SIGGRAPH2005

Course 10
Realistic Materials in Computer Graphics

Introduction

Hendrik P.A. Lensch
Stanford University

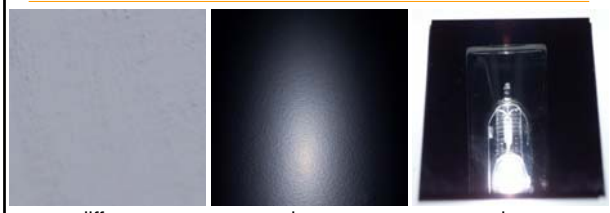
Material Samples

SIGGRAPH2005

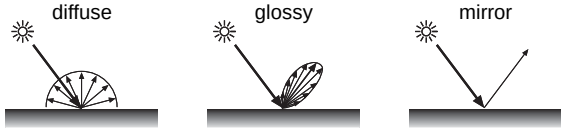
diffuse glossy mirror

Material Samples

SIGGRAPH2005

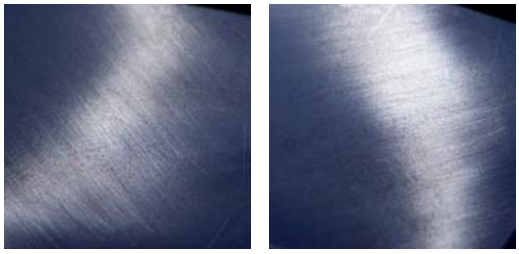


diffuse glossy mirror



Material Samples

SIGGRAPH2005



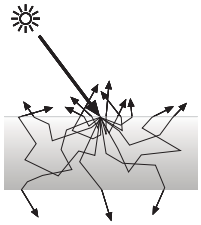
anisotropic

Material Samples

SIGGRAPH2005

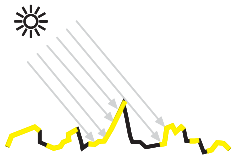
translucent

Material Samples



translucent

Material Samples



complex surface structure

Material Samples

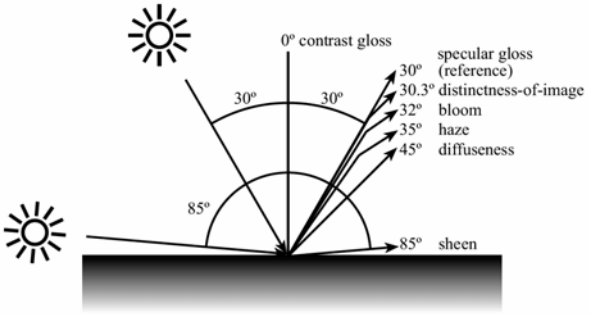
fibers

How to describe materials?

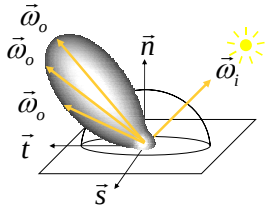
- mechanical, chemical, electrical properties
- reflection properties
- surface roughness
- geometry/meso-structure

- **relightable** representation of appearance

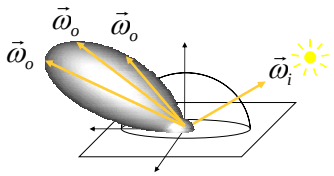
Gloss Model



Reflection of an Opaque Surface



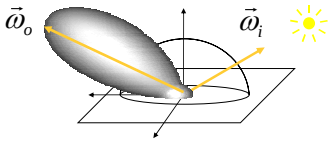
Reflection of an Opaque Surface



BRDF – 4D

(bidirectional reflectance distribution function)

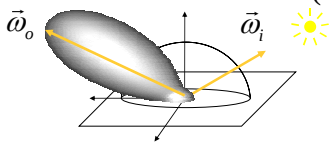
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



BRDF – 4D

(bi-directional reflectance distribution function)

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{\omega}_o)}{dE(\vec{\omega}_i)}$$

