

## Sampling and Reconstruction of Visual Appearance

CSE 274 [Fall 2018], Lecture 10

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### Applications

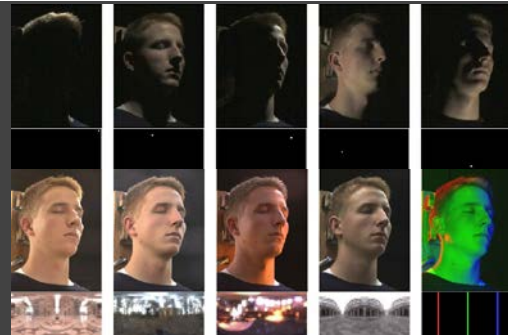
- Monte Carlo Rendering (biggest application)
  - *Light Transport Acquisition / Many Light Rendering*
  - Light Fields and Computational Photography
  - Animation/Simulation (not covered in course)
- 
- Introduce concepts of sparsity, coherence, compressive sensing for reconstruction

### Acquiring Reflectance Field of Human Face [Debevec et al. SIGGRAPH 00]

Illuminate subject from many incident directions



### Example Images



### Motivation: Image-based Relighting

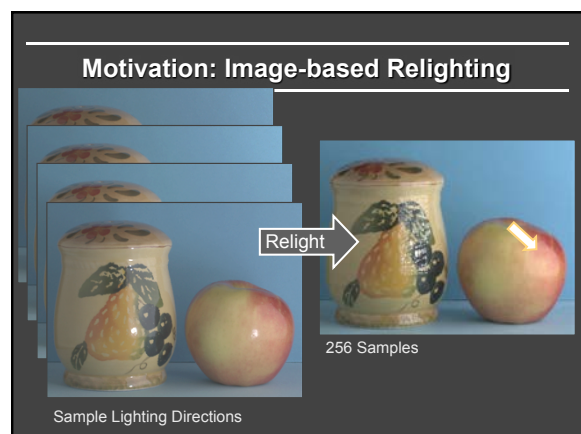
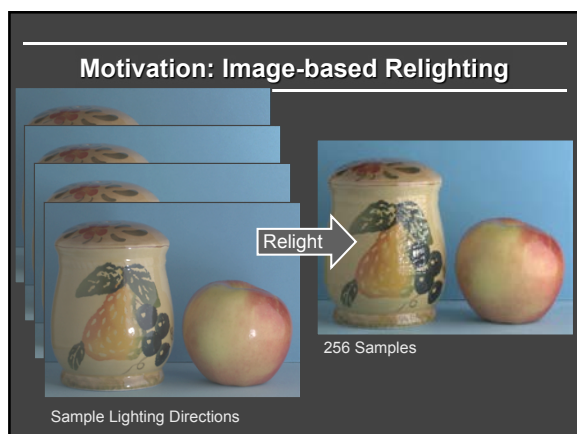
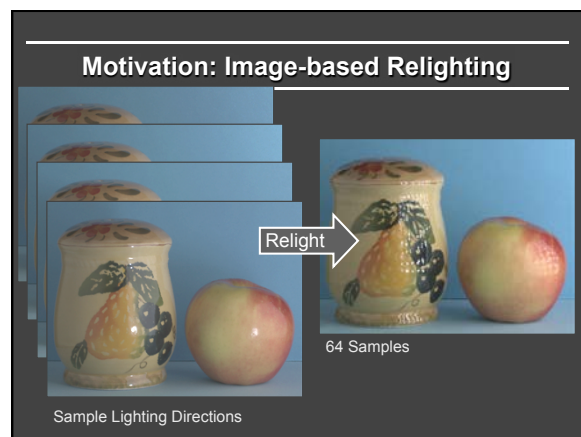
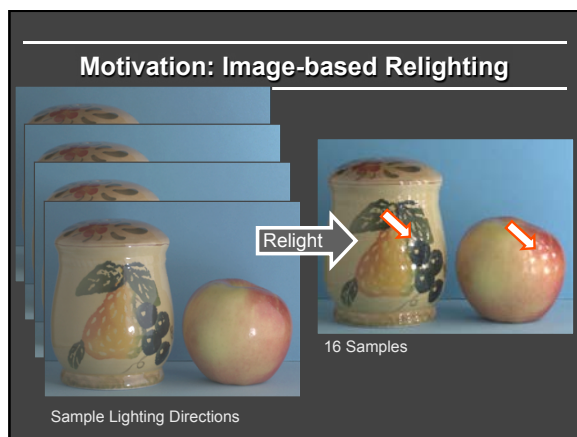
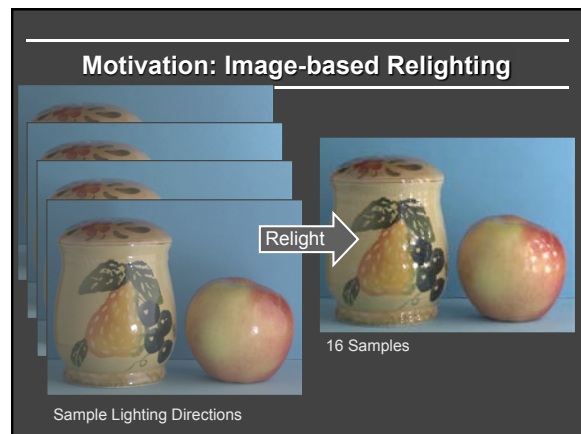
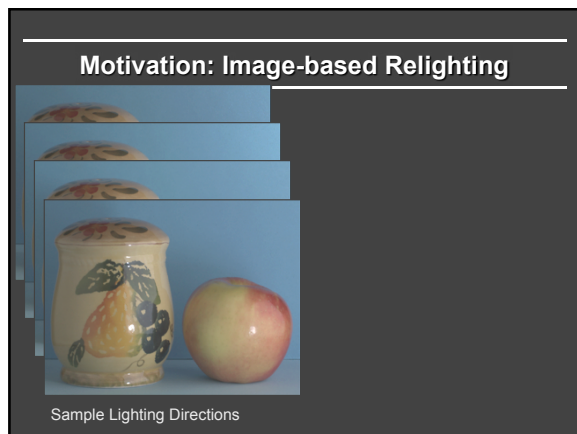


