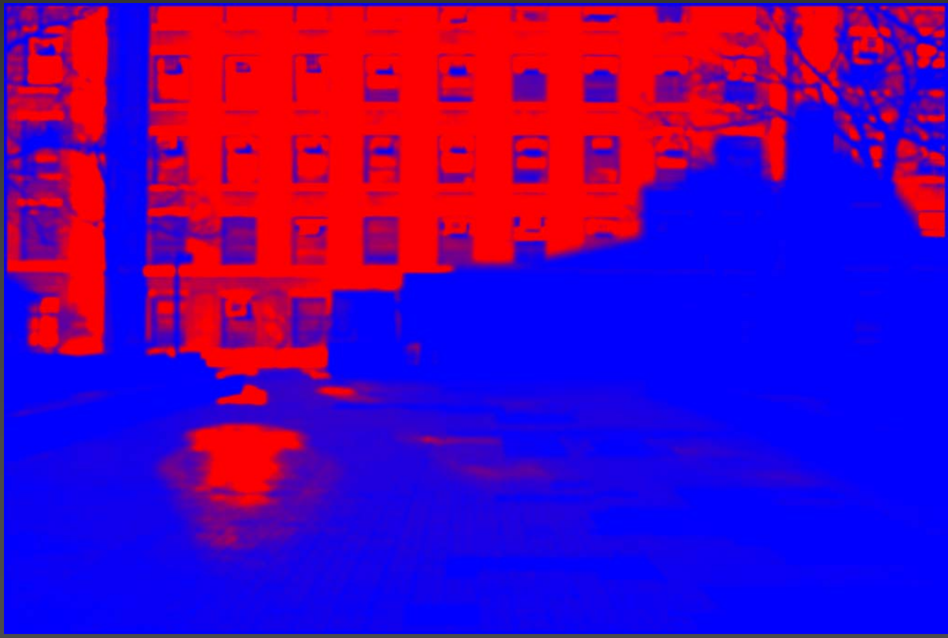


Image based shadow map

# Image based shadow detection

- Two thresholds $S_0$ and $S_1$
  - Everything below $S_0$ = shadow
  - Everything above $S_1$ = not shadowed
  - In between = penumbra
- After we compute the IRMs
  - Update penumbra values in the region of overlap