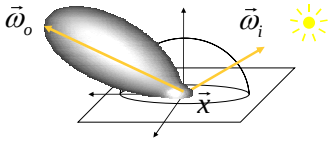


ratio of reflected radiance to incident irradiance

Spatially Varying BRDF – 6D

- heterogeneous materials

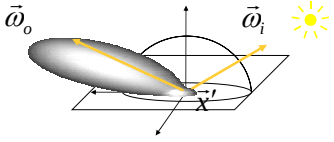
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Spatially Varying BRDF – 6D

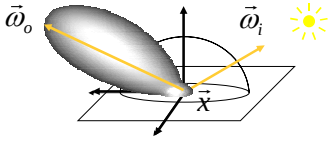
- heterogeneous materials

$$f_r(\vec{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Isotropic BRDF – 3D

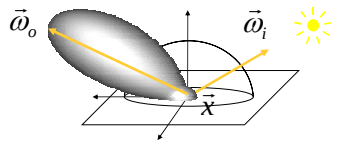
- invariant with respect to rotation about the normal



Isotropic BRDF – 3D

- invariant with respect to rotation about the normal

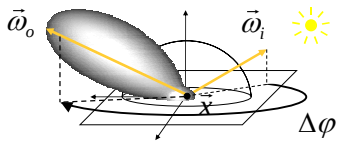
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



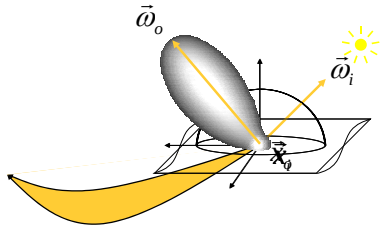
Isotropic BRDF – 3D

- invariant with respect to rotation about the normal

$$f_r((\theta_i, \varphi_i) \rightarrow (\theta_o, \varphi_o))$$



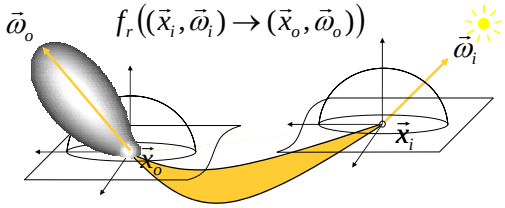
Subsurface Scattering



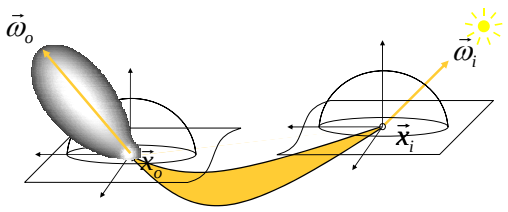
BSSRDF – 8D

(bidirectional scattering surface reflectance distribution function)

$$f_r((\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o))$$

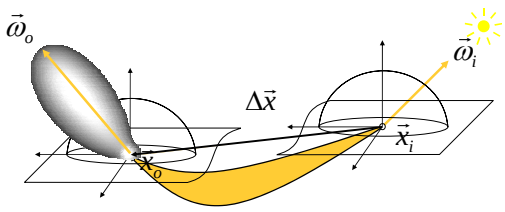


Subsurface Scattering Homogeneous Material



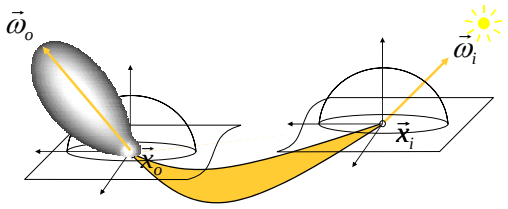
Homogeneous Material BSSRDF – 6D

$$f_r((\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o))$$



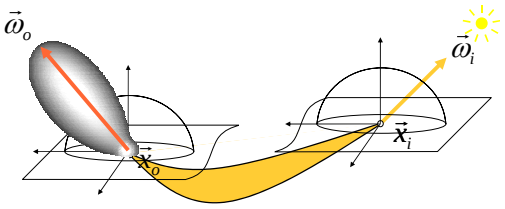
Generalization – 12D

$$f_r\left(\lambda;(\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Generalization – 12D

