


  
 SIGGRAPH2005

---


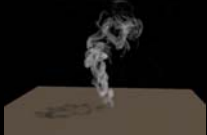
Course 10  
 Realistic Materials in Computer Graphics  
**Reflectance Fields**  
  
 Tim Hawkins  
 USC Institute for Creative Technologies

  
 SIGGRAPH2005


## Traditional Image Generation

---

- Surfaces + BRDFs
- Volumetric scattering, density fields, phase functions

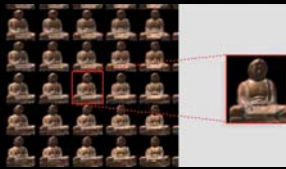



Course 10: Realistic Materials in Computer Graphics Tim Hawkins

  
 SIGGRAPH2005

## The Light Field

---




Levoy & Hanrahan. Light Field Rendering. SIGGRAPH '96

Gortler, Grzeszczuk, Szeliski, Cohen. The Lumigraph. SIGGRAPH '96


- Images captured from all directions
- Allows realistic images from arbitrary viewpoint
- No geometry, no material properties

Course 10: Realistic Materials in Computer Graphics Tim Hawkins


  
 SIGGRAPH2005

## The Light Field

---

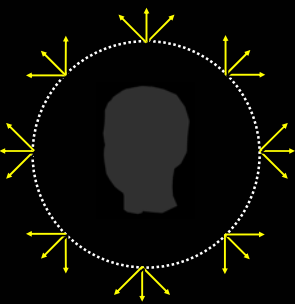


Course 10: Realistic Materials in Computer Graphics Tim Hawkins


  
 SIGGRAPH2005

## The Light Field

---



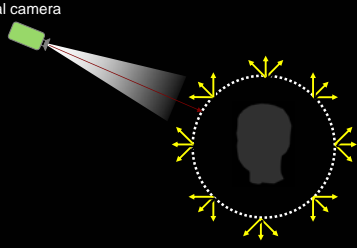
Course 10: Realistic Materials in Computer Graphics Tim Hawkins

  
 SIGGRAPH2005

## The Light Field

---

virtual camera



Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# The Light Field

virtual camera

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# The Light Field

virtual camera

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# The Light Field

virtual camera

SIGGRAPH2005

- Assumes "free space"—no occluders

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# The Light Field

$(\theta_r, \phi_r)$

$(u_r, v_r)$

$L_r(u_r, v_r, \theta_r, \phi_r)$

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# The Light Field

SIGGRAPH2005

- Photorealistic renderings
- Illumination cannot be varied

Levoy, SIGGRAPH 96

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

# How Can Illumination be Quantified?

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

## How Can Illumination be Quantified?

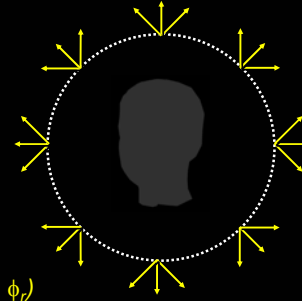


- Answer: As a light field!

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Radiant Light Field

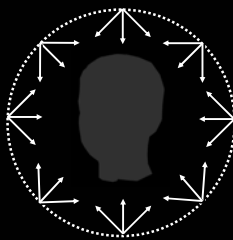


$$L_r(u_r, v_r, \theta_r, \phi_r)$$

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Incident Light Field



$$L_i(u_i, v_i, \theta_i, \phi_i)$$

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Light Transport

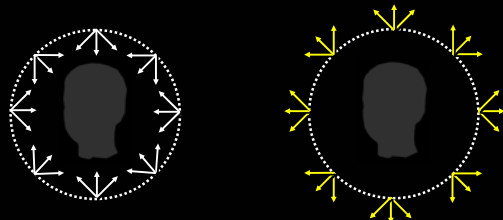


$$L_i(u_i, v_i, \theta_i, \phi_i)$$

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Light Transport



$$L_i(u_i, v_i, \theta_i, \phi_i) \longrightarrow L_r(u_r, v_r, \theta_r, \phi_r)$$