# Relighting shadows

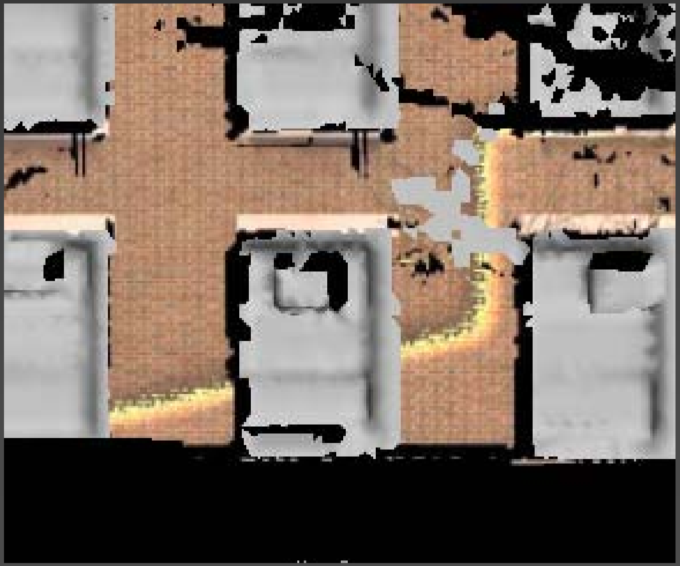
Per pixel

1. Lookup normal
2. Lookup shadow bits
3. Select ratio map
4. Lookup irradiance ratio
5. Multiply

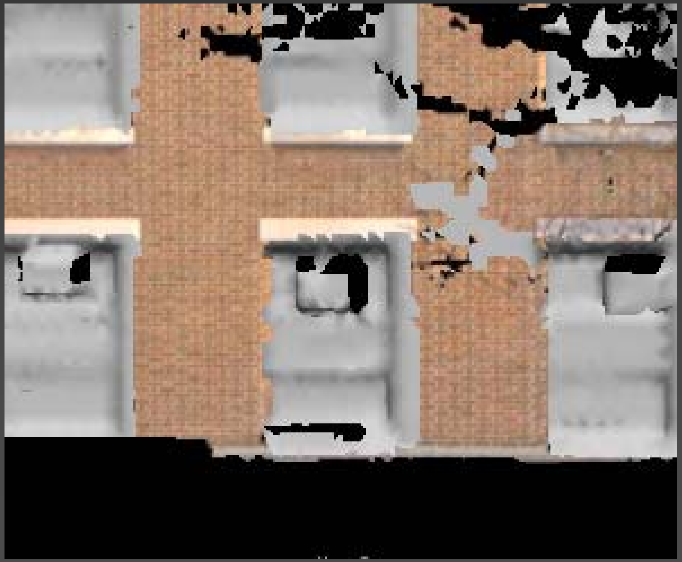
# Relighting penumbras

Penumbras: between shadow and non-shadow

Interpolate between irradiance ratio maps



Before interpolation



After interpolation

# Relighting vs de-shadowing

- Relighting
  - Keep shadows of target illumination
- De-shadowing
  - Set all pixels in target shadow mask as lit