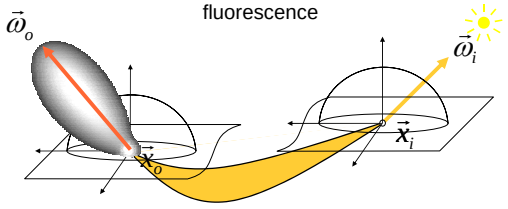
$$f_r\left(\lambda;(\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Generalization – 12D

$$f_r\left((\vec{x}_i,\vec{\omega}_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,\lambda_o)\right)$$

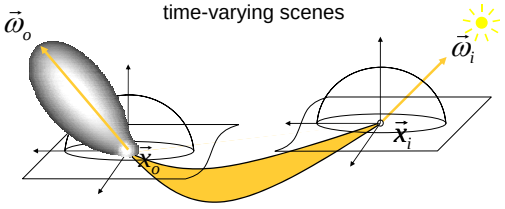
fluorescence



Generalization – 12D

$$f_r\left(t;(\vec{x}_i,\vec{\omega}_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,\lambda_o)\right)$$

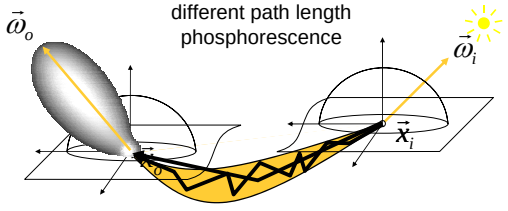
time-varying scenes



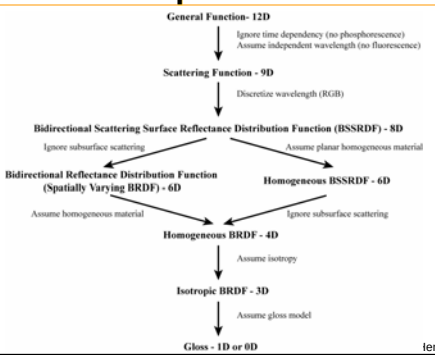
Generalization – 12D

$$f_r\left((\vec{x}_i,\vec{\omega}_i,t_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,t_o,\lambda_o)\right)$$

different path length
phosphorescence



Taxonomy of Appearance Representations

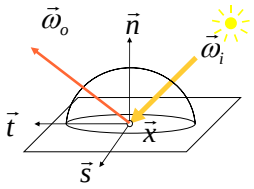


Properties of Reflectance Functions

- Helmholtz reciprocity
- energy conservation
- Fresnel effect

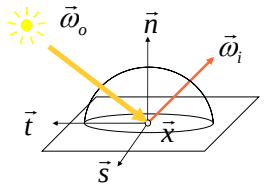
Helmholtz Reciprocity

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Helmholtz Reciprocity

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = f_r(\vec{\omega}_o \leftarrow \vec{\omega}_i)$$



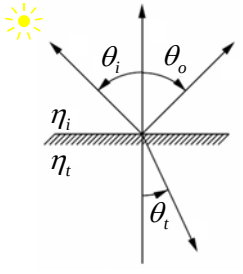
Energy Conservation

- The sum of energy reflected into all directions has to be smaller or equal than the incident energy.

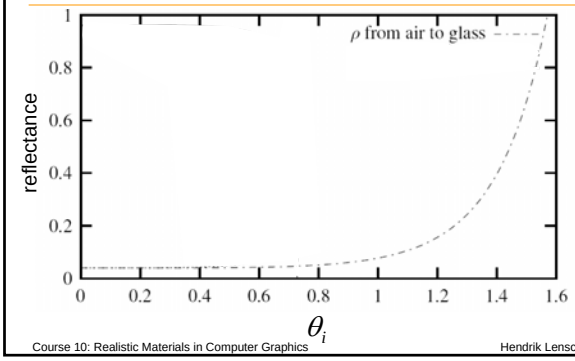
$$\int_{\Omega_o} f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)\cos(\theta_i)d\omega_o \leq 1$$

