Sampling and Reconstruction of Visual Appearance: From Denoising to View Synthesis

CSE 274 [Fall 2021], Lecture 9
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Applications
- Monte Carlo Rendering
- Light Transport Acquisition / Many Light Rendering
- Light Fields and Computational Photography
- View Synthesis
- Animation/Simulation (not covered in course)
- Introduce concepts of sparsity, coherence, compressive sensing for reconstruction

Acquiring Reflectance Field of Human Face [Debevec et al. SIGGRAPH 00]
Illuminate subject from many incident directions

Example Images

Motivation: Image-based Relighting
Sample Lighting Directions

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Sample Lighting Directions

Relight 256 Samples

Relight 4096 Samples

Relight +10000 Samples

Brute Force Capture Practically Impossible

Relighting as a Matrix-Vector Multiply

\[
\begin{bmatrix}
T_{11} & T_{12} & \cdots & T_{1M} \\
T_{21} & T_{22} & \cdots & T_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
T_{N1} & T_{N2} & \cdots & T_{NM}
\end{bmatrix}
\begin{bmatrix}
P_1 \\
P_2 \\
\vdots \\
P_N
\end{bmatrix} =
\begin{bmatrix}
L_1 \\
L_2 \\
\vdots \\
L_M
\end{bmatrix}
\]

Input Lighting (Cubemap Vector)

Output Image (Pixel Vector)

Precomputed Transport Matrix
Matrix Columns (Images)

\[
\begin{bmatrix}
T_{11} & T_{12} & \ldots & T_{1M} \\
T_{21} & T_{22} & \ldots & T_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
T_{N1} & T_{N2} & \ldots & T_{NM}
\end{bmatrix}
\]

(Pre)compute: Ray-Trace Image Cols

\[
\begin{bmatrix}
T_{11} & T_{12} & \ldots & T_{1M} \\
T_{21} & T_{22} & \ldots & T_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
T_{N1} & T_{N2} & \ldots & T_{NM}
\end{bmatrix}
\]

(Pre)compute 2: Rasterize Matrix Rows

\[
\begin{bmatrix}
T_{11} & T_{12} & \ldots & T_{1M} \\
T_{21} & T_{22} & \ldots & T_{2M} \\
T_{31} & T_{32} & \ldots & T_{3M} \\
\vdots & \vdots & \ddots & \vdots \\
T_{N1} & T_{N2} & \ldots & T_{NM}
\end{bmatrix}
\]

Outline

- Matrix Row-Column Sampling (Many Lights)
  (clustering for matrix completion of light transport)
- Compressive Sensing for Light Transport
- Matrix Completion

Hasan, Pellacini, Bala SIGGRAPH 07

Complex Illumination: A Challenge

Conversion to Many Lights

- Area, indirect, sun/sky

Courtesy Walter et al., Lightcuts, SIGGRAPH 05/06
A Matrix Interpretation

Problem Statement

- Compute sum of columns

\[ \text{Lights} = \sum (\text{Pixels}) \]

- Note: We don’t have the matrix data

Image as a Weighted Column Sum

- The following is possible:

  - Compute very small subset of columns
  - Compute weighted sum

- Use rows to choose a good set of columns!

Exploration and Exploitation

- Compute rows (explore)
- How to choose columns and weights?
- Compute columns (exploit)
- Weighted sum

Reduced Matrix

Clustering Approach

- Reduce columns
- Choose k clusters
- Choose representative columns
Reduced to Full

Representative columns
Use the same representatives for the full matrix
Weighted sum

Full Algorithm

Assemble rows into reduced matrix
Choose representatives
Compute columns (GPU)
Weighted sum

Results

• We show 5 scenes:
  - Temple
  - Trees
  - Bunny
  - Grand Central

• Show reference and 5x difference image
• All scenes have 100,000+ lights
• Timings
  – NVidia GeForce 8800 GTX
  – Light / surface sample creation not included

Results: Temple

• 2.1m polygons
• Mostly indirect & sky illumination
• Indirect shadows

Our result: 16.9 sec
(532 rows + 864 columns)
Reference: 20 min
(using all 100k lights)