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Superposition Principle



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Superposition Principle

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Superposition Principle

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Superposition Principle

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Superposition Principle

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Impulse Light Field

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Adding Impulse Light Fields

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

### Adding Impulse Light Fields

SIGGRAPH2005

$L_1 + L_2$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

### Impulse Light Field

SIGGRAPH2005

$L_1 + L_2 + L_3$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

### Impulse Light Field

SIGGRAPH2005

$L_1 + L_2 + L_3 + \dots$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

### Linearity of Light Transport

SIGGRAPH2005

$L(r_1)$

$L_1$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

### Linearity of Light Transport

SIGGRAPH2005

$L(r_1) * 2$

$L_1 * 2$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

### The Reflectance Field

SIGGRAPH2005

$R(u_i, v_i, \theta_i, \phi_i; u_r, v_r, \theta_r, \phi_r)$

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

## Reflectance Field Rendering



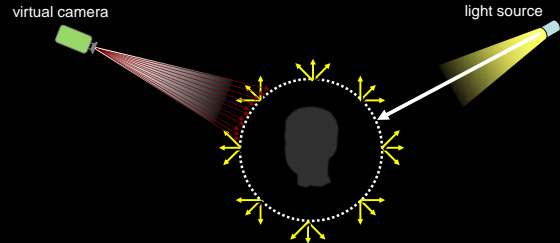
$$L_r(u_r, v_r, \theta_r, \phi_r) =$$

$$\iint_S \int_{\Omega} R(u_i, v_i, \theta_i, \phi_i; u_r, v_r, \theta_r, \phi_r) L_i(u_i, v_i, \theta_i, \phi_i) d\omega dA$$

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Reflectance Fields Are Powerful



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Contrast with Traditional Models



- Complex geometry with simple reflectance becomes very simple geometry (sphere) with complex reflectance (8D reflectance field)
- Ray tracing and visibility calculations are not needed, rendering is simple "convolution"

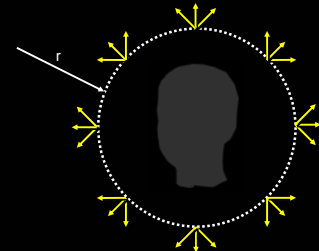
Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Measuring a Reflectance Field



- Use a laser or projector to send in every ray
- Use a camera array to record all of the resulting radiant light fields



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## 8 Dimensions!

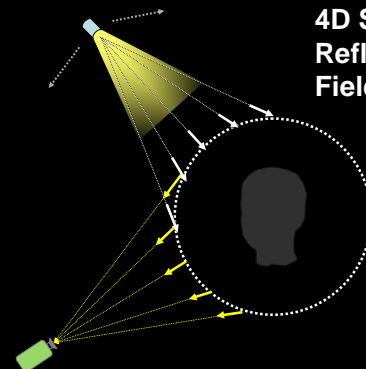


- Assume a resolution of 100 samples for each dimension
  - $100^8 = 10^{16}$  samples (10 million gigabytes)
- Too much data
- Lower dimensional variants are more practical, and can still give considerable control over lighting

