Introduction to Computer Graphics
GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 18:
Advanced Topics in Rendering

Announcements

• Homework 7 will be released soon

• Final project timeline
  - [Apr 14] Ideas will be released next Tuesday
  - [Apr 19] Submit your proposal one week later
  - [May 5] Submit your work

• Final project logistics
  - Work on Graphics topics, write code on your own

• Today’s lecture
  - Advanced (?) light transport and materials
  - A lot, but extremely high-level. Mostly FYI.
Advanced Light Transport
Advanced Light Transport

• Unbiased light transport methods
  - Bidirectional path tracing (BDPT)
  - Metropolis light transport (MLT)

• Biased light transport methods
  - Photon mapping
  - Vertex connection and merging (VCM)

• Instant radiosity (VPL / many light methods)
Biased vs. Unbiased Monte Carlo Estimators

• An **unbiased** Monte Carlo technique does not have any systematic error
  
  - The expected value of an unbiased estimator will always be the correct value, no matter how many samples are used

• Otherwise, **biased**
  
  - One special case, the expected value converges to the correct value as infinite samples are used — **consistent**

• We’ll look again at this page after introducing Photon Mapping
Bidirectional Path Tracing (BDPT)

• Recall: a path connects the camera and the light

• BDPT
  - Traces sub-paths from both the camera and the light
  - Connects the end points from both sub-paths

[Veach 1997]
Bidirectional Path Tracing (BDPT)

- Suitable if the light transport is complex on the light's side
- Difficult to implement & quite slow

(a) Path tracer, 32 samples/pixel
(b) Bidirectional path tracer, 32 samples/pixel
Metropolis Light Transport (MLT)

• A Markov Chain Monte Carlo (MCMC) application
  - Jumping from the current sample to the next with some PDF
• Very good at **locally** exploring difficult light paths
• Key idea
  - Locally perturb an existing path to get a new path
Metropolis Light Transport (MLT) — Pros

- Works great with difficult light paths
- Also unbiased
Metropolis Light Transport (MLT) — Cons

- Difficult to estimate the convergence rate
- Does not guarantee equal convergence rate per pixel
- So, usually produces “dirty” results
- Therefore, usually not used to render animations
Photon Mapping

- A biased approach & A two-stage method
- Very good at handling Specular-Diffuse-Specular (SDS) paths and generating caustics
Photon Mapping — Approach (variations apply)

- **Stage 1 — photon tracing**
  - Emitting photons from the light source, bouncing them around, then recording photons on diffuse surfaces

- **Stage 2 — photon collection (final gathering)**
  - Shoot sub-paths from the camera, bouncing them around, until they hit diffuse surfaces
Photon Mapping

- Calculation — local density estimation
  - Idea: areas with more photons should be brighter
  - For each shading point, find the nearest N photons. Take the surface area they over
Photon Mapping

• Why biased?
• Local Density estimation
dN / dA ≠ ΔN / ΔA
• But in the sense of limit
  - More photons emitted ->
  - the same N photons covers a smaller ΔA ->
  - ΔA is closer to dA
• So, biased but consistent!

Small N <-> noisy

large N <-> blurry
Photon Mapping

• An easier understanding bias in rendering
  - Biased == blurry
  - Consistent == not blurry with infinite #samples

• Why not do a “const range” search for density estimation?
Vertex Connection and Merging

• A combination of BDPT and Photon Mapping

• Key idea
  - Let’s not waste the sub-paths in BDPT if their end points cannot be connected but can be merged
  - Use photon mapping to handle the merging of nearby “photons”

[Georgiev et al. 2012]
Instant Radiosity (IR)

- Sometimes also called many-light approaches

- Key idea
  - Lit surfaces can be treated as light sources

- Approach
  - Shoot light sub-paths and assume the end point of each sub-path is a Virtual Point Light (VPL)
  - Render the scene as usual using these VPLs
Instant Radiosity

- Pros: fast and usually gives good results on diffuse scenes
- Cons
  - Spikes will emerge when VPLs are close to shading points
  - Cannot handle glossy materials

[Liu et al. 2019] (many-light rendering, not IR)  [Rendered using Mitsuba]
Advanced Appearance Modeling
Advanced Appearance Modeling

• Non-surface models
  - Participating media
  - Hair / fur / fiber (BCSDF)
  - Granular material

• Surface models
  - Translucent material (BSSRDF)
  - Cloth
  - Detailed material (non-statistical BRDF)

• Procedural appearance
Non-Surface Models
Participating Media: Fog
Participating Media: Cloud
Participating Media

- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered.