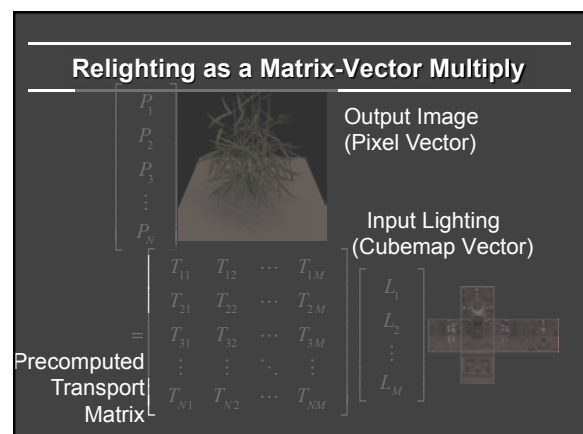
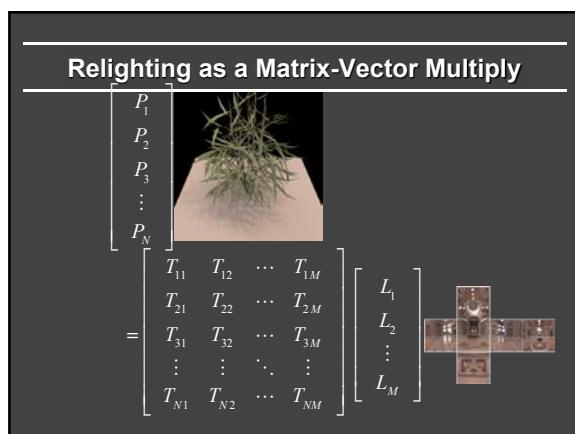
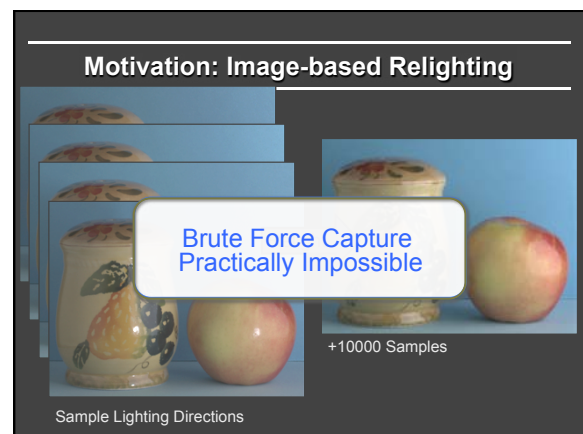
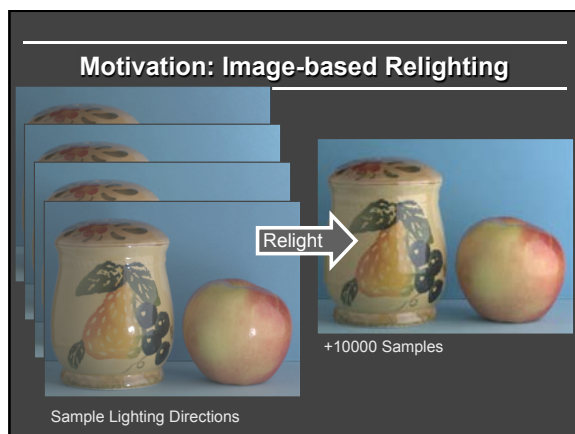
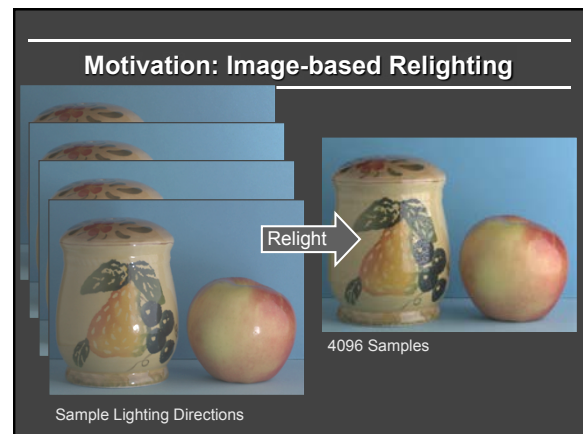
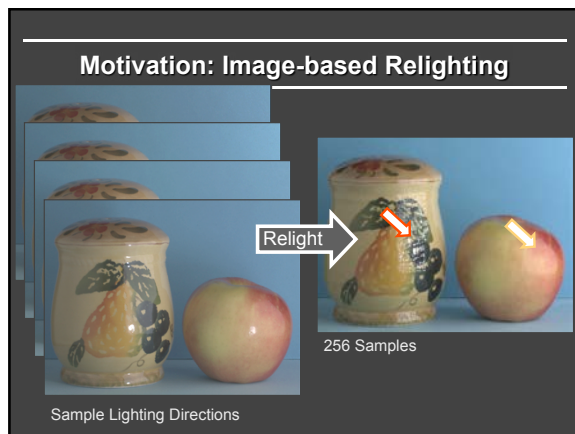
Sample Lighting Directions