Snell's Law

$$\eta_i(\lambda)\sin\theta_i = \eta_t(\lambda)\sin\theta_t$$



Fresnel Formula



Material Acquisition

- single picture
  - no interaction

Material Acquisition

- diffuse color + geometry model
  - no relighting

Material Acquisition

- BRDF + geometry model
  - moving highlights

Material Acquisition

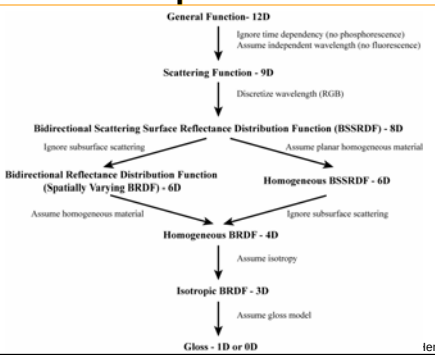
- spatially-varying BRDF + geometry model
  - moving highlights

Acquisition Approaches

- hard to sample an 8D function
- dimensionality reduction
- sampling density

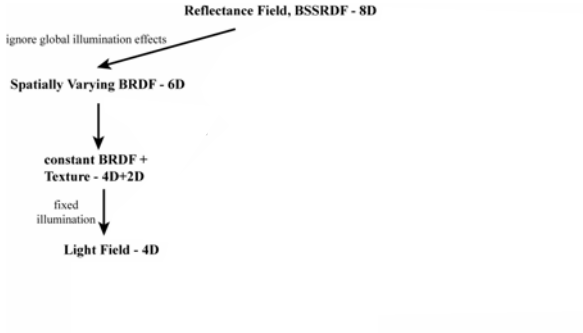
- restricted viewing and relighting capabilities
- restriction to a specific class of materials/objects

Taxonomy of Appearance Representations

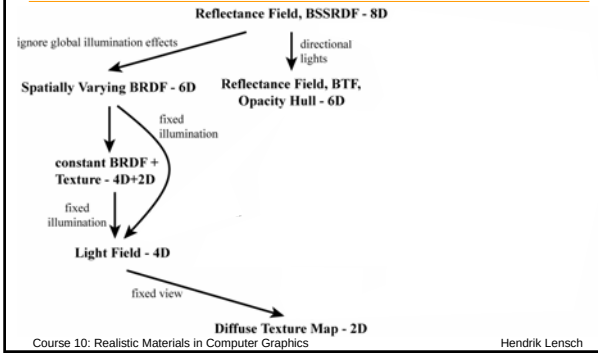


Acquisition Taxonomy

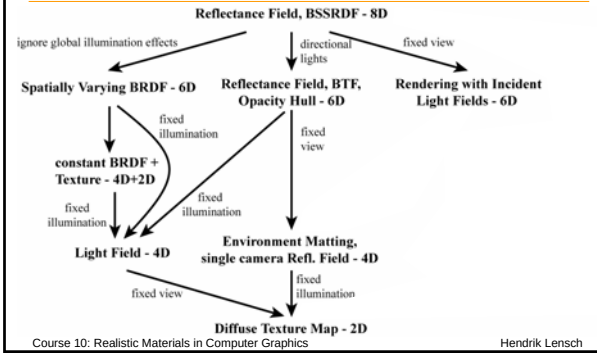
Acquisition Taxonomy



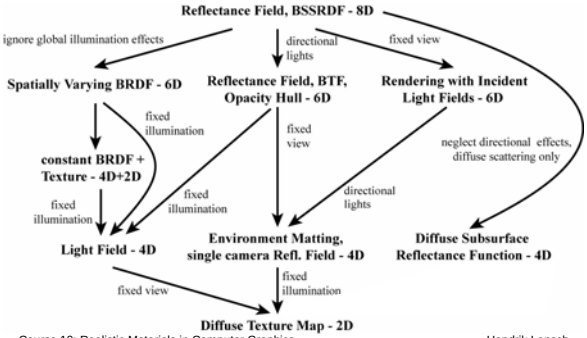
Acquisition Taxonomy



Acquisition Taxonomy



Acquisition Taxonomy



Comparison

Technique
texture maps
light fields
image-based BRDF
SBRDFs
reflectance fields/BTFs
relighting with 4D incident LFs
environment mattes
opacity hulls
translucent

