Advanced Computer Graphics Introduction

Matthias Teschner

Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Contact

– Matthias Teschner
052 / 01-005
teschner@informatik.uni-freiburg.de
https://cg.informatik.uni-freiburg.de/

Course Information

- Key course
  - Pattern recognition and computer graphics (rasterization)
- Specialization courses
  - Advanced computer graphics (ray tracing)
  - Simulation in computer graphics (e.g., fluids)
- Master project, lab course, Master thesis
  - Simulation track
  - Rendering track

Seminars / Projects / Theses

Semester	Simulation Track	Rendering Track
Winter	Rasterization Course Simulation Course	Rasterization Course
Summer	Lab Course - Simple fluid solver Simulation Seminar	Ray Tracing Course Lab Course - Simple ray tracer
Winter	Master Project - PPE fluid solver	Master Project - Monte Carlo ray tracer Rendering Seminar
Summer	Master Thesis - Research-oriented topic	Master Thesis - Research-oriented topic

Course Goals

- Ray tracing techniques
- Photorealistic rendering
- Global illumination techniques

- Requirements:
  - Key course in graphics and image processing
  - C / C++ / C#
  - Basics in linear algebra

Course Topics

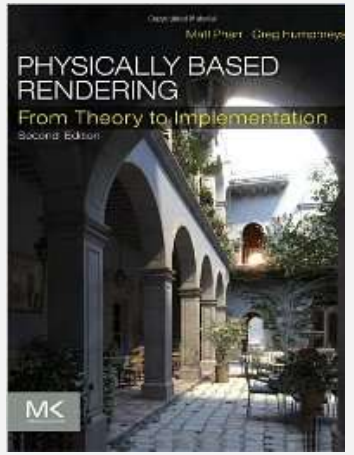
- Aspects for efficient and high-quality rendering
  - Radiometric quantities
  - Rendering equation
  - Monte Carlo integration
  - Primitives
  - Ray traversal / ray shooting
  - Sampling / antialiasing

Material

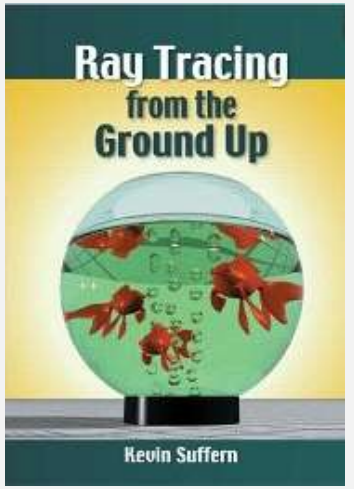
– Slide sets on https://cg.informatik.uni-freiburg.de/teaching.htm

Material

– Matt Pharr, Greg Humphreys
Physically Based Rendering
Morgan Kaufmann

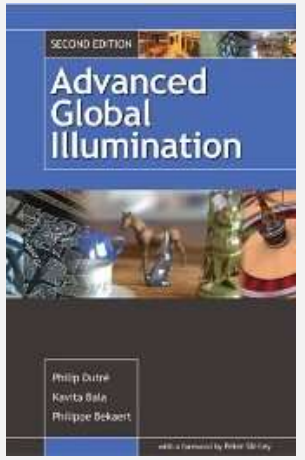


– Kevin Suffern
Ray Tracing from the Ground Up
A K Peters

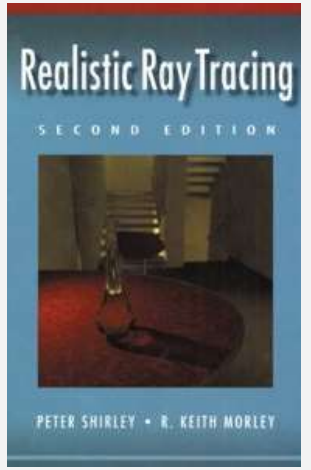


Material

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



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



Tutorials / Exercises

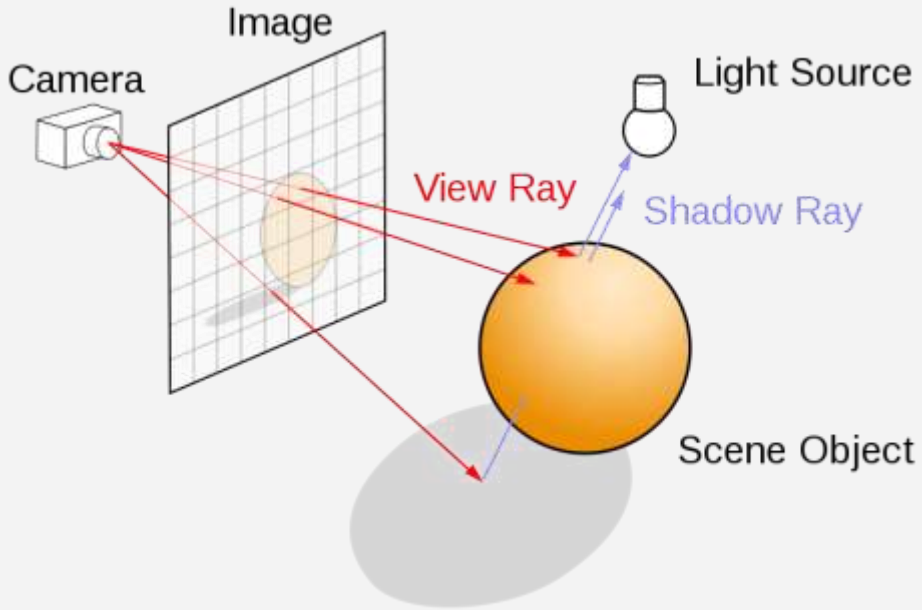
- Every second Wednesday, starting on May 9
  - Check web page for changes
- Practical exercises
  - Development of ray tracing components
  - Check web page for information and example frameworks

Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Ray Tracing

- Tracing rays through a scene to compute the radiance that is perceived by a sensor, i.e. transported along rays
- Tracing a path from a camera through a pixel position of a virtual image plane to compute the color / radiance of an object that is visible along the path



[Wikipedia: Ray Tracing]

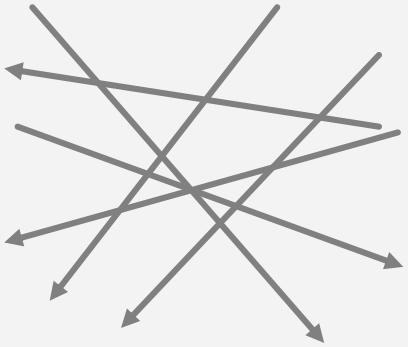
Light

- Is modeled as geometric rays
  - Travels in straight lines (e.g., no diffraction / bending)
  - Travels at infinite speed (steady state of light is computed)
  - Is emitted by light sources
  - Is absorbed / scattered at surfaces

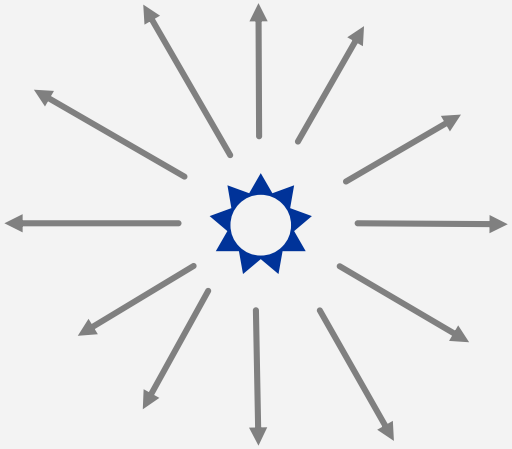
Measuring Light

- Radiance
  - Characterizes strength and direction of radiation / light
  - Is measured by sensors
  - Is computed in computer-generated images
  - Is preserved along lines in space
  - Does not change with distance