### Motivation: Image-based Relighting



Sample Lighting Directions





### Matrix Columns (Images)

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



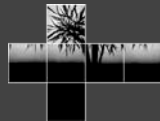
### (Pre)compute: Ray-Trace Image Cols

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



### (Pre)compute 2: Rasterize Matrix Rows

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

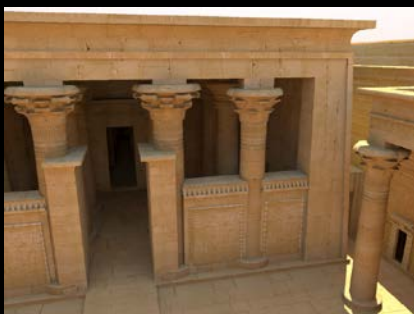


### Outline

- 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



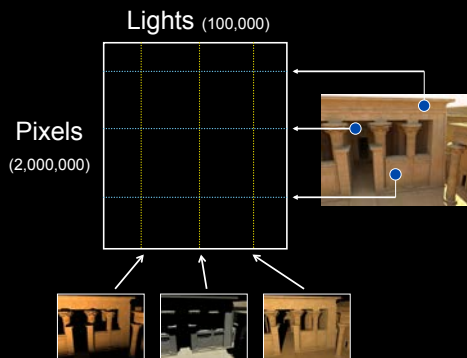
### Conversion to Many Lights

- Area, indirect, sun/sky



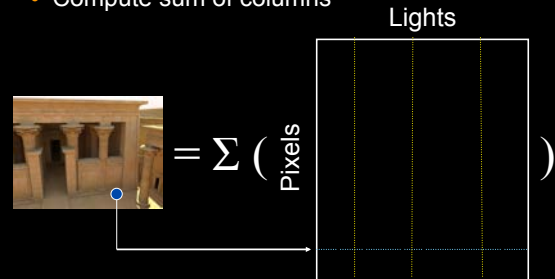
Courtesy Walter et al., Lightcuts, SIGGRAPH 05/06

## A Matrix Interpretation



## Problem Statement

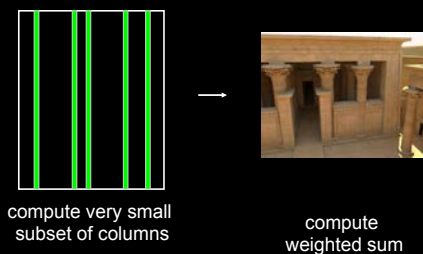
- Compute sum of columns



- **Note:** We don't have the matrix data

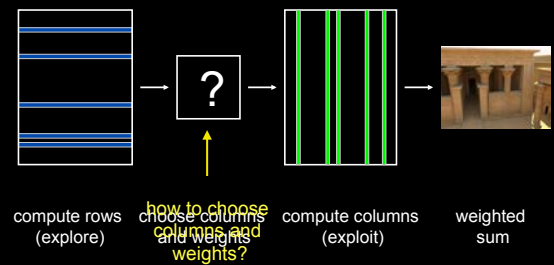
## Image as a Weighted Column Sum

- The following is possible:

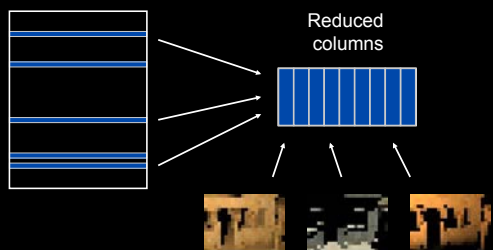


- Use rows to choose a good set of columns!

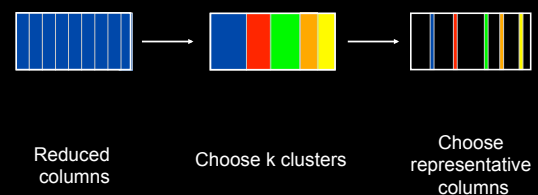
## Exploration and Exploitation



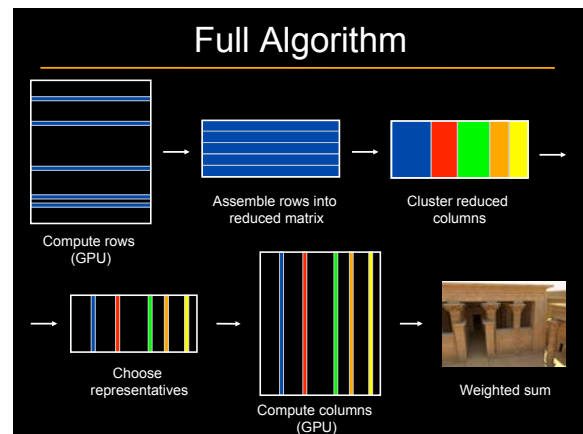
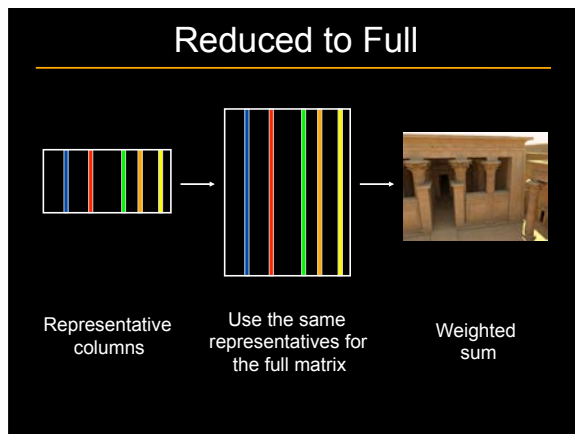
## Reduced Matrix



## Clustering Approach







## Results

- We show 5 scenes:

Kitchen   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: Kitchen

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

5x diff

Our result: 13.5 sec  
(432 rows + 864 columns)

Reference: 13 min  
(using all 100k lights)

## Results: Temple

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

5x diff

Our result: 16.9 sec  
(300 rows + 900 columns)

Reference: 20 min  
(using all 100k lights)

## Results: Trees

- 328k polygons
- Complex incoherent geometry


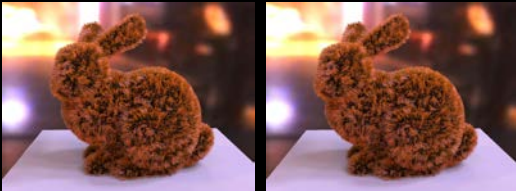
5x diff

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  
(588 rows + 1176 columns)

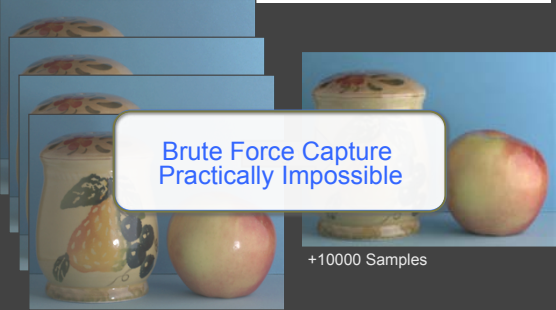
Reference: 44 min  
(using all 100k lights)