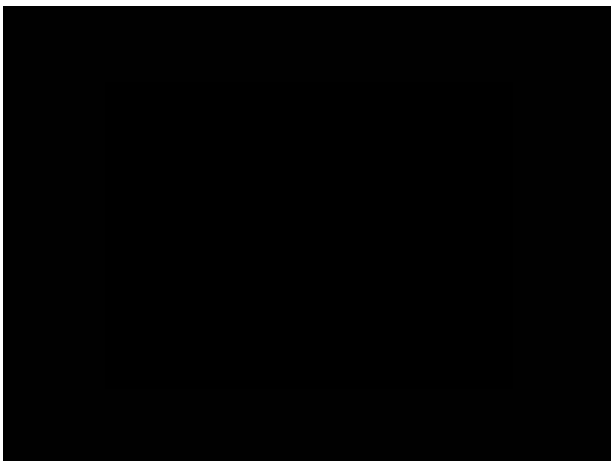
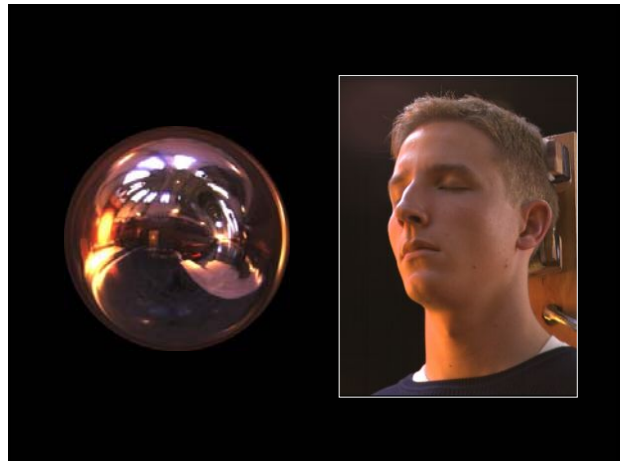
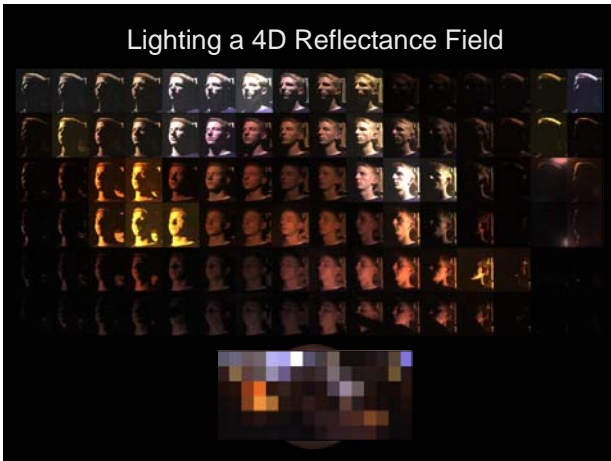
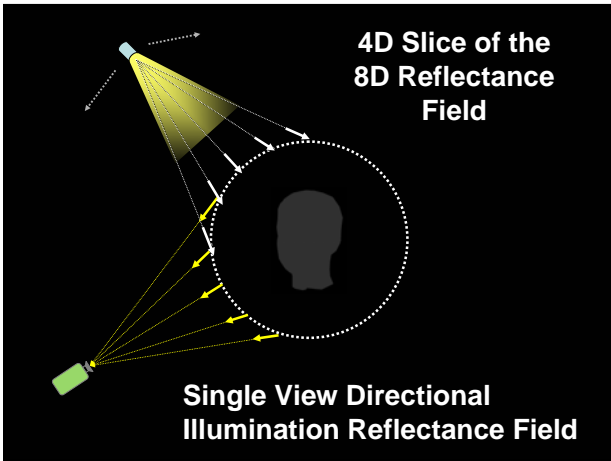
Course 10: Realistic Materials in Computer Graphics