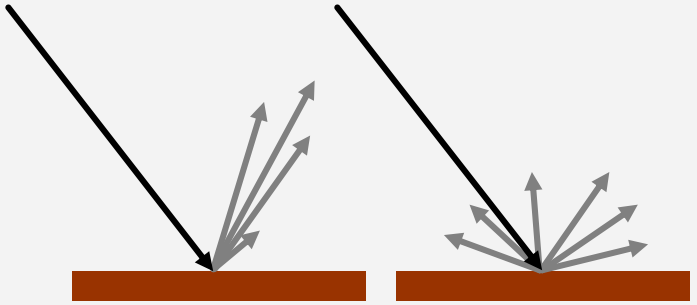
Light / Radiance



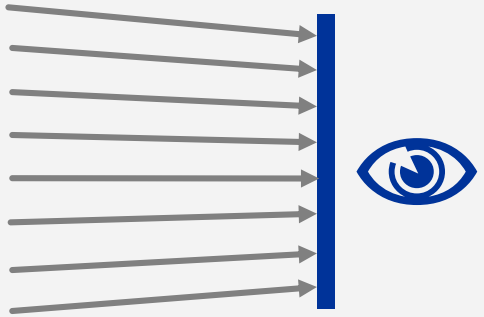
Light / radiance
travels along rays



Light / radiance
is emitted at
light sources

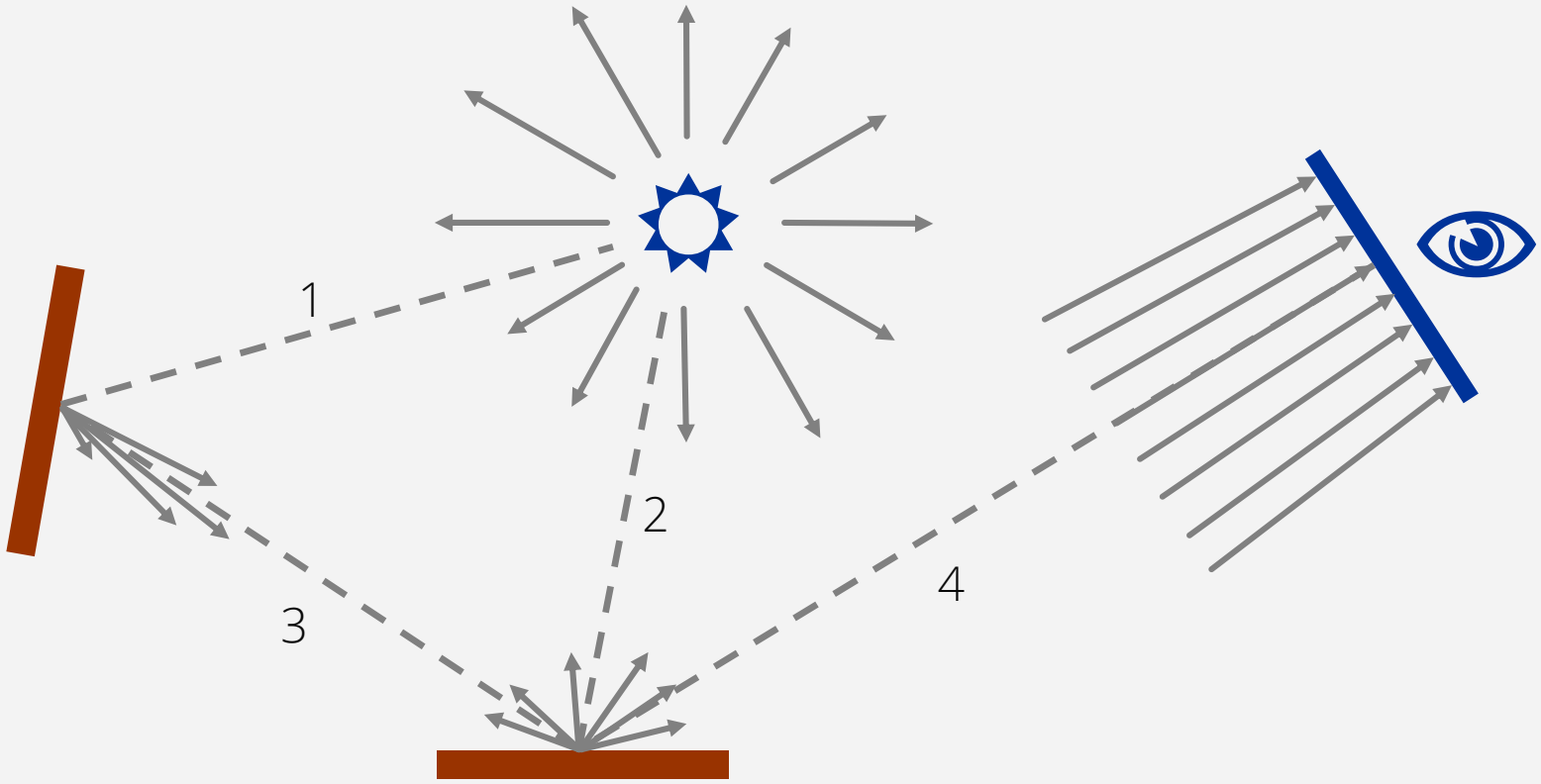


Incoming light /
radiance is absorbed
and scattered at surfaces



Cameras capture
light / radiance

Ray Tracing - Setting



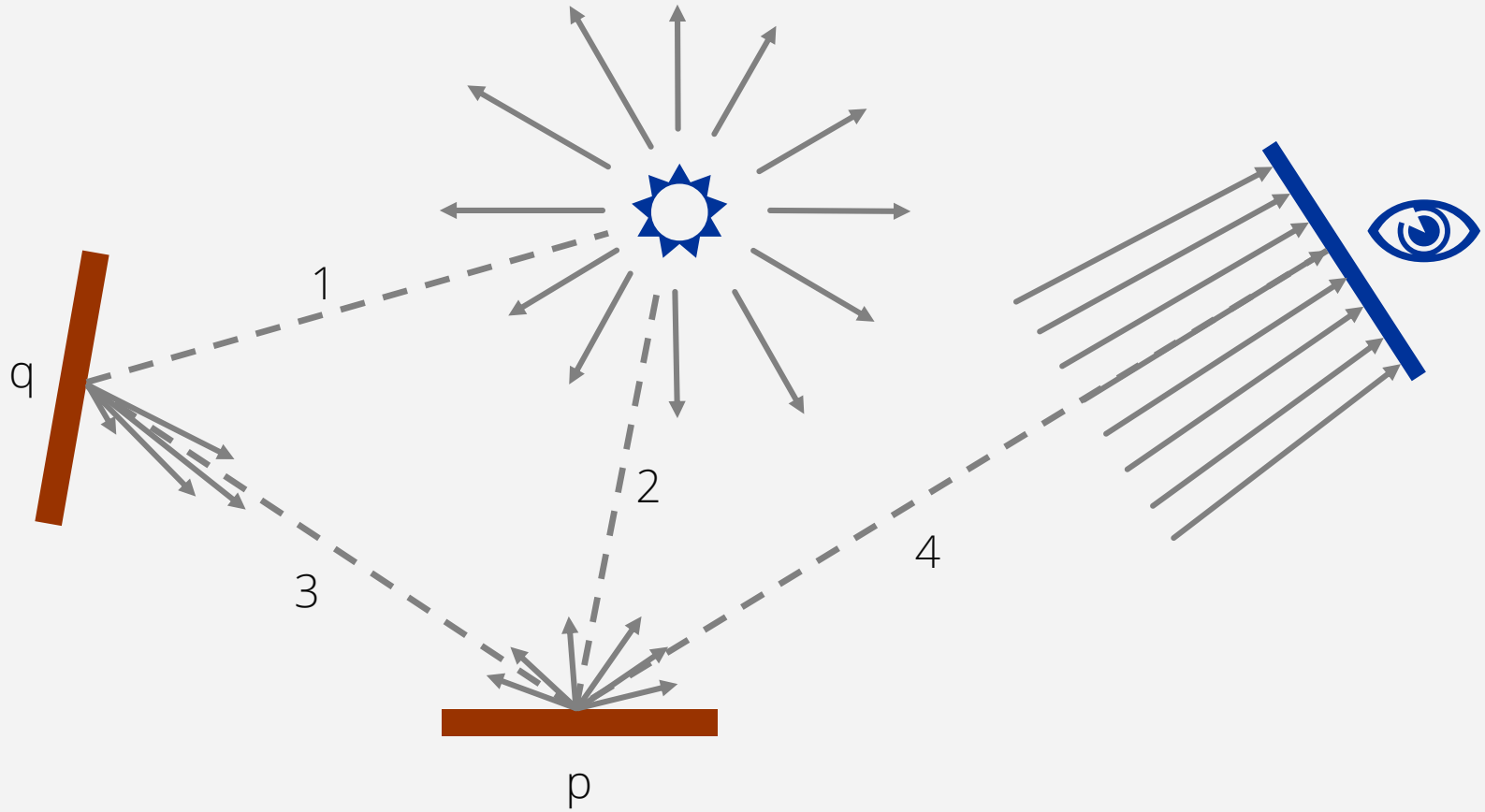
Path 1
Outgoing radiance from light
Incoming radiance at surface
Direct illumination