### Outline

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

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

### Motivation: Image-based Relighting

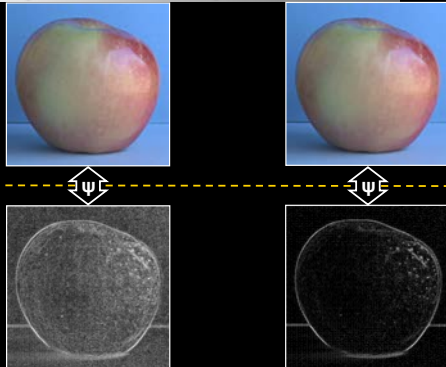


Brute Force Capture  
Practically Impossible

+10000 Samples

Sample Lighting Directions

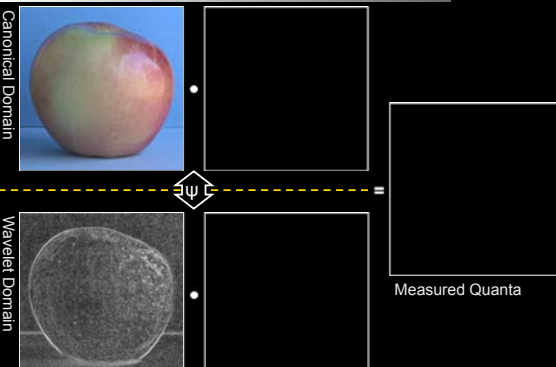
### Compressible / Sparseness



All Coefficients

5% Largest Coeff.

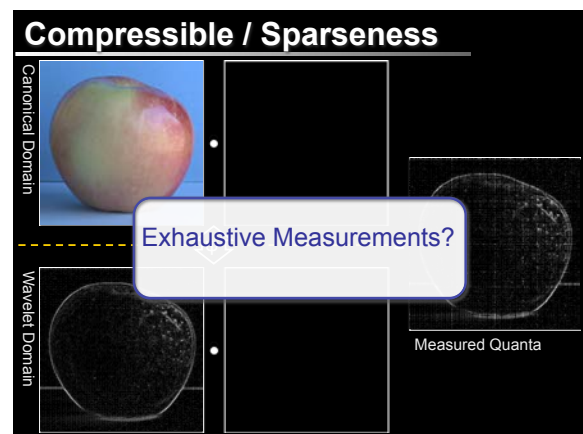
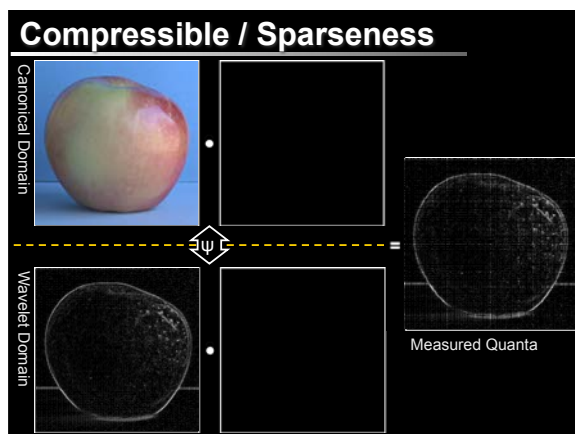
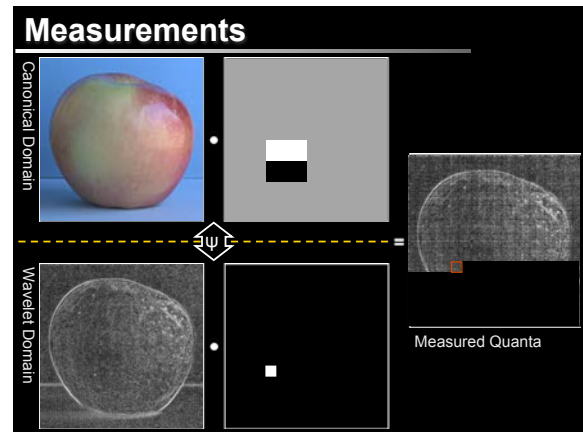
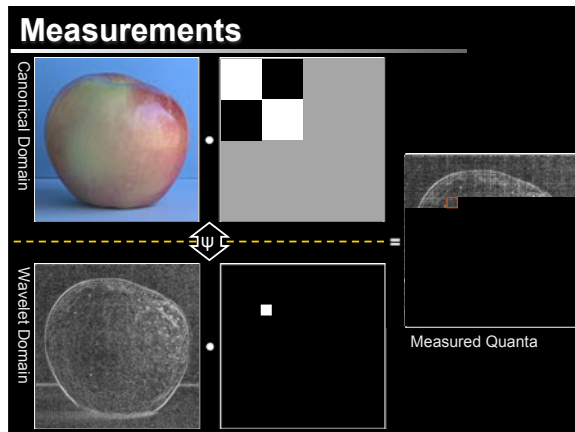
### Measurements