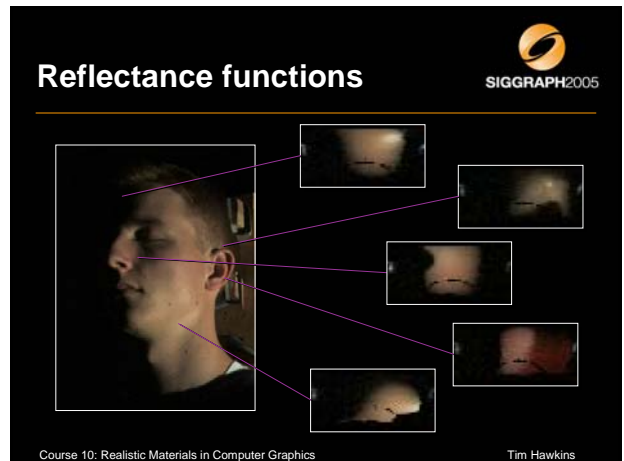
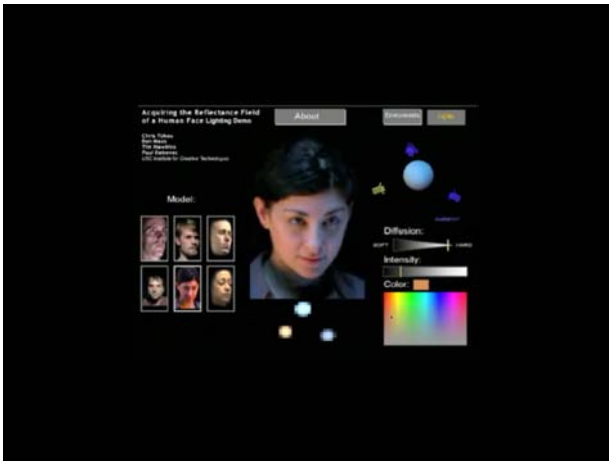
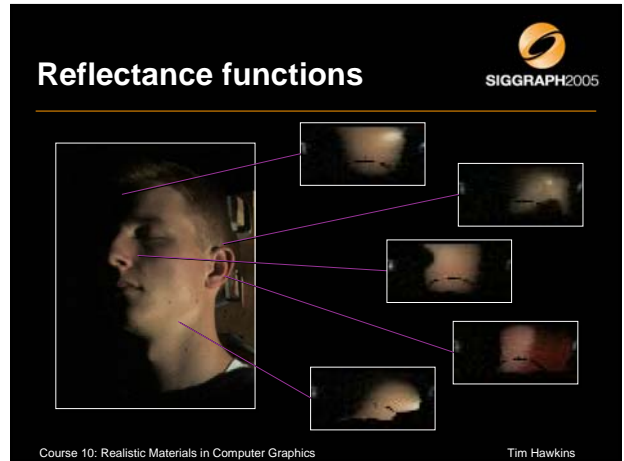
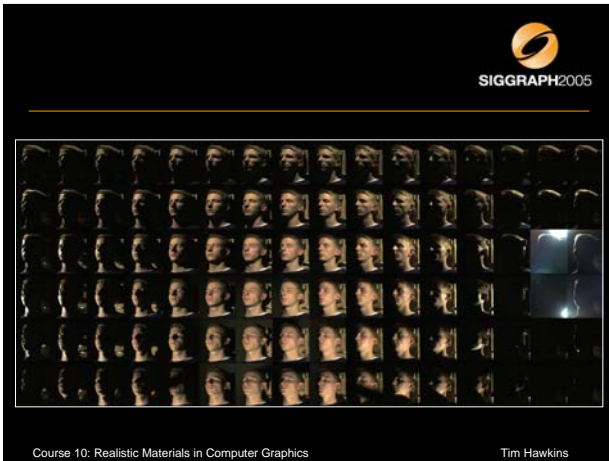
Tim Hawkins

## 4D Slice of Reflectance Field



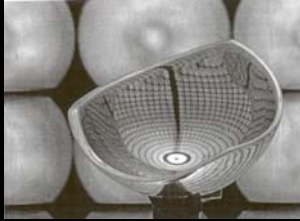
$$R(u_i, v_i, \theta_i, \phi_i; u_r, v_r, \theta_r, \phi_r)$$