# Experimental verification

Campus example

At 10am

At 2pm

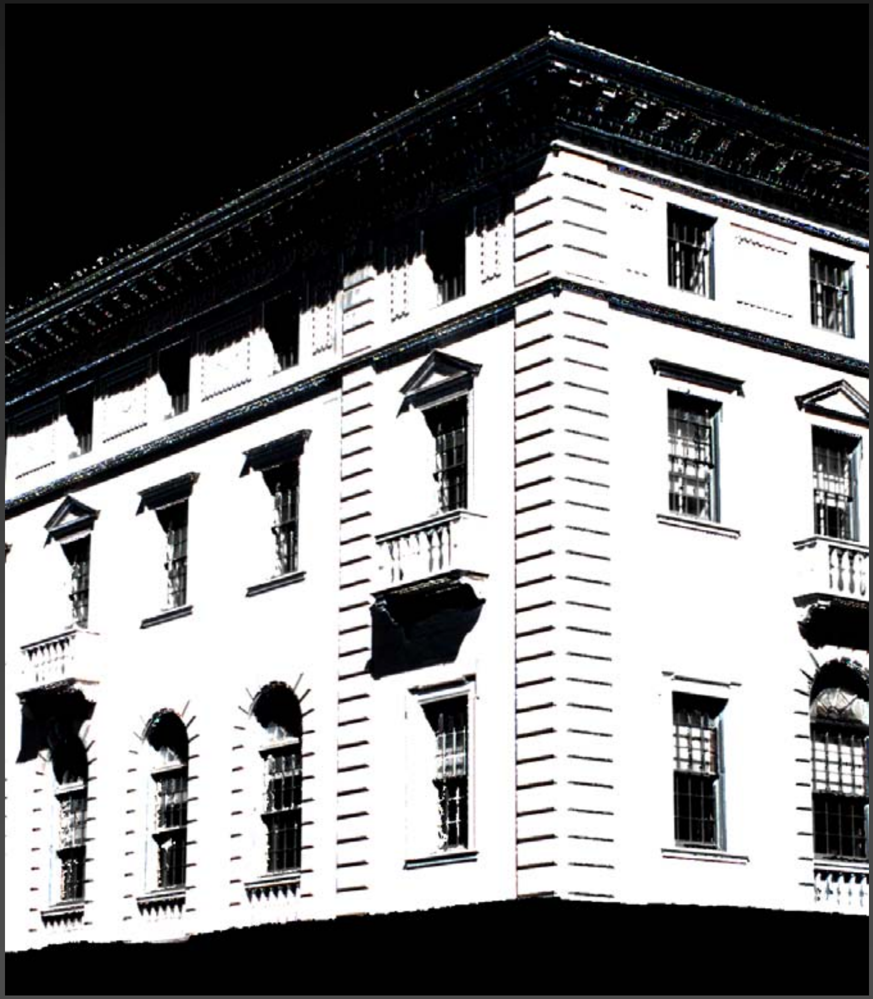
Masked out windows, trees and ground

# Results Pupin Hall

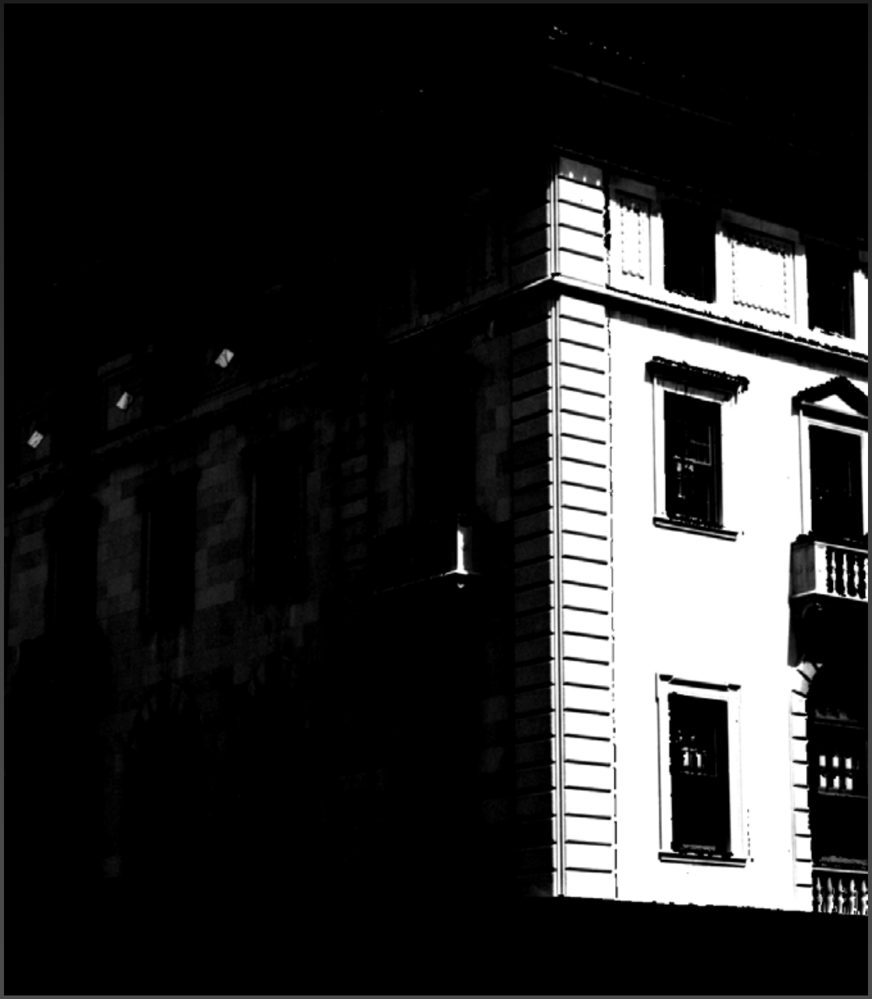