Canonical Domain

Wavelet Domain

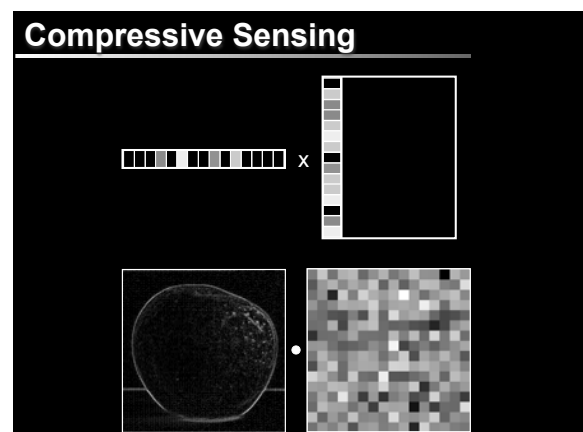
Measured Quanta



### Compressive Sensing: A Brief Introduction

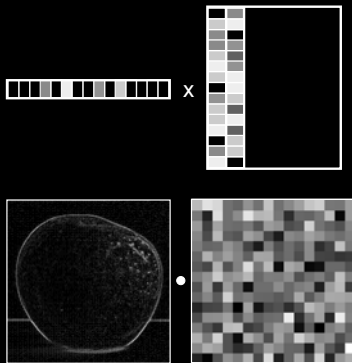
[Candes et al., 06][Donoho, 06]...

- 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**.

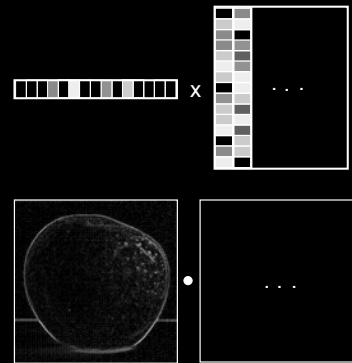
$$A \begin{bmatrix} \text{Measurement Ensemble} \\ m \times n, \text{ where } m < n \end{bmatrix} \begin{bmatrix} \text{Signal} \\ n \times 1 \end{bmatrix} x = \begin{bmatrix} \text{Measurements} \\ m \times 1 \end{bmatrix} b$$




