Advanced Computer Graphics
Introduction

Matthias Teschner
Computer Graphics

Modeling - Rendering - Simulation
Computer Graphics

Modeling - Rendering - Simulation

© Warner Bros. Scanline VFX V-Ray
Outline

- Organization
- Concepts
- Applications
- History
Graphics Courses

- Key course
  - Image processing and computer graphics (modeling, rendering, simulation)

- Specialization courses
  - Advanced computer graphics (global illumination)
  - Simulation in computer graphics (deformable and rigid solids, fluids)

- Master project, lab course, Master thesis
  - Simulation track, rendering track
# Seminars / Projects / Theses in Graphics

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Course Goals

– Concepts for image synthesis / global illumination approaches
– Governing equation and solution techniques
  – Radiometric quantities
  – Rendering equation
  – Radiosity
  – Monte Carlo ray tracing
– Requirements:
  – Key course in graphics and image processing
Material

- Slide sets and video recordings on https://cg.informatik.uni-freiburg.de/teaching.htm
Material

– Matt Pharr, Greg Humphreys
  Physically Based Rendering
  Morgan Kaufmann
  http://www.pbr-book.org/

– Kevin Suffern
  Ray Tracing from the Ground Up
  A K Peters
Material

- Philip Dutre, Kavita Bala, Philippe Bekaert
  Advanced Global Illumination
  A K Peters

- Peter Shirley, R. Keith Morley
  Realistic Ray Tracing
  A K Peters
Material

- Andrew Glassner
  Principles of Digital Image Synthesis

Available online from
http://www.realtimerendering.com
Exercises

– Development of ray tracing components
– Check web page for information and example frameworks
– Voluntary
Exam

- Written
- Based on slide sets and recordings
- Relevant material will be summarized
Outline

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Light

- Modeled as energy parcels / photons that travel
  - Along geometric rays (radiance $L$)
  - At infinite speed
- Emitted by light sources
- Scattered / absorbed at surfaces
- Scattered / absorbed by participating media
- Absorbed / measured by sensors
Light travels along rays

Light is generated at light sources

Incoming light is scattered and absorbed at surfaces

Participating media scatters and absorbs light

Sensors absorb light
Color

- Photons are characterized by a wavelength within the visible spectrum
- Distribution of wavelengths $\leftrightarrow$ spectrum $\leftrightarrow$ color

$$\Phi(\lambda_1)$$

$$\Phi(\lambda_2)$$

$$\Phi(\lambda_3)$$

$\Phi(\lambda)$: number of photons per time with a wavelength in a range $\Delta \lambda_i$ around $\lambda_i$.

$$\Phi = \int_{\text{Visible Spectrum}} \Phi(\lambda) d\lambda$$

$$\approx \sum_i \Phi(\lambda_i) \Delta \lambda_i$$

$$\approx \Phi_{\text{red}} \Delta \lambda + \Phi_{\text{green}} \Delta \lambda + \Phi_{\text{blue}} \Delta \lambda$$
Governing Equations

- Light transport is governed by surfaces and by participating media
- Interactions of light with surfaces and volumes are described by governing equations
  - Rendering equation
  - Volume rendering equation
Light at Surfaces – Rendering Equation

- Governing equation for reflected light at surfaces into a particular direction given incident light from all directions.

Rendering equation:
Outgoing light into direction $\omega_o$ is a sum of incident light from all directions weighted with material properties $f_r(p, \omega_i, \omega_o)$. 

\[ L_o(p, \omega_o) = \int_{\Omega} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i) \cos \theta_i \, d\omega_i \]

- $L_i(p, \omega_i)$: Incoming light from direction $\omega_i$.
- $L_o(p, \omega_o)$: Outgoing light into direction $\omega_o$.
- $p$: Position.
- $\omega_i$: Direction of incoming light.
- $f_r(p, \omega_i, \omega_o)$: Material properties.
- $\theta_i$: Angle between incoming and outgoing light.
Light in Volumes

- Governing equations for light changes along rays through participating media, e.g. haze or fog

- Setting
  \[ L(p_1, \omega) = L(p, \omega) + s \frac{dL}{ds} \]

- Absorption
  \[ \frac{dL}{ds} = -\kappa L(p, \omega) \]

- Emission
  \[ \frac{dL}{ds} = L_e(p, \omega) \]

- Out-scattering
  \[ \frac{dL}{ds} = -\sigma L(p, \omega) \]

- In-scattering
  \[ \frac{dL}{ds} = L_j(p, \omega) \]
Light Transport

– Governing equations enable the computation of light at all points in space into all direction.
Rendering of the Result

- At an arbitrarily placed and oriented sensor
  - Cast rays into the scene
  - Lookup light that is transported along these rays
Rendering Algorithms

– Goal: Solving the entire light transport in a scene as accurate as possible
Radiosity

– Computes reflected light at all surface points into all directions
– Typical simplifications: No participating media, diffuse surfaces, equal reflected light per finite-size surface patch, e.g. triangle
– Linear system with unknown reflected light per surface patch
Ray Tracing

- Computation of light transport along selected line segments / rays
- Minimal setup
  - Consideration of rays from the scene towards the sensor (viewing rays)
  - Consideration of rays from the light source towards visible scene elements (shadow rays)
Ray Tracing - Challenge

Path 4
Computation of outgoing radiance from surface towards camera is the main goal of a ray tracer.