[Absorption] [Emission] [Out-scattering] [In-scattering]

[Wojciech Jarosz]
Use Phase Function to describe the angular distribution of light scattering at any point $x$ within participating media.

- $g < 0$: back-scattering
- $g = 0$: isotropic-scattering
- $g > 0$: forward-scattering

[Wojciech Jarosz]
Participating Media: Rendering

- Randomly choose a direction to bounce
- Randomly choose a distance to go straight
- At each ‘shading point’, connect to the light

[Shadow Connections]

[Derek Nowrouzezahrai]
Participating Media: Application

[Big Hero 6, 2014 Disney]
Participating Media: Application

[Assassin’s Creed Syndicate. 2015 Ubisoft]
Participating Media: Demo

[Stomakhin et al. 2014]
Hair Appearance
Kajiya-Kay Model

[Image courtesy of Chiwei Tseng]
Kajiya-Kay Model

[Yuksel et al. 2008]
Marschner Model

[Image courtesy of Chiwei Tseng]
Marschner Model

- Glass-like cylinder

- 3 types of light interactions: R, TT, TRT
  (R: reflection, T: transmission)

[Marschner et al. 2003]
Marschner model

[Marschner et al. 2003]  [d’Eon et al. 2011]
Hair Appearance Model: Application

[Final Fantasy XV. 2016 Square Enix]
Hair Appearance Model: Application
Fur Appearance — As Human Hair

- Cannot represent diffusive and saturated appearance

Rendered as human hair
[Marschner et al. 2003]

Rendered as animal fur
[Yan et al. 2015]
Human Hair vs Animal Fur

Common for hair/fur fibers

Cortex
- Contains pigments
- Absorbs light

Medulla
- Complex structure
- Scatters light

Cuticle
- Covered with scales

Difference between hair/fur fibers
Importance of Medulla

Increasing medulla size
Importance of Medulla

Without medulla

With medulla (15%)
Double Cylinder Model

Cortex (absorbs)

Single layered

Marschner Model

Multi layered

Cortex (absorbs)

Medulla (scatters)

Double Cylinder Model

[Yan et al. 2015, 2017]
Double Cylinder Model — Lobes

- **medulla**
- **cortex**

**Left Panel:**
- TTs
- TRTs

**Right Panel:**
- TRTs
- TRT

**Legend:**
- R
- TTs
- TT

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Double Cylinder Model — Lobes

All = RTTTRT TTs TRTs
Double Cylinder Model: Rendering
Changing medulla's size

- 600,000 fur fibers
- 1024 samples / pixel
- 36.9 min / frame

Hamster
Double Cylinder Model: Application

Double Cylinder Model: Application

Granular Material

- What is granular material?

[Meng et al. 2015]
Granular Material

- Can we avoid explicit modeling of all granules?
  - Yes with **procedural** definition.
Granular Material

[Meng et al. 2015]
Granular Material: Application

[Piper. 2016 Pixar]
Surface Models
Translucent Material: Jade
Translucent Material: Jellyfish
Subsurface Scattering

Visual characteristics of many surfaces caused by light exiting at different points than it enters

- Violates a fundamental assumption of the BRDF

[Jensen et al 2001]

[Donner et al 2008]
Scattering Functions

- BSSRDF: generalization of BRDF; exitant radiance at one point due to incident differential irradiance at another point:
  \[ S(x_i, \omega_i, x_o, \omega_o) \]

- Generalization of rendering equation: integrating over all points on the surface and all directions (!)
  \[
  L(x_o, \omega_o) = \int_A \int_{H^2} S(x_i, \omega_i, x_o, \omega_o) L_i(x_i, \omega_i) \cos \theta_i \, d\omega_i \, dA
  \]

[Jensen et al. 2001]
Dipole Approximation [Jensen et al. 2001]

- Approximate light diffusion by introducing two point sources.
BRDF

[Jensen et al. 2001]
BSSRDF

[Jensen et al. 2001]
BRDF vs BSSRDF

[Jensen et al. 2001]
BSSRDF: Demo
BSSRDF: Application

[Artist: Teruyuki and Yuka]