Path 2
Outgoing radiance from light
Incoming radiance at surface
Direct illumination

Path 3
Outgoing radiance from surface
Incoming radiance at surface
Indirect illumination

Path 4
Outgoing radiance from surface
Incoming radiance at camera

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

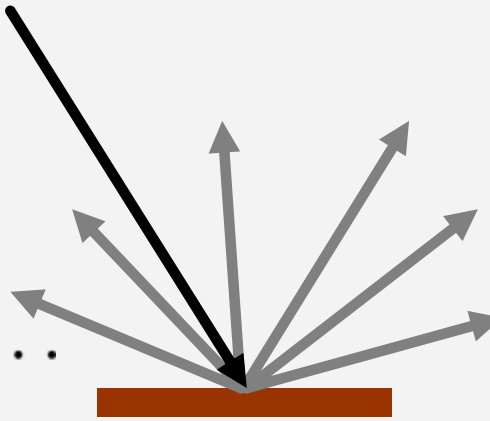
Path 3
Two surfaces illuminate each other. Outgoing radiance from q towards p depends on outgoing radiance from p towards q which depends on …

Surfaces

- Reflection properties at surfaces can be described with a function f_r (BRDF, alternative to Phong model)
- How much incident light from a particular direction is reflected into a particular direction

$L_i(p, \omega_i)$

Incoming radiance from direction ω_i



$L_o(p, \omega_o) \sim f_r(p, \omega_i, \omega_o) L_i(p, \omega_i)$

Outgoing radiance into direction ω_o

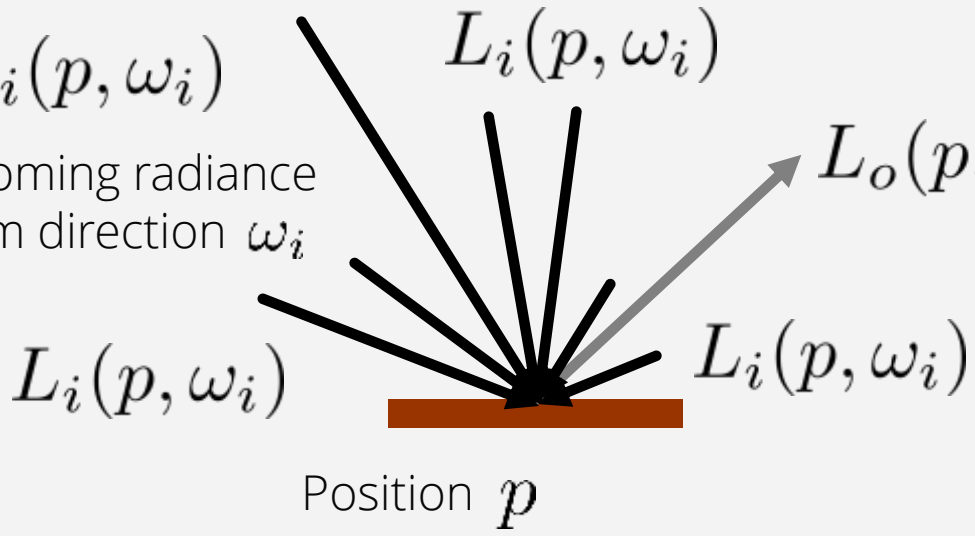
$L_o(p, \omega_o) = \ldots$

$L_o(p, \omega_o) = \ldots$

Position p

Rendering Equation

– The Rendering equation computes reflected radiance into a particular direction given incident radiance from all possible directions



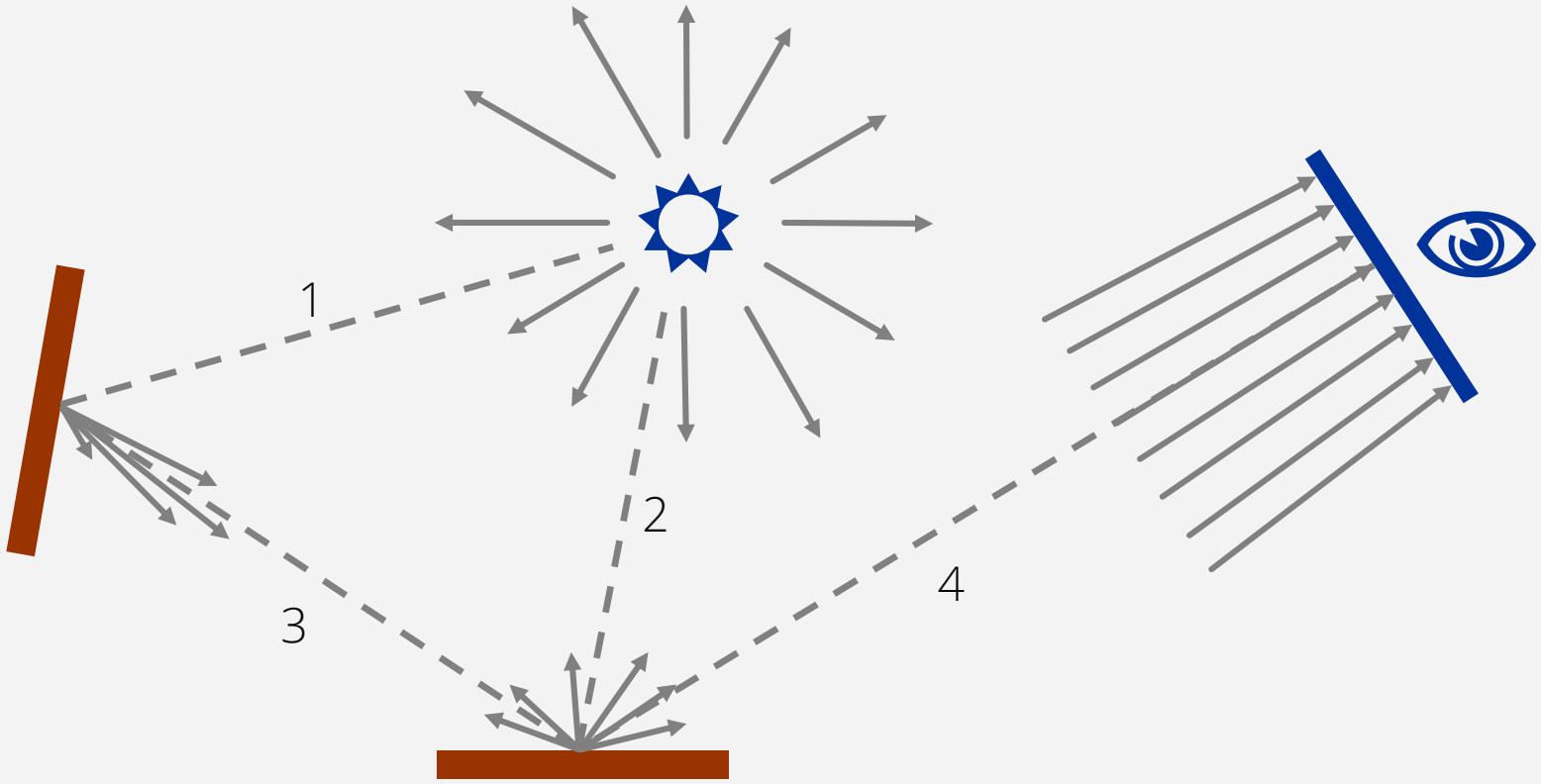
$$L_o(p, \omega_o) \sim \sum_{\omega_i} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i)$$