Before relighting

After relighting

# Results Casa Italiana



3:22pm



1:28pm

# Results Casa Italiana

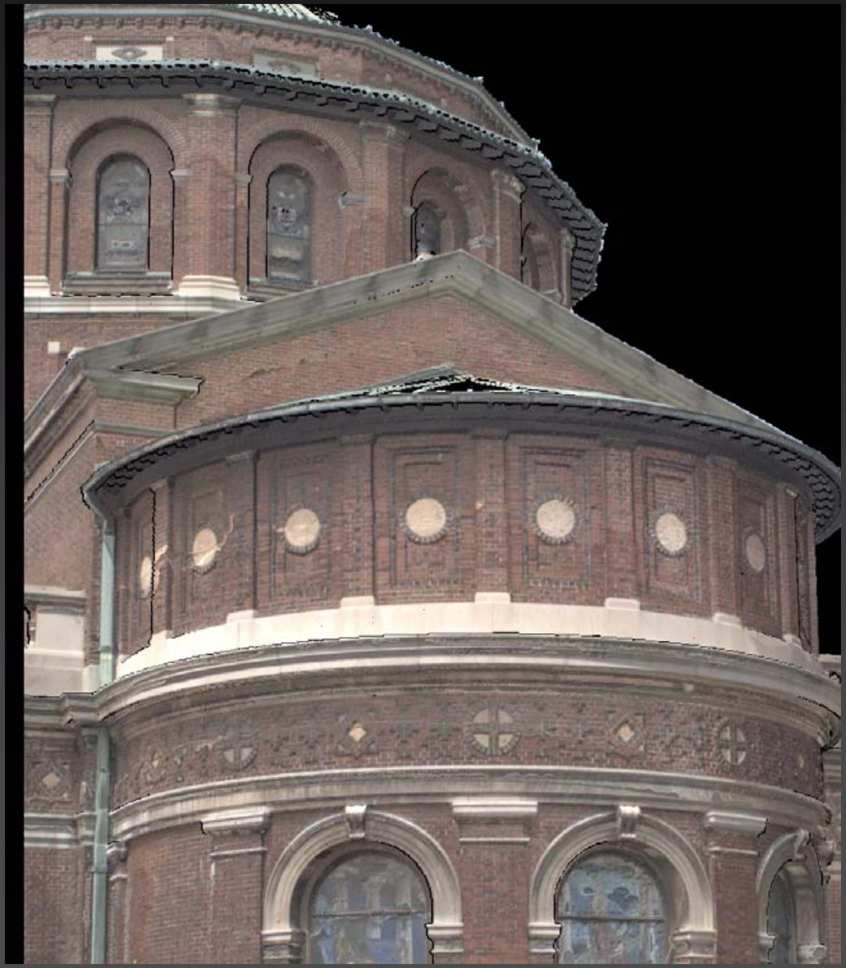
3:22pm | 1:28pm | After relighting / After deshadowing