## Highly Specular Objects



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

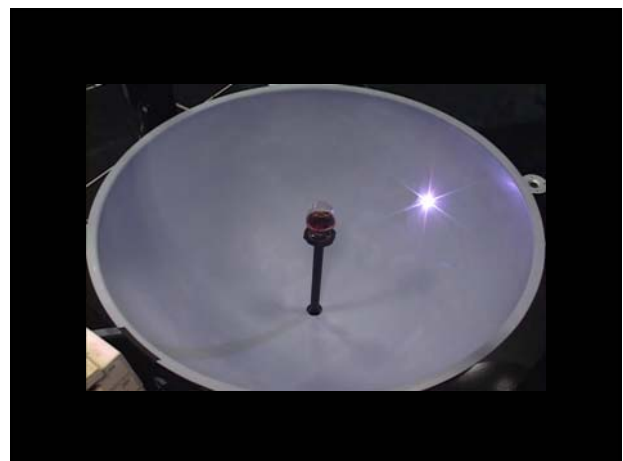
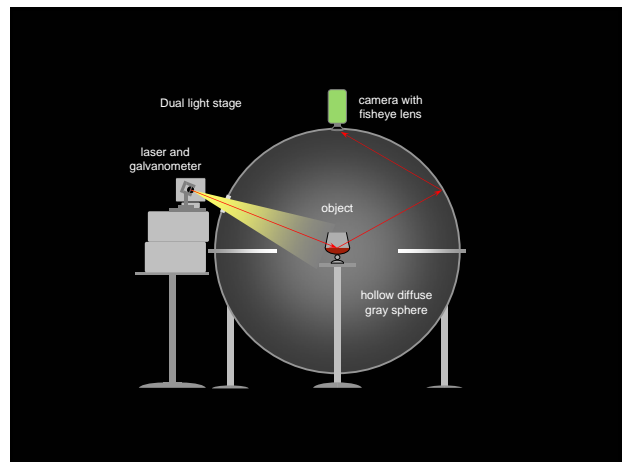
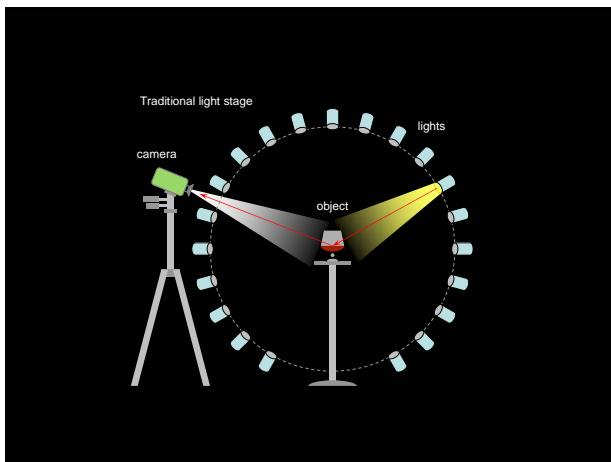
## Capturing High Resolution Reflectance Functions