Rendering equation
Outgoing radiance into direction ω_o, e.g., towards the camera, is a sum of weighted incident radiances

Ray Tracing / Rendering Equation

- Ray tracers approximately solve the Rendering equation
  - $L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{2\pi+} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i) \cos\theta_i \mathrm{d}\omega_i$
  - Outgoing radiance is the sum of emitted and reflected radiance
  - Incident radiance - weighted with the BRDF f_r - is integrated over the hemisphere to compute the outgoing radiance

Ray Tracing / Rendering Equation



Path 4
Computation of outgoing radiance from surface towards camera corresponds to **solving the Rendering equation**

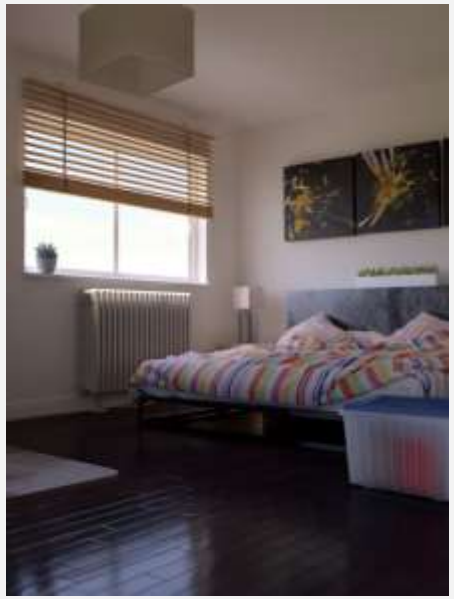
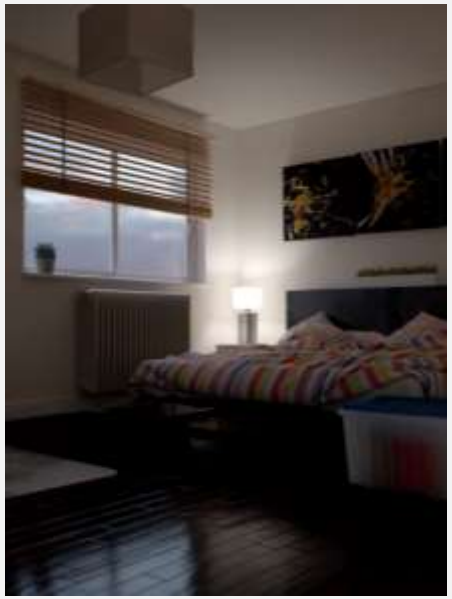
Path 3
Requires **solving the Rendering equation**

Many paths require **solving the Rendering equation**

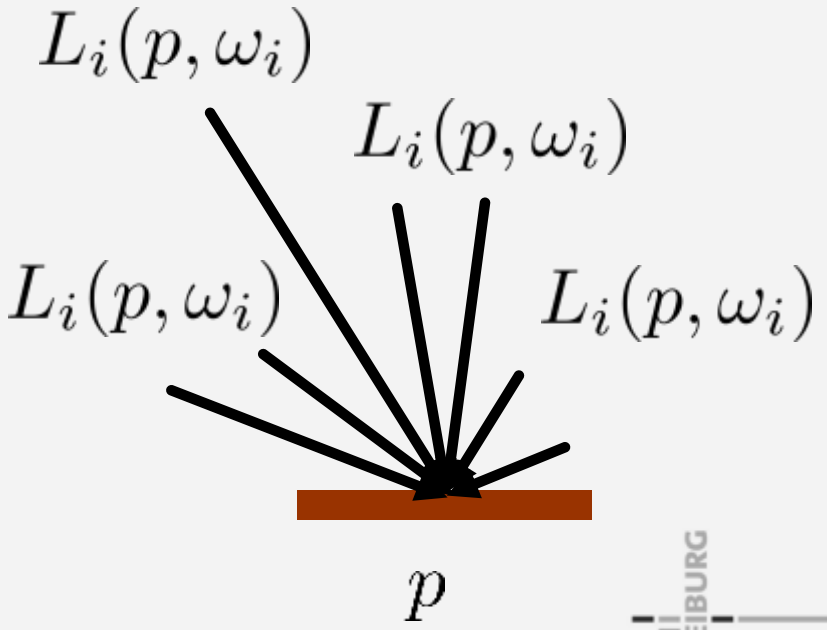
Ray tracer variants differ in the approximation quality of the rendering equation:
The more accurate, the more expensive.

Towards Realistic Images

- Capturing global illumination from all directions everywhere in a scene
  - Less realistic images consider few and simple light sources


https://imgur.com/gallery/MXbNt

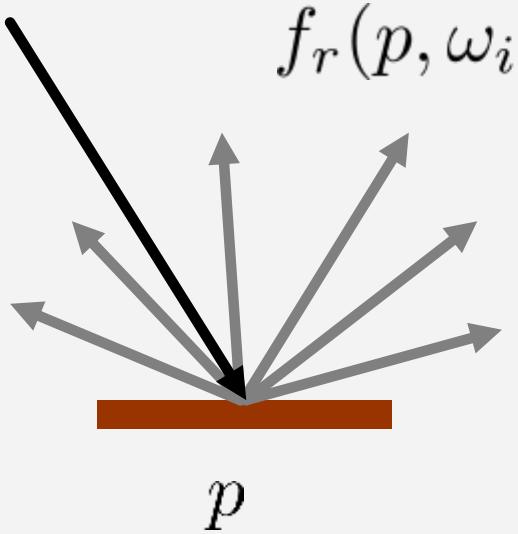


Towards Realistic Images

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

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

$$L_i(p, \omega_i) \quad L_o(p, \omega_o) \sim f_r(p, \omega_i, \omega_o) L_i(p, \omega_i)$$