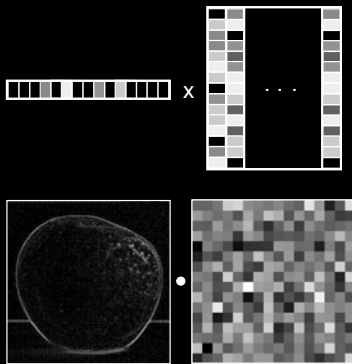
## Compressive Sensing



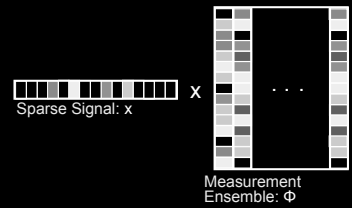
## Compressive Sensing



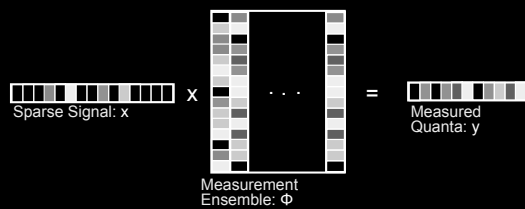
## Compressive Sensing



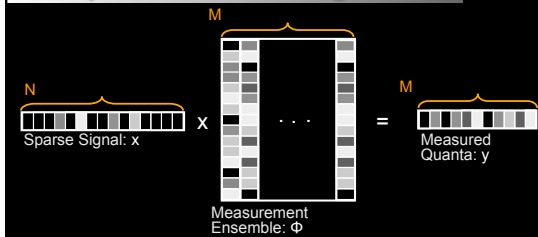
## Compressive Sensing



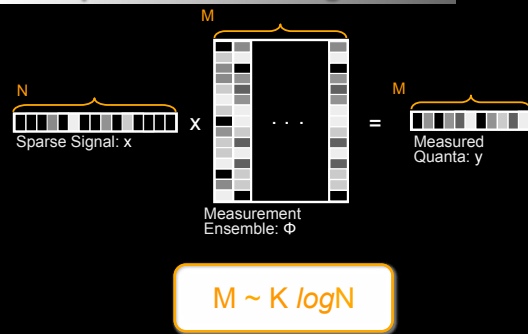
## Compressive Sensing



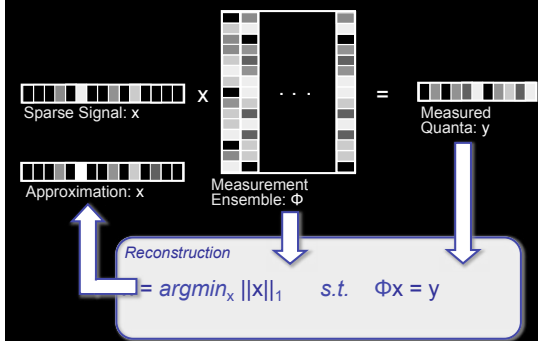
## Compressive Sensing



## Compressive Sensing



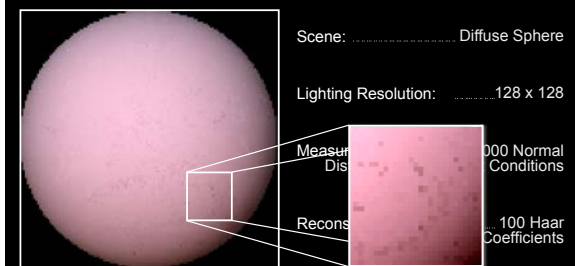
## Compressive Sensing



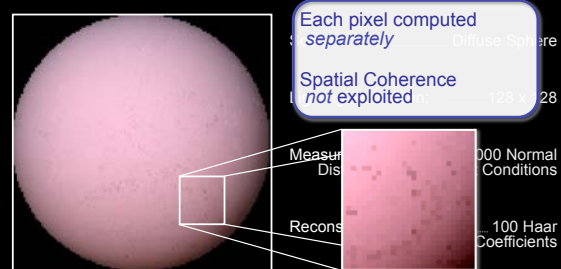
## Brute Force: Result



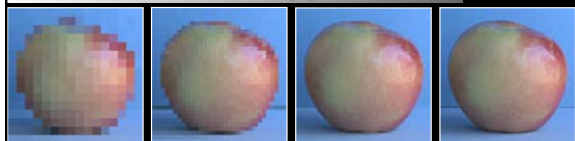
## Brute Force: Result



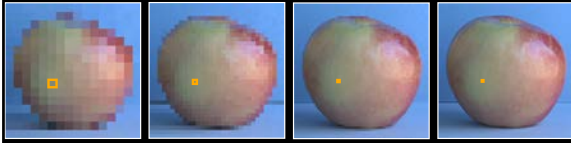
## Brute Force: Result



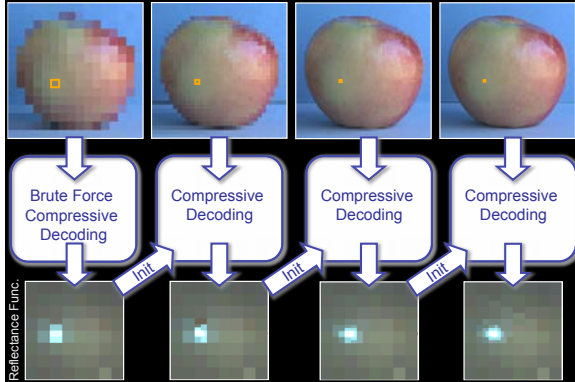
## Multi-resolution Approach



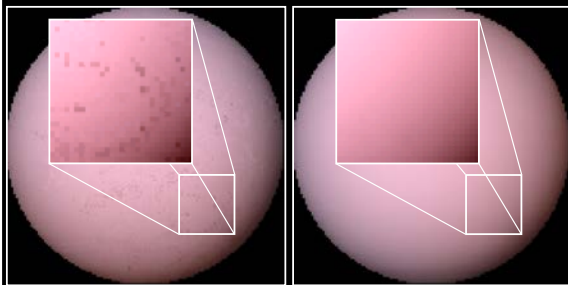
## Multi-resolution Approach



## Multi-resolution Approach



## Results



Brute Force Algorithm

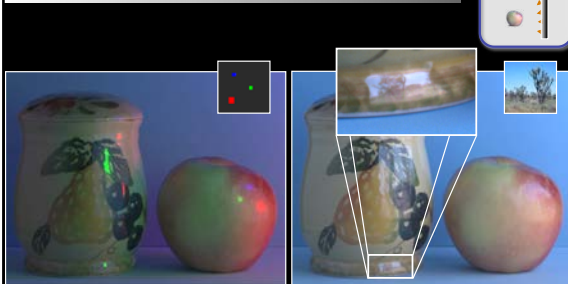
Hierarchical Algorithm

## Resolution



1000 Measurements  
128 x 128 Lighting Resolution  
128 Haar Wavelet Coefficients

## Resolution



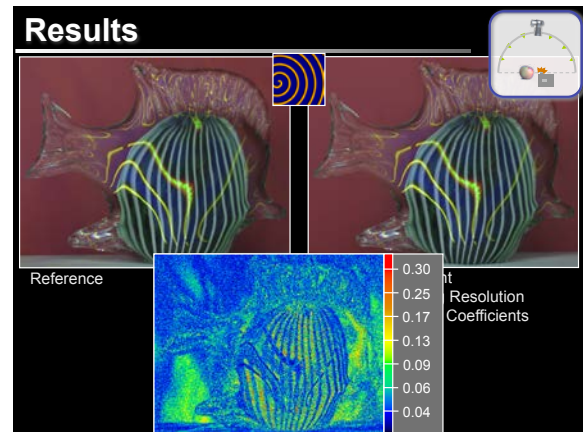
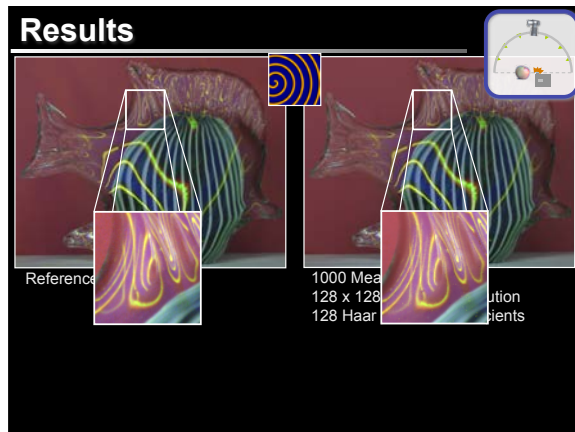
1000 Measurements  
128 x 128 Lighting Resolution  
128 Haar Wavelet Coefficients

## Results



Reference

1000 Measurement  
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.

Drifting Smoke of Incense (532fps Camera)

Mixing a Pink Drink with Water (1000fps Camera)

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

This slide contains two side-by-side images. The left image shows 'Drifting Smoke of Incense' captured with a 532fps camera. The right image shows 'Mixing a Pink Drink with Water' captured with a 1000fps camera. The text above the images states 'Inhomogeneous Participating Media' and 'Volume densities rather than boundary surfaces. Efficiency in acquisition is critical, especially for time-varying participating media.' The source 'Video clips are from http://www.lucidmovement.com' is noted at the bottom.