Path 1, 2, 3 ...
Incoming / outgoing radiance at all other paths is required to compute radiance at path 4.

Path 3
Two surfaces illuminate each other. Outgoing radiance from \( q \) towards \( p \) depends on outgoing radiance from \( p \) towards \( q \) which depends on ...
Towards Realistic Images

– Accurate modeling of the light interaction with surfaces and participating media
– Parameterizing realistic light sources and materials
– Computing the light transport for as many rays as possible
– In case of limited resources, choose relevant rays with larger radiances
Towards Realistic Images

– Capturing all direct and indirect illumination from all directions
  – Less realistic images consider few and simple light sources

https://imgur.com/gallery/MXbNt
Towards Realistic Images

- Realistic reflection properties of materials
  - Surfaces are not perfectly diffuse or specular

Next Limit / Maxwell Render
http://support.nextlimit.com/display/maxwelldocs/IOR+files
Towards Realistic Images

Emitted light

Reflected light due to material properties
Outline

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Areas

- Movies and commercials
- Architecture
- Automotive
- Flight and car simulators
- Computer games
Architecture

Mies van der Rohe Farnsworth House
(Artist Alessandro Prodan)

Delta Tracing
[www.mentalimages.com]
Automotive

zerone cgi GmbH and Daimler AG  [www.mentalimages.com]
Commercials

– Spellwork Pictures

Modeling

Rendering
Commercials

– Spellwork Pictures

Animation

Animation + Rendering
Commercials

– Spellwork Pictures
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Rasterization

1965: Rasterized lines (Bresenham)
1967: Rasterized flat-shaded polygons (Wylie)
1973: Phong illumination model
1974: Depth buffer (Catmull)
1977: Shadow volumes (Crow)
1978: Shadow maps (Williams)
Ray Tracing

- Ray casting
  1968: viewing and shadow rays, non-recursive (Appel)

- Recursive ray tracing
  1980: ideal reflection, refraction (Whitted)

- Rendering equation
  1986: general description of light interaction at surfaces (Kajiya): \[ L_o(p, \omega_o) = L_e(p, \omega_o) + \int_\Omega f_r(p, \omega_i, \omega_o) L_i(p, \omega_i) \cos \theta_i d\omega_i \]

- Stochastic ray tracing
  1986: Monte-Carlo integration for approximately solving the rendering equation (Kajiya), e.g. path tracing
Ray Casting and Rasterization

– Solve the visibility problem

Ray Casting computes ray-scene intersections to estimate $q$ from $p$.

Rasterizers apply transformations to $p$ in order to estimate $q$. $p$ is projected onto the sensor plane.

Transform

$$\begin{bmatrix}
a & b & c & d \\
e & f & g & h \\
i & j & k & l \\
m & n & o & p \\
\end{bmatrix}$$

Matrix in homogeneous notation
Ray Tracing and Rasterization

- Ray tracing
  - Can potentially compute entire light transport in a scene
  - Natural incorporation of numerous visual effects with unified concepts
  - Trade-off between quality and performance
- Rasterization
  - Focus on light transport along viewing rays
  - Specialized realizations of global illumination effects
  - Well-established, parallelizable algorithms
  - Popular in interactive applications
Some Ray Tracing History

- Ray generation
- Ray traversal
- Intersection
- Shading
- Frame buffer

Viewing and shadow rays return a radiance value / transported light along the ray.
**Some Ray Tracing History**

Recursive Ray Tracing

- Ray generation
- Ray traversal
- Intersection
- Shading
- Frame buffer

Viewing rays return a radiance. Shadow rays return a radiance. Reflection and refraction rays return a radiance.
Recursive Ray Tracing

Stochastic Ray Tracing

– Consider **randomly** sampled reflection / refraction rays to approximately solve the rendering equation

\[
L_o(p, \omega_o) = \int_{\Omega} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i) \cos \theta_i \, d\omega_i
\]

Rendering equation:
Outgoing light into direction $\omega_o$ is a sum of incident light from all directions weighted with material properties $f_r(p, \omega_i, \omega_o)$
Ray Tracing

- More light transport paths → more visual effects, realism and improved accuracy


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Ray Tracing - Capabilities

- Reflection
- Refraction
- Soft shadows
- Caustics
- Diffuse interreflections
- Specular interreflections
- Depth of field
- Motion blur

[sean.seanie, www.flickr.com]
rendered with POVRay 3.7
Ray Tracing - Challenges

- Ray-primitive intersections
  - Spatial data structures for accelerated ray traversal
  - Dynamic scenes are particularly challenging
- Number of rays (quality vs. costs)
  - More rays generally improve the rendering quality
- Recursion depth (quality vs. costs)
  - Dependent on the recursion depth, effects are captured or not, e.g. transparency or caustics
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Aspects for High-quality Image Synthesis

- Radiometric quantities
- Reflection properties of surfaces / materials
- Rendering equation
- Radiosity
- Monte Carlo ray tracing
- Ray-primitive intersections (see key course)
- Data structures for ray traversal