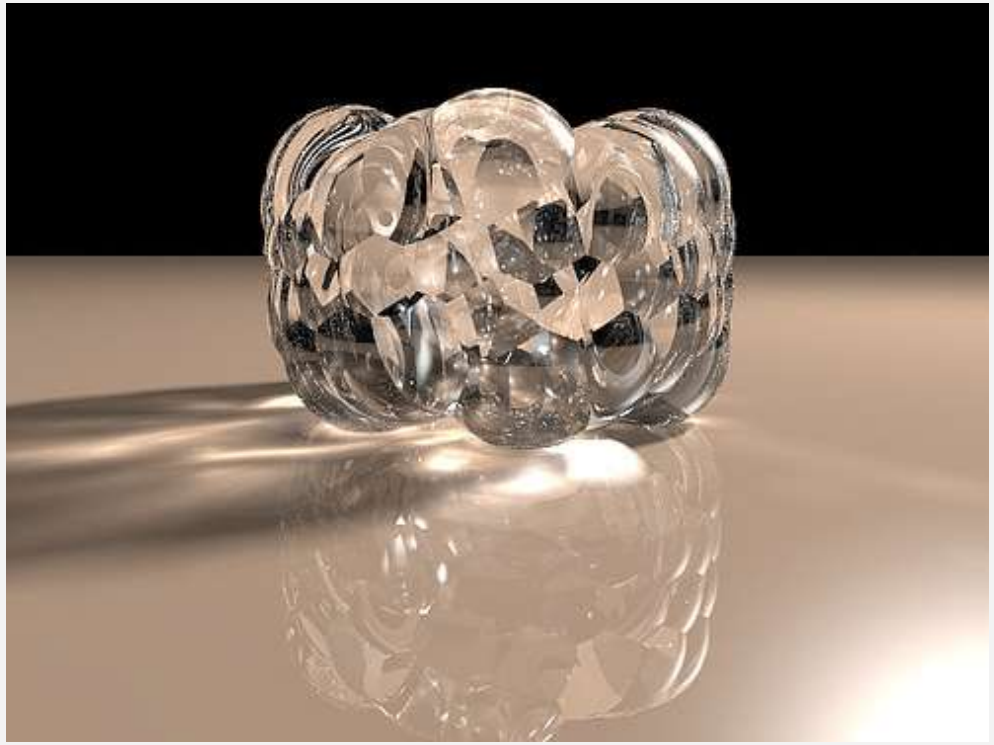


$$L_o(p, \omega_o) = \ldots$$

$$L_o(p, \omega_o) = \ldots$$

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 shooting
  - Spatial data structures for accelerated ray shooting
  - Dynamic scenes are particularly challenging
- Number of rays (quality vs. costs)
  - At ray-object intersections (solving the Rendering equation)
  - Per pixel (antialiasing)
- Recursion depth (quality vs. costs)

Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Areas

- Visual effects in movies and commercials
  - Major software packages have built-in ray tracers, e.g. Maya, 3ds Max (Autodesk), Houdini (Side Effects Software)
- Visualization of architectural design
  - Consideration of realistic indoor and outdoor illumination
- Automotive design
- Flight and car simulators
- Computer games

Software

- Mental ray (NVIDIA ARC)
- Maxwell Render (Next Limit Technologies)
- Brazil (SplutterFish)
- Arnold (Solid Angle)
- POV-Ray
- Blender
- Pbrt
- Mitsuba Renderer (Wenzel Jakob)

Examples

– Mental ray

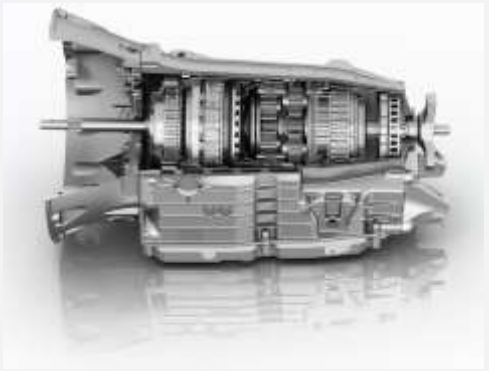
Mies van der Rohe Farnsworth House
(Artist Alessandro Prodan)

Delta Tracing

[www.mentalimages.com]

Examples

– Mental ray



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

Examples

– Spellwork Pictures

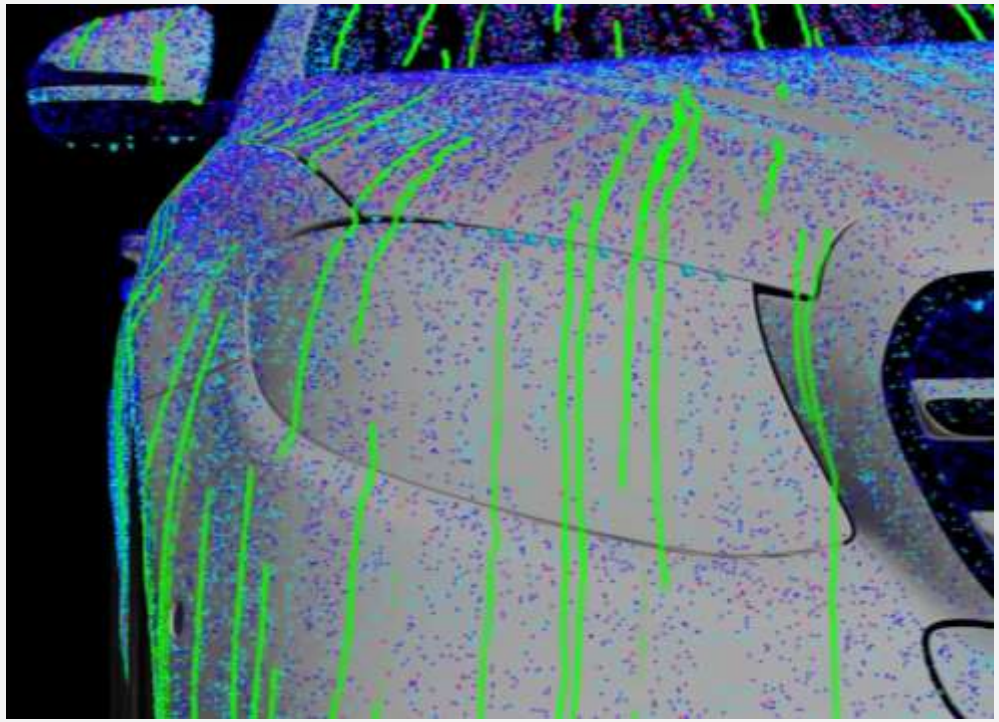
https://www.youtube.com/watch?v=DMFhM4ZfRRE

Examples

– Spellwork Pictures

Examples

– Spellwork Pictures



Examples

– Spellwork Pictures

Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Photorealistic Rendering

- Rasterization
  - 1965: rasterized lines (Bresenham)
  - 1967: rasterized flat-shaded polygons (Wylie)
  - 1971: Gouraud shading
  - 1973: Phong illumination model
  - 1974: texture mapping (Blinn)
  - 1974: depth buffer (Catmull)
  - 1975: Phong shading
  - 1977: shadow volumes (Crow)
  - 1978: shadow maps (Williams)

Photorealistic Rendering

- Ray tracing
  - 1968: viewing and shadow rays, non-recursive (Appel)
- Recursive ray tracing
  - 1980: ideal reflection, refraction (Whitted)
- Rendering equation
  - 1986: general description of light distribution (Kajiya)
    - $L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{2\pi^+} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i) \cos\theta_i \mathrm{d}\omega_i$
    - Arbitrary global illumination effects can be considered
- Distribution ray tracing
  - 1986: Monte-Carlo evaluation of integrals (Cook)
  - Approximately solves the Rendering equation