# Results St Paul’s Chapel

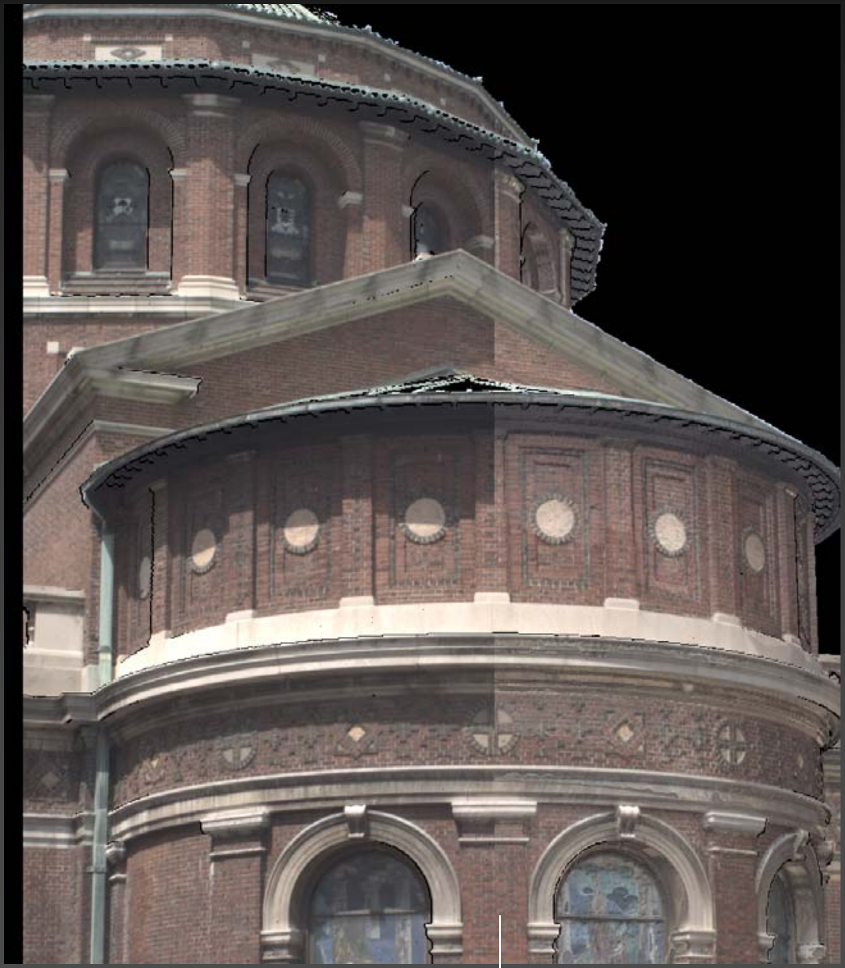
11:22 am

12:35 pm

# Results St Paul's Chapel



Deshadowed



Before | After

# Potential sources of error

- Image registration errors
- Shadow detection errors
- Non-Lambertian reflectance and interreflections

# Talk outline

- Motivation √
- Contributions √
- Methodology and results
  - Line-based image registration √
  - Shadow based registration √
  - Texture integration √
  - **Shading and texture factorization**
- Future work and conclusions

# Factorization

- Compute diffuse shading of each image
- Solve for spatially varying albedo map

- Advantages over relighting:
  - Ability to create new renderings under different illuminations

# Factorization

**INPUTS**

Input image 1

Input image 2

Normals map

**Factorization algorithm**

**OUTPUTS**

Irradiance Image 1

Irradiance image 2

Albedo map

# Factorization steps

**Compute ratio image** → **Solve for irradiance maps** → **Solve for albedo map**

*Ratio images of a Lambertian object are texture-free, and only depend on the illumination of the scene.*

*Select illumination model: point light source or generalized illumination*

*Albedo map is computed taking the ratio of the original images and the irradiance maps.*

# Compute ratio image

Ratio image: $$R(x,y)=\frac{I_1(x,y)}{I_2(x,y)}$$

For a Lambertian object under distant illumination, ratio image is texture-free:

# Solving for irradiance

## Model 1. Point light sources

Irradiance: $$E(\vec{n}) = L \max(\vec{n} \cdot \vec{l}, 0)$$

Ratio: $$R(x,y) = \frac{L_1 \max[\vec{n}(x,y) \cdot \vec{l}_1, 0]}{L_2 \max[\vec{n}(x,y) \cdot \vec{l}_2, 0]}$$

Solve for: $l_1$, $l_2$ and $L_1/L_2$

# Solving for irradiance

## Model 2. SH illumination

Irradiance: $$E(\vec{n}) = \sum L_i A_i Y_i(\vec{n})$$

Ratio: $$R(x,y) = \frac{\sum L_{2i} A_i Y_i(\vec{n}(x,y))}{\sum L_{1i} A_i Y_i(\vec{n}(x,y))}$$

Solve for: $L_{1[1..n]}$, $L_{2[0..n]}$, $L_{10} = 1$

Alternatively, replace **SH** basis by **PCA** basis computed analytically.