Results: Kitchen

• 388k polygons
• Mostly indirect illumination
• Glossy surfaces
• Indirect shadows

Our result: 13.5 sec
(432 rows + 864 columns)
Reference: 13 min
(using all 100k lights)

Results: Trees

• 328k polygons
• Complex incoherent geometry

Our result: 2.9 sec
(100 rows + 200 columns)
Reference: 14 min
(using all 100k lights)
### Results: Bunny
- 869k polygons
- Incoherent geometry
- High-frequency lighting
- Kajiya-Kay hair shader

Our result: 3.8 sec (100 rows + 200 columns)
Reference: 10 min (using all 100k lights)

### Results: Grand Central
- 1.5m polygons
- Point lights between stone blocks

Our result: 24.2 sec (988 rows + 1176 columns)
Reference: 44 min (using all 100k lights)

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Gu et al. ECCV 08
Peers et al. SIGGRAPH 09
Sen and Darabi EG 09 (reading)

### Motivation: Image-based Relighting
Brute Force Capture Practically Impossible

Sample Lighting Directions

### Compressible / Sparseness

### Measurements
Compressible / Sparseness

• Sparsity / Compressibility:
  - Signals can be represented as a few non-zero coefficients in an appropriately-chosen basis, e.g., wavelet, gradient, PCA.

• For sparse signals, acquire measurements (condensed representations of the signals) with random projections.

\[ A \text{ Measurement Ensemble (m \times n) } \quad x \text{ Signal (n \times 1) } = \quad b \text{ Measurements (m \times 1) } \]

Compressive Sensing: A Brief Introduction

[Candes et al., 06][Donoho, 06]...
Compressive Sensing

Measurement Ensemble: $\Phi$

Sparse Signal: $x$

$N$ $M$

$M$

$N$

$y$

$y$

$y$
Compressive Sensing

\[ x = \arg\min_x \|x\|_1 \text{ s.t. } \Phi x = y \]

M ~ K \log N

Brute Force: Result

Scene: Diffuse Sphere
Lighting Resolution: 128 x 128
Measurements: 1000 Normal Distributed Noise Light Conditions
Reconstruction: 100 Haar Wavelet Coefficients

Each pixel computed separately
Spatial Coherence not exploited

Multi-resolution Approach
**Multi-resolution Approach**

- Brute Force Algorithm
- Compressive Decoding
- Reflectance Func.

**Results**

1000 Measurements
128 x 128 Lighting Resolution
128 Haar Wavelet Coefficients

**Resolution**

1000 Measurements
128 x 128 Lighting Resolution
128 Haar Wavelet Coefficients
Inhomogeneous Participating Media

Volume densities rather than boundary surfaces. Efficiency in acquisition is critical, especially for time-varying participating media.

Video clips are from http://www.lucidmovement.com

- Drifting Smoke of Incense
- Mixing a Pink Drink with Water

Gu, Nayar, Grinspun, Belhumeur, Ramamoorthi 08, 13

Compressive Structured Light

- Projector: DLP, 1024x768, 360 fps
- Camera: Dragonfly Express 8bit, 320x140 at 360 fps
- 24 measurements per time instance, and thus recover dynamic volumes up to 360/24 = 15 fps.

Milk Dissolving: One Instance of time

- Milk drops dissolving in a water tank.

Photograph
Measurements (24 images of size 128x250)
Reconstructed Volume (128x128x250)

Milk Dissolving: Time-varying Volume

- Milk drops dissolving in a water tank.

Video (15fps)
Reconstructed Volume (128x128x250)
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  - Extension to compressive sensing: Low rank matrices
  - Minimize matrix norm (rank), given some entries
  - Combine many ideas seen previously

Huo et al. SIGGRAPH Asia 16

Outline

- Matrix Completion
  - Extension to compressive sensing: Low rank matrices
  - Minimize matrix norm (rank), given some entries
  - Combine many ideas seen previously

Results (Participating Media)

- Light Transport for Acquisition, Many Light Rendering
- Compressive Sensing for projected patterns
- Matrix Completion for many light rendering
- Leverages popular ideas in applied math
- Consider all forms of coherence
- Think about modern extensions with deep learning