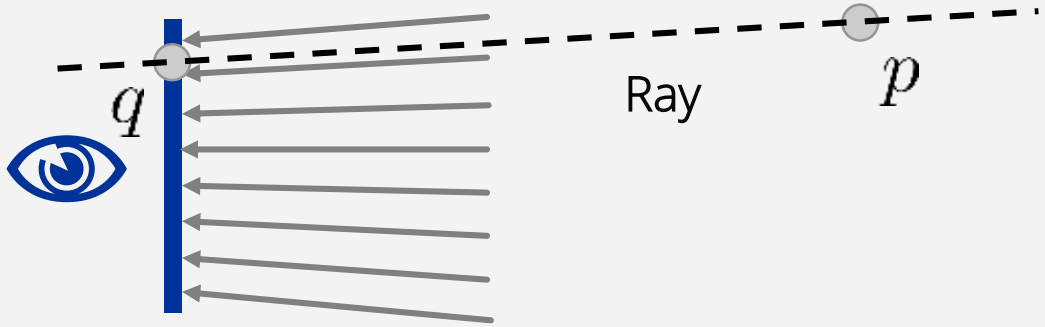
Ray Tracing vs. Rasterization

- Rasterization
  - Given a set of viewing rays and a primitive, efficiently compute the subset of rays hitting the primitive
  - Loop over all primitives
  - Implicit ray representation
- Ray tracing
  - Given a viewing ray and a set of primitives, efficiently compute the subset of primitives hit by the ray
  - Loop over all viewing rays
  - Explicit ray representation

[Ray Tracing Course: SIGGRAPH 2005]

Ray Tracing vs. Rasterization

– Solve the same problem



Ray Tracers
Compute ray-object intersections to estimate q from p

Rasterizers
Apply modelview, projection and viewport transform to p in order to estimate q

[Ray Tracing Course: SIGGRAPH 2005]

Ray Tracing vs. Rasterization

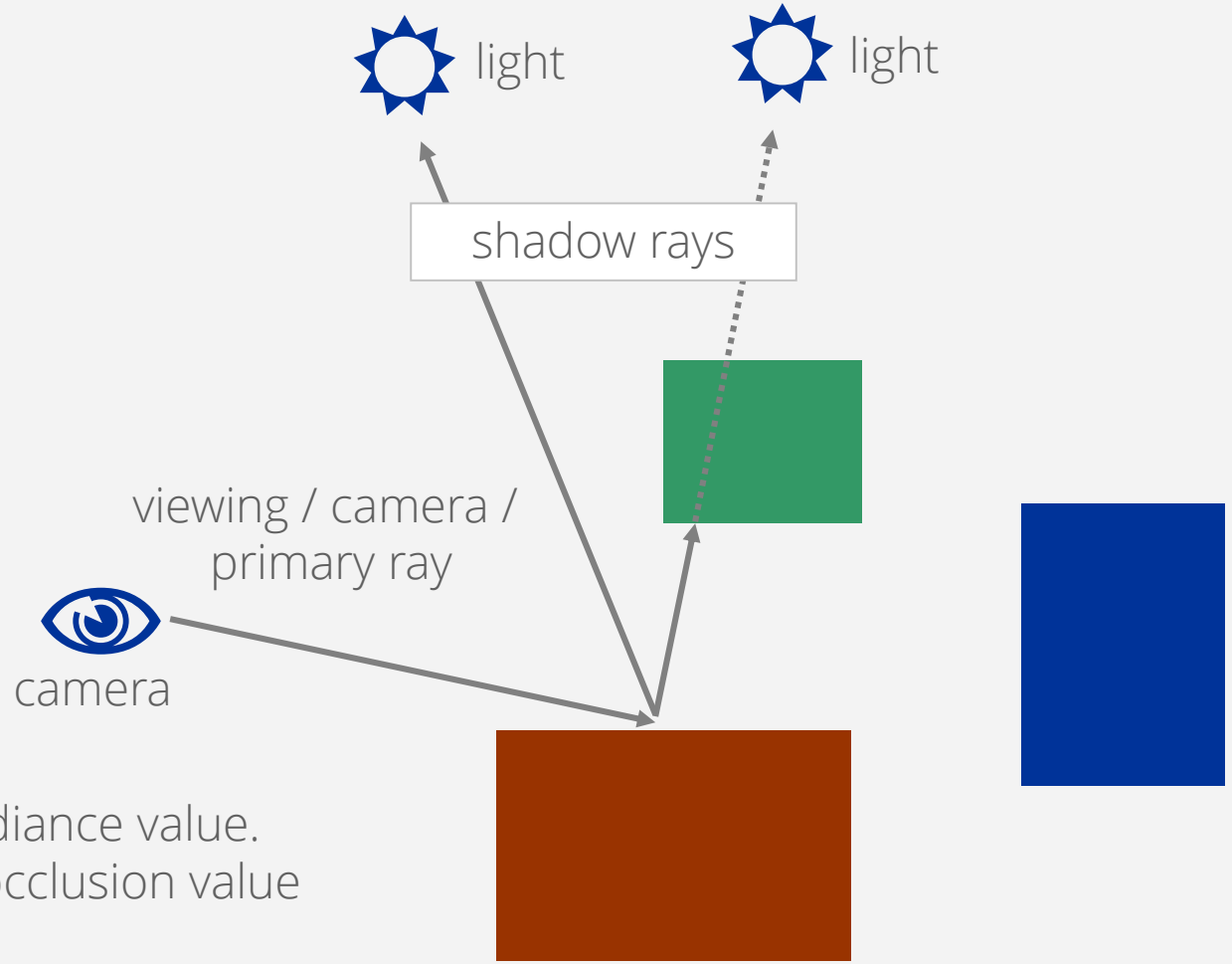
- Rasterization
  - Well-established, parallelizable algorithms
  - Popular in interactive applications
  - Specialized realizations of global illumination effects
- Ray tracing
  - Natural incorporation of numerous visual effects
  - Unified algorithms for global illumination effects
  - Trade-off between quality and performance

Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Ray Tracing

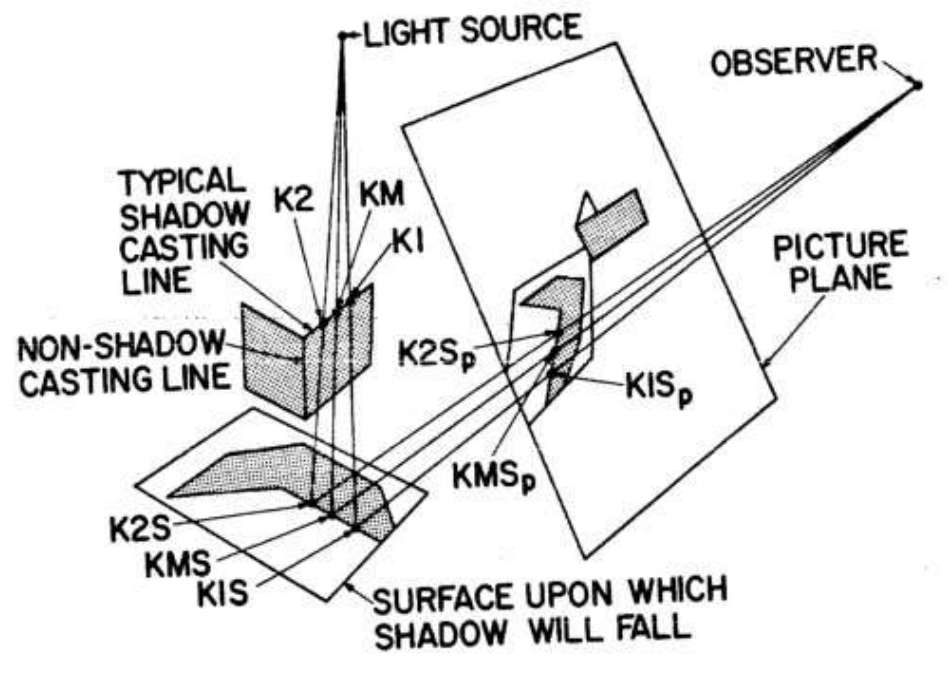
- Ray generation
- Ray traversal
- Intersection
- Shading
- Frame buffer