### 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.

Projector

Camera

Milk Drops

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

This slide is titled 'Compressive Structured Light'. It lists the following specifications: 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. Below the text is a diagram showing a projector and camera setup for measuring 'Milk Drops'. The source 'Gu, Nayar, Grinspun, Belhumeur, Ramamoorthi 08, 13' is noted at the bottom.

### Milk Dissolving: One Instance of time

- Milk drops dissolving in a water tank.

Photograph

Measurements (24 images of size 128x250)

Reconstructed Volume (128x128x250)

This slide is titled 'Milk Dissolving: One Instance of time'. It lists the following specifications: Milk drops dissolving in a water tank. Below the text are three side-by-side images: a 'Photograph' of a milk drop, 'Measurements (24 images of size 128x250)', and a 'Reconstructed Volume (128x128x250)'.

### Milk Dissolving: Time-varying Volume

- Milk drops dissolving in a water tank.

Video (15fps)

Reconstructed Volume (128x128x250)

This slide is titled 'Milk Dissolving: Time-varying Volume'. It lists the following specifications: Milk drops dissolving in a water tank. Below the text are two side-by-side images: a 'Video (15fps)' and a 'Reconstructed Volume (128x128x250)'.

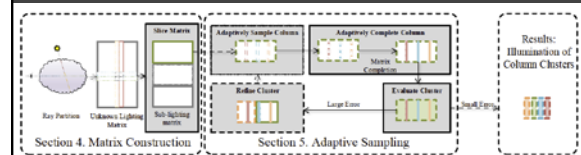
## Outline

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

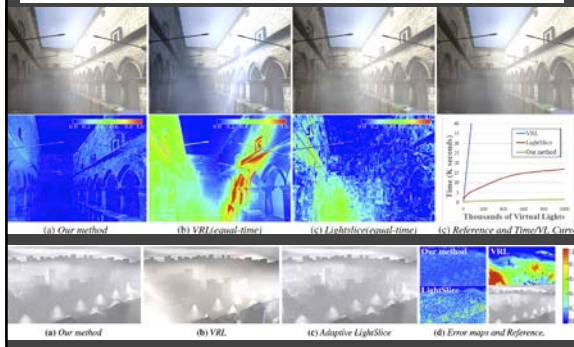
## Outline

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



Huo et al. SIGGRAPH Asia 16

## Results (Participating Media)



## Summary

- 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