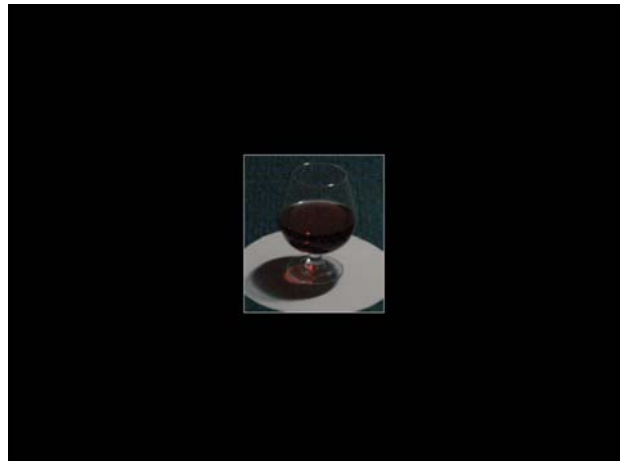
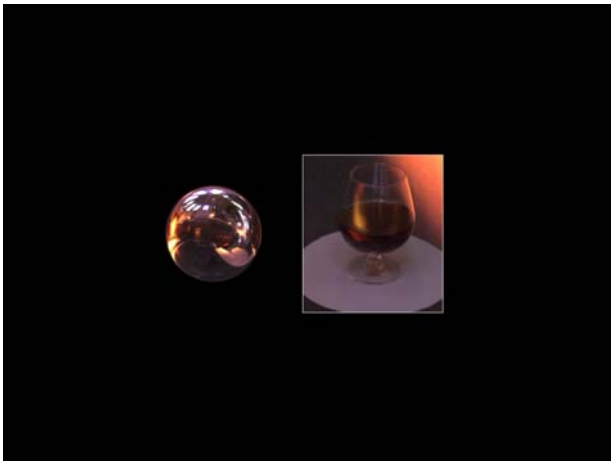
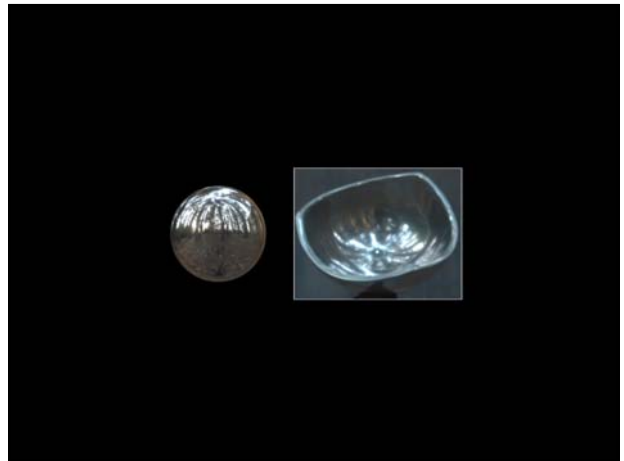
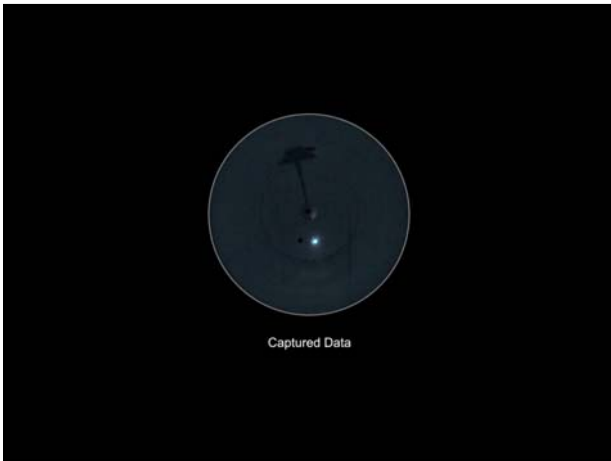


Hawkins, Einarsson, Debevec. A Dual Light Stage. EGSR 2005.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins





## Dual Light Stage Renderings

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

## Helmholtz Reciprocity at SIGGRAPH 2005

SIGGRAPH2005

- Sen, Chen, Garg, Marschner, Horowitz, Levoy, Lensch. Dual Photography. SIGGRAPH 2005

Course 10: Realistic Materials in Computer Graphics Tim Hawkins

## Limitations



- Limited resolution
- *Fixed viewpoint*
- Spatially uniform lighting
- Static object



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Varying the Viewpoint



- Full light field capture for every direction of illumination → 6D Reflectance Field
- Directional Illumination Reflectance Field

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

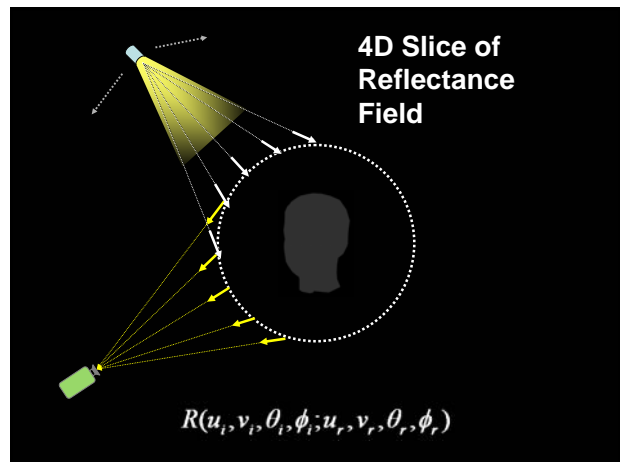
## Varying the Viewpoint



- Problem: With no geometry, an enormous amount of data is needed to avoid ghosting artifacts.
- Solution: Capture as many viewpoints as is feasible, then use a geometric model to help with view interpolation.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins



## Light Stage 1 – Moving the Viewpoint



Debevec, Hawkins, Tchou, Duiker, Sarokin, Sagar. Acquiring the Reflectance Field of a Human Face. SIGGRAPH 2000.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Light Stage 1 – Moving the Viewpoint



Debevec, Hawkins, Tchou, Duiker, Sarokin, Sagar. Acquiring the Reflectance Field of a Human Face. SIGGRAPH 2000.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Reflectance functions

SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# Transforming a Reflectance Function

Original RF

Subsurface Component

Surface Normal Estimate

Specular Component

⇒ Torrance-Sparrow microfacet distribution

Shifted and Scaled Specular

Final RF

Comparison RF

# Point-Source Comparison

Original Image

Novel Viewpoint



# 6D Reflectance Fields

SIGGRAPH2005

- Matusik, Pfister, Ngan, Beardsley, Ziegler, McMillan. Image-Based 3D Photography with Opacity Hulls. SIGGRAPH 2002.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

# 6D Reflectance Fields on Opacity Hull Geometry

SIGGRAPH2005

- Rotating arc of lights
- Static arc of cameras
- Rotating platform
- Two plasma monitors
- Captures medium resolution 6D reflectance field + rough geometry + opacity

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Obects Integrated Into Environments



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Opacity Hull



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

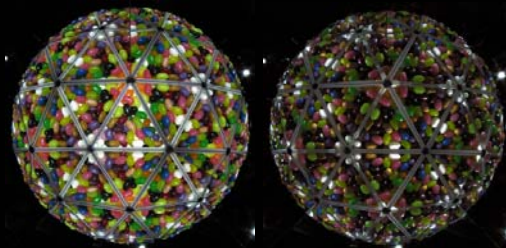
## Relighting Example



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Kaleidoscopic Reflectometry

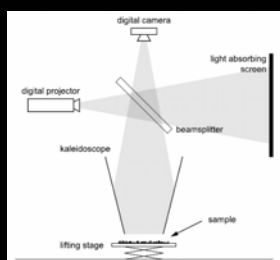


Han & Perlin. Measuring Bidirectional Texture Reflectance with a Kaleidoscope. SIGGRAPH 2003.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

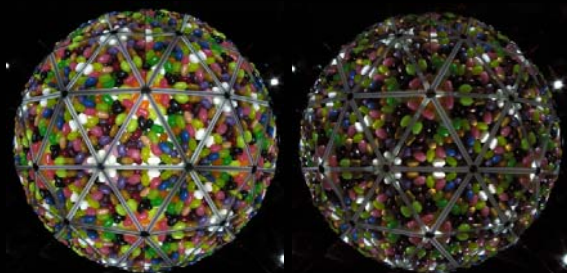
## Kaleidoscopic Reflectometry



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Kaleidoscopic Reflectometry



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins



## Limitations




SIGGRAPH2005

- Limited resolution
- Fixed viewpoint
- *Spatially uniform lighting*
- Static object





Course 10: Realistic Materials in Computer Graphics
Tim Hawkins

## Spatially Varying Incident Light



SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics
Tim Hawkins

## Capturing Spatially Varying Incident Light




SIGGRAPH2005

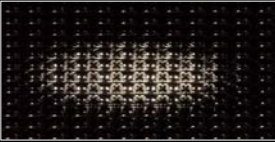
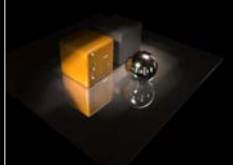



Unger, Wenger, Hawkins, Gardner, and Debevec. Capturing and Rendering with Incident Light Fields. EGSR 2003

Course 10: Realistic Materials in Computer Graphics
Tim Hawkins



SIGGRAPH2005

Course 10: Realistic Materials in Computer Graphics
Tim Hawkins

## Relighting with Incident Light Fields



SIGGRAPH2005

- Masselus, Peers, Dutre, Willems. Relighting with 4D Incident Light Fields. SIGGRAPH '03.