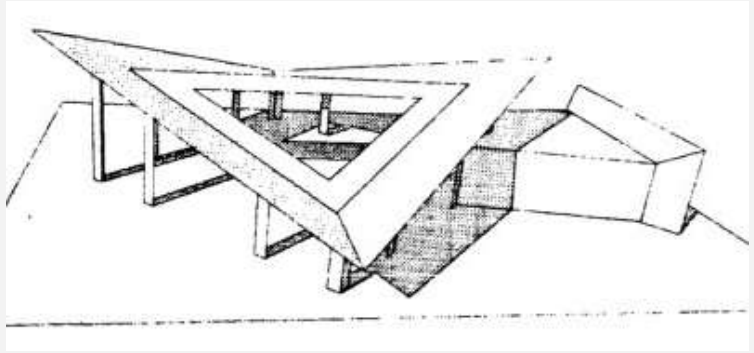


Viewing rays return a radiance value.
Shadow rays return an occlusion value
which is also a radiance.

Ray Tracing

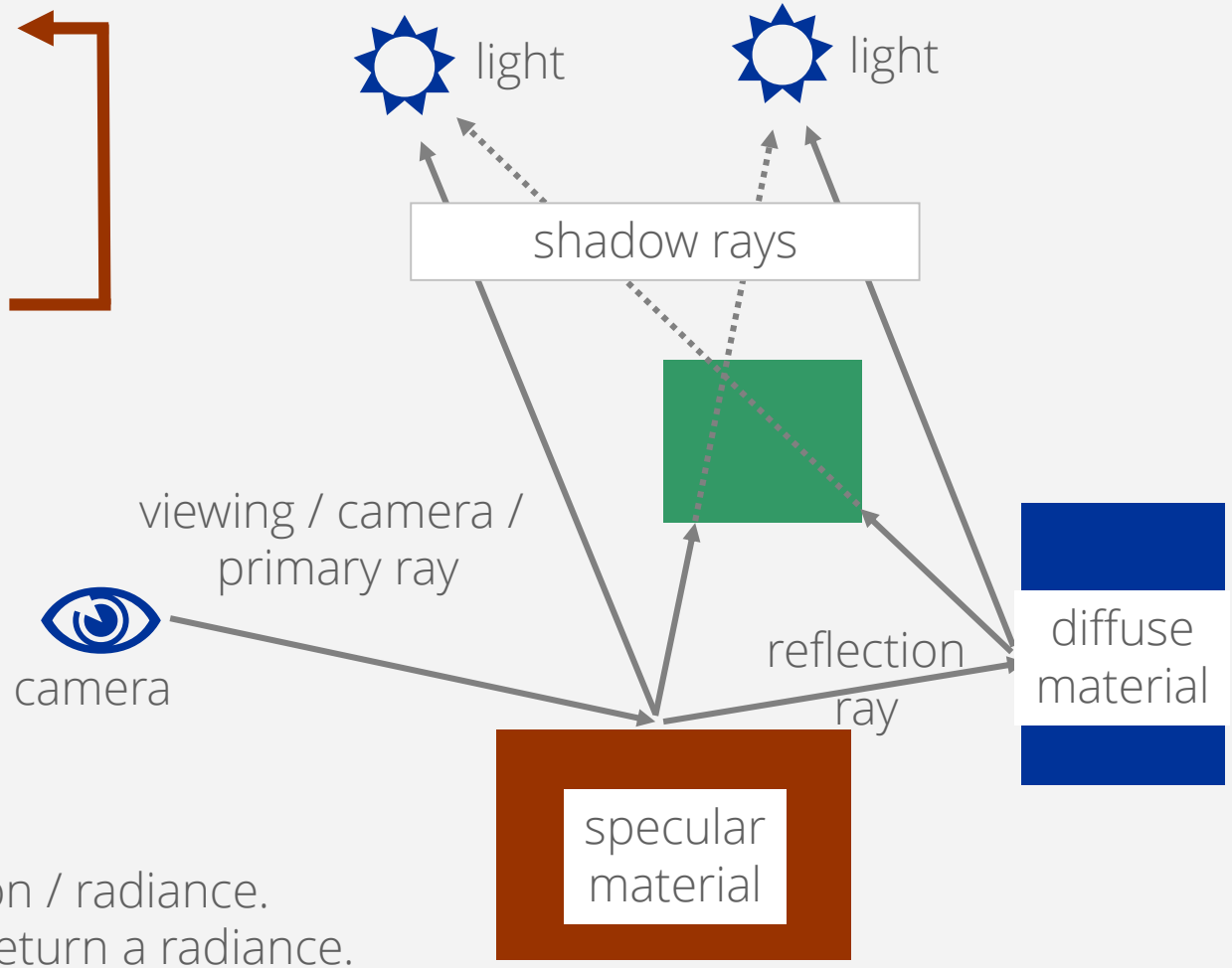
– Arthur Appel: Some techniques for shading machine renderings of solids, 1968.





Recursive Ray Tracing

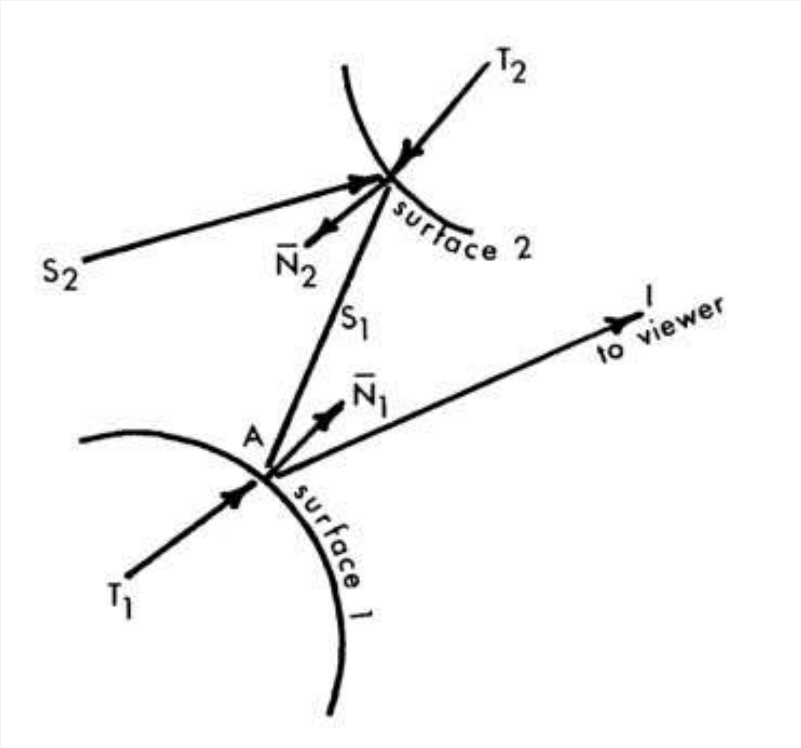
- Ray generation
- Ray traversal
- Intersection
- Shading
- Frame buffer