[Artist: Hyun Kyung]

https://cgeels.com/10-most-realistic-human-3d-models-that-will-wow-you/

[Artist: Dan Roarty]
Cloth

- A collection of twisted fibers!
- Two levels of twist

Yarn

- Woven or knitted

Fibers

Ply

Ply #1

Ply #2

Ply #3
Cloth: Render as Surface

• Given the weaving pattern, calculate the overall behavior
• Render using a BRDF

[Sadeghi et al. 2013]
Render as Surface — Limitation

[Westin et al. 1992]
Cloth: Render as Participating Media

• Properties of individual fibers & their distribution -> scattering parameters
• Render as a participating medium

[Jakob et al. 2010] [Schroder et al. 2011]
Cloth: Render as Actual Fibers

- Render every fiber explicitly!
Cloth: Demo

[Shuang et al. 2012]
Cloth: Application

[The BFG. 2016 Disney]
Detailed Appearance: Motivation

- Not looking realistic, why?

[Car rendered in NVIDIA Iray]  
[Mouse rendered in Autodesk 3DS Max]
Real world is more complicated

[Real photograph of a car]  [Real video of a mouse]
Why details?

Microfacet model
Why details?

[Yan et al. 2014, 2016]
Why details?

[Yan et al. 2014, 2016]
Recap: Microfacet BRDF

Surface = Specular microfacets + statistical normals

\[ f(i, o) = \frac{F(i, h)G(i, o, h)D(h)}{4(n, i)(n, o)} \]

NDF: Normal Distribution Function
Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

What we have
(microfacet — statistical)

What we want
Define details

isotropic noise
normal map

Normal map resolution:
\( \approx 200K \times 200K \)
Define details
Different details

Metallic flakes
Rendering? Too difficult!

our result

zoom of a single pixel

naive sampling (2h)

(⇒ 21.3 days to converge)
Difficult path sampling problem

pinhole camera

bumpy specular surface

lightsource

miss

miss

miss
Solution: BRDF over a pixel

pinhole camera

light source

half vector $h$

$\mathcal{P}$-NDF

patch $\mathcal{P}$
p-NDFs have sharp features

normal map

$p$-NDFs
p-NDF shapes

normal maps

\( \mathcal{P} \)-NDFs
Blender

brushed metal

ellipsoid bumps
Blender: Zoom

brushed metal
ellipsoid bumps
Ocean waves
Detailed / Glinty Material: Application

[Rise of the Tomb Raider. 2016 Square Enix]
Recent Trend: Wave Optics

compact disk (CD)  
[Cuypers 11]

metallic film  
[Laurent 17]

phone screen  
[Toisoul 17]
Observations

photos of scratched metal
Observations

- photo of a Macbook
- photo of an aluminum patch
Detailed Material under Wave Optics

Heightfields
- isotropic
- brushed
- scratched

BRDFs
- geometric
- wave
- geometric
- wave
- geometric
- wave
Detailed Material under Wave Optics

MacBook rendered using wave optics

[Yan et al. 2018]
What is it about?

Body Level One

• Body Level Two

• Body Level Three

• Body Level Four

• Body Level Five

Latest Work on Wave Optics (submitted)

— phase delay
What is it about?

Body Level One

• Body Level Two

• Body Level Three

• Body Level Four

• Body Level Five

Latest Work on Wave Optics

(Submitted)
What is it about?

Wave optics
Procedural Appearance
Procedural Appearance

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.

[Lagae et al. 2009]
Procedural Appearance

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - 3D noise ->
    internal structure
    if cut or broken

[Lagae et al. 2009]
Procedural Appearance

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - Thresholding (noise -> binary noise)

Example:

```python
if noise(x, y, z) > threshold:
    reflectance = 1
else:
    reflectance = 0
```
Procedural Appearance

- Complex noise functions can be very powerful.
Procedural Appearance

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Procedural Appearance

- Complex noise functions can be very powerful.

[Liu et al. 2016]
Procedural Appearance

- Complex noise functions can be very powerful.

[Liu et al. 2016]
Thank you!

(And thank Prof. Ren Ng for many of the slides!)