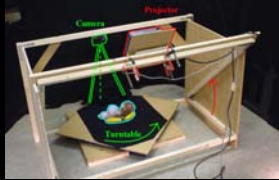



Course 10: Realistic Materials in Computer Graphics
Tim Hawkins

## Relighting with Incident Light Fields



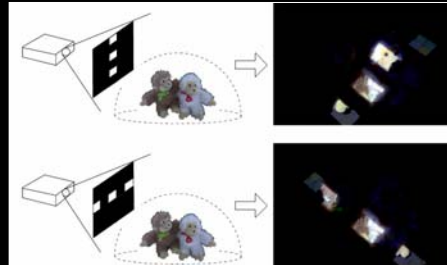
- Captures a basis for illumination by any incident light field, but from a fixed viewpoint
- 6D reflectance field, but different than the directional illumination reflectance field
- Single view reflectance field



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

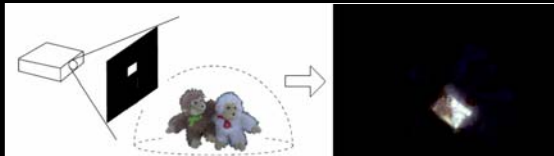
## Scanning Patterns



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Derived Pulse Response



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Relighting with Incident Light Fields



- Relit with synthetic incident light fields

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Relighting with Incident Light Fields



- Relit with synthetic incident light fields

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Spatially Varying Illumination at SIGGRAPH 2005



- Sen, Chen, Garg, Marschner, Horowitz, Levoy, Lensch. Dual Photography. SIGGRAPH 2005.



- Jones, Gardner, Bolas, McDowall, Debevec. Performance Geometry Capture for Spatially Varying Relighting. SIGGRAPH 2005.



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Limitations



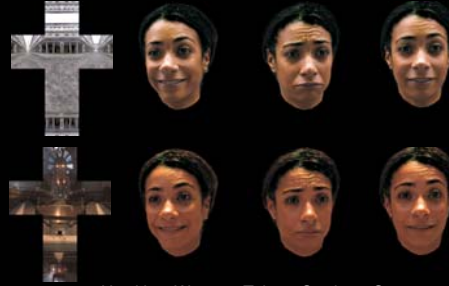
- Limited resolution
- Fixed viewpoint
- Spatially uniform lighting
- *Static object*



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Animatable Facial Reflectance Fields



Hawkins, Wenger, Tchou, Gardner, Goransson, Debevec.  
Animatable Facial Reflectance Fields. EGSR 2004.

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Light Stage 2



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Light Stage 2



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Captured Expressions



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Six Viewpoints



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins



## Animatable Model

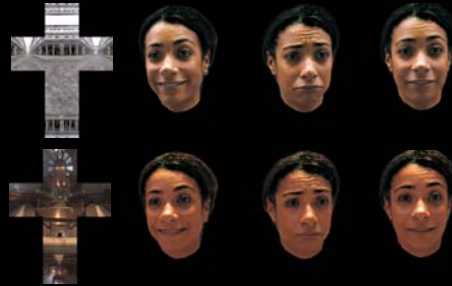


- Registering all expressions and views gives a morphable model across expression, viewpoint, and lighting
- Rough geometric model for view interpolation
- Raw data size is 60 expressions x 6 views x 480 lights x 1 MB per image = 160 GB

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Results



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Expression Morphing



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Expression morphing



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Performance Driven Reflectance Fields



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Performance Driven Reflectance Fields



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Performance Driven Reflectance Fields



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Real Time Reflectance Field Capture



- Wenger, Gardner, Tchou, Unger, Hawkins, Debevec. Performance Relighting and Reflectance Transformation with Time-Multiplexed Illumination. SIGGRAPH 2005



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Conclusion



- Reflectance field capture can provide highly realistic relightable image based models of real scenes and objects
- Capturing and rendering with reflectance fields becomes challenging at high dimension
- Relatively new research area, plenty of future work

Course 10: Realistic Materials in Computer Graphics

Tim Hawkins

## Questions?



Course 10: Realistic Materials in Computer Graphics

Tim Hawkins