# Solving for irradiance

**Model 3. Sun + sky illumination**

Irradiance:
$$E(\vec{n}) = \underbrace{P(\vec{n}\cdot\vec{s})^{+}}_{\text{Point light}} + \sum \underbrace{L_i A_i Y_i(\vec{n})}_{\text{Ambient}}$$

Ratio:
$$\frac{P_2(\vec{n}(x,y)\cdot\vec{s}_2)^{+} + \sum L_{2i} A_i Y_i(\vec{n}(x,y))}{P_1(\vec{n}(x,y)\cdot\vec{s}_1)^{+} + \sum L_{1i} A_i Y_i(\vec{n}(x,y))}$$

Solve for: $P_2$, $L_{1[0..n]}$, $L_{2[0..n]}$, $P_1 = 1$

# Solving for irradiance

Solve linear system of equations

$$\begin{bmatrix} \vec{n}_0^T & -R_0\,\vec{n}_0^T \\ \vec{n}_1^T & -R_1\,\vec{n}_1^T \\ \vec{n}_2^T & -R_2\,\vec{n}_2^T \\ \vdots & \vdots \\ \vec{n}_k^T & -R_k\,\vec{n}_k^T \end{bmatrix} \begin{bmatrix} \vec{l}_1 \\ L_2\,\vec{l}_2 \end{bmatrix} = \mathbf{0}$$

(e.g. matrix for model 1.)

- Linear systems of the form ***A***x = 0. Solution is null-space of ***A.***
- One system of equations per R,G,B channel
- Scale and chromatic ambiguity – solved by fixing one of the unknowns to 1.

# Solving for albedo maps

- Once irradiance maps are known

$$\rho_1(x, y) = \frac{I_1(x, y)}{E_1(\vec{\mathrm{n}}(x, y))}$$

# Factorization results - PL

## Model 1. Point light sources

Synthetic (known geometry)

Normal maps from photometric stereo

Scanned models

# Factorization results - PL

Resulting albedo map

Resulting irradiance map 1

Resulting irradiance map 2

# Factorization results - PL

| | Point source 1 | | | Point source 2 | | | Rel. intensity |
|---|---|---|---|---|---|---|---|
| | x | y | z | x | y | z | (R, G, B) |
| Actual position | -0.58 | 0.36 | 0.73 | 0.28 | -0.28 | 0.92 | (5.00, 10.00, 20.00) |
| Sphere | -0.58 | 0.36 | 0.73 | 0.27 | -0.28 | 0.92 | (5.03, 10.10, 20.48) |
| Armadillo | -0.58 | 0.35 | 0.73 | 0.27 | -0.28 | 0.92 | (5.11, 10.27, 20.88) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Actual position | 0.40 | 0.48 | 0.78 | -0.32 | 0.49 | 0.86 | (1.00, 1.00, 1.00) |
| Buddha | 0.39 | 0.57 | 0.71 | -0.34 | 0.54 | 0.76 | (1.03, 1.03, 1.04) |
| Cat | 0.39 | 0.49 | 0.78 | -0.33 | 0.47 | 0.82 | (1.09, 1.09, 1.05) |
| Owl | 0.39 | 0.48 | 0.78 | -0.31 | 0.44 | 0.84 | (1.02. 1.01, 1.00) |

# Factorization results - SH

Resulting albedo map

Resulting irradiance map 1

Resulting irradiance map 2

# Factorization results - SH

Relative squared error

$$err = \frac{\left\| I^1 - I^0 \right\|^2}{\left\| I^0 \right\|^2}$$

| Model | Method | Error 1 | Error 2 |
|---|---|---|---|
| Sphere | PL | $< 0.1\%$ | $< 0.1\%$ |
| | PCA 5 | 0.40% | 0.20% |
| Armadillo | PL | $< 0.1\%$ | $< 0.1\%$ |
| | PCA 3 | 3.50% | 4.30% |
| Buddha | PL | 0.40% | 0.50% |
| | PCA 3 | 0.10% | 1.60% |
| Cat | PL | $< 0.1\%$ | $< 0.1\%$ |
| | PCA 3 | 4.40% | 4.50% |
| Owl | PL | $< 0.1\%$ | $< 0.1\%$ |
| | PCA 3 | 3.80% | 3.50% |

# Factorization: Eglise de Chappes

# Factorization: Eglise de Chappes

# Relighting Chappes

# Extending to multiple illum.

- For more than two images under different illuminations
  - Compute pair wise IRM
  - Transitive composition