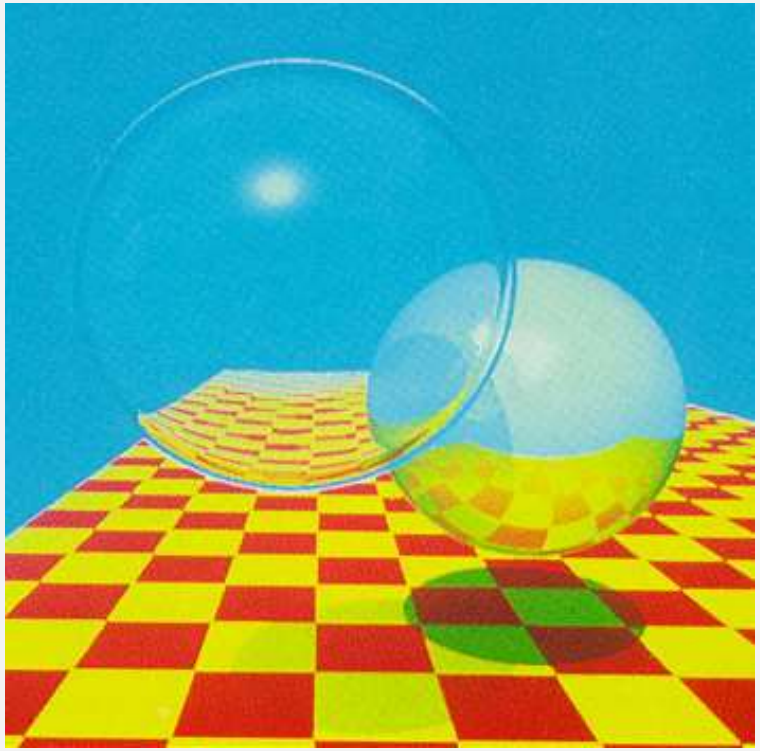


Viewing rays return a radiance.
Shadow rays return an occlusion / radiance.
Reflection and refraction rays return a radiance.

Recursive Ray Tracing

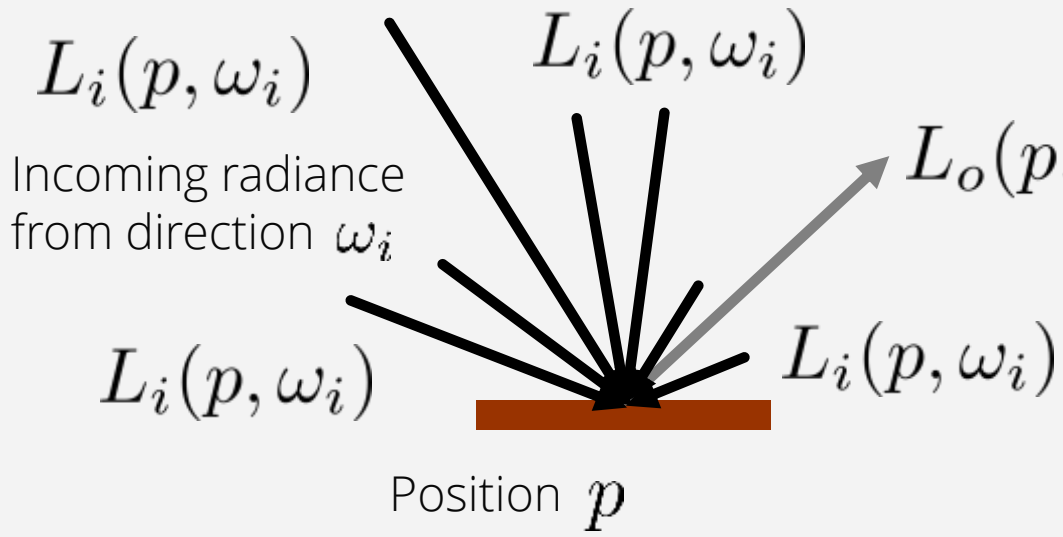
– Turner Whitted: An Improved Illumination Model for Shaded Display, 1980.





Distribution Ray Tracing (Stochastic Ray Tracing)

– Consider more than one randomly perturbed reflection / refraction ray at a surface point, e.g.



$$L_o(p, \omega_o) \sim \sum_{\omega_i} f_r(p, \omega_i, \omega_o) L_i(p, \omega_i)$$

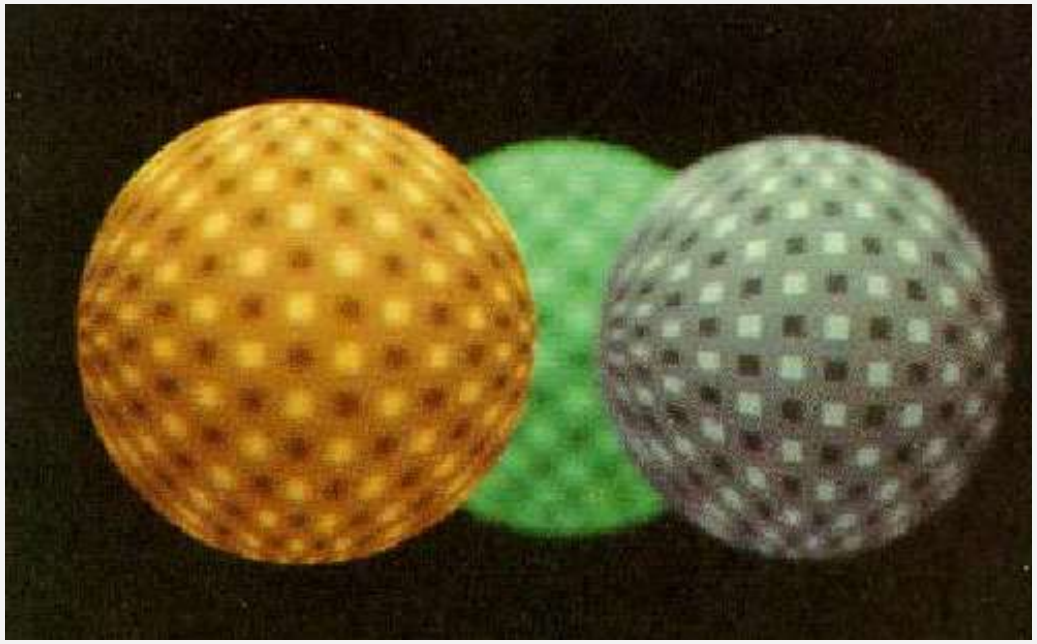
Rendering equation
Outgoing radiance into direction ω_o, e.g., towards the camera, is a sum of weighted incident radiances

Distribution Ray Tracing (Stochastic Ray Tracing)

- Examples
  - Distributing rays over the hemisphere to capture the incident radiance (Monte Carlo integration for solving the rendering equation)
  - Shadow rays over an area light source for soft shadows
  - Perturbing ray origins to enable depth-of-field effects
  - Rays per pixel over time to get motion blur effects

Distribution Ray Tracing

– Robert Cook, Thomas Porter, Loren Carpenter: Distributed Ray Tracing, 1984.



Outline

- Organization
- Concepts
- Applications
- History
- Selected variants
- Components

Overview

- Camera generates viewing rays
- Location and radiant intensity of light sources
- Ray-object intersections
- Visibility of light sources
- Surface scattering model
- Recursion
- Participating media

Camera

- Generates viewing rays
- Pinhole camera with a virtual image plane (near plane) in front of the pinhole
- Pinhole is referred to as the eye
- For a position on