Comparison

Technique	View Res. spatial	View Res. dir.	Light Res. spatial	Light Res. dir.
texture maps	hi	-	-	-
light fields	hi	med	-	-
image-based BRDF	hi	hi	hi	hi
SBRDFs	hi	hi	hi	hi
reflectance fields/BTFs	hi	med	-	med
relighting with 4D incident LFs	hi	-	med	lo
environment mattes	hi	-	-	hi
opacity hulls	hi	med	-	hi
translucent	hi	-	hi	-

Comparison

Technique	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	hi	-	-	-
light fields	hi	med	-	-
image-based BRDF	hi	hi	hi	hi
SBRDFs	hi	hi	hi	hi
reflectance fields/BTFs	hi	med	-	med
relighting with 4D incident LFs	hi	-	med	lo
environment mattes	hi	-	-	hi
opacity hulls	hi	med	-	hi
translucent	hi	-	hi	-

Comparison

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	diffuse illum.	10-20	hi	-	-	-

Comparison

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	diffuse illum.	10-20	hi	-	-	-
light fields	fixed illum.	100-500	hi	med	-	-

Comparison

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	diffuse illum.	10-20	hi	-	-	-
light fields	fixed illum.	100-500	hi	**med**	-	-

Comparison

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	diffuse illum.	10-20	hi	-	-	-
light fields	fixed illum.	100-500	hi	med	-	-
image-based BRDF	point light	20-60	hi	hi	hi	hi
SBRDFs	point light	10-40	hi	hi	hi	hi

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med
relighting with 4D incident LFs	projector	50000-100000	hi	-	med	lo

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med
relighting with 4D incident LFs	projector	50000-100000	hi	-	med	lo
environment mattes	monitor	1-1200	hi	-	-	hi

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med
relighting with 4D incident LFs	projector	50000-100000	hi	-	med	lo
environment mattes	monitor	1-1200	hi	-	-	hi
opacity hulls	point light + monitor	20000-60000	hi	med	-	hi

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
reflectance fields/BTFs	point light	500-10000	hi	med	-	med
relighting with 4D incident LFs	projector	50000-100000	hi	-	med	lo
environment mattes	monitor	1-1200	hi	-	-	hi
opacity hulls	point light + monitor	20000-60000	hi	med	-	hi
translucent	laser beam	500000-1000000	hi	-	hi	-

Comparison

SIGGRAPH2005

Technique	#Images
texture maps	10-20
light fields	100-500
image-based BRDF	20-60
SBRDFs	10-40
reflectance fields/BTFs	500-10000
relighting with 4D incident LFs	50000-100000
environment mattes	1-1200
opacity hulls	20000-60000
translucent	500000-1000000

Comparison

SIGGRAPH2005

Technique	Light Source
texture maps	diffuse illum.
light fields	fixed illum.
image-based BRDF	point light
SBRDFs	point light
reflectance fields/BTFs	point light
relighting with 4D incident LFs	projector
environment mattes	monitor
opacity hulls	point light + monitor
translucent	laser beam

Comparison

SIGGRAPH2005

Technique	Light Source	#Images	View Res. $\vec{x}_o$	View Res. $\vec{\omega}_o$	Light Res. $\vec{x}_i$	Light Res. $\vec{\omega}_i$
texture maps	diffuse illum.	10-20	hi	-	-	-
light fields	fixed illum.	100-500	hi	med	-	-
image-based BRDF	point light	20-60	hi	hi	hi	hi
SBRDFs	point light	10-40	hi	hi	hi	hi
reflectance fields/BTFs	point light	500-10000	hi	med	-	med
relighting with 4D incident LFs	projector	50000-100000	hi	-	med	lo
environment mattes	monitor	1-1200	hi	-	-	hi
opacity hulls	point light + monitor	20000-60000	hi	med	-	hi
translucent	laser beam	500000-1000000	hi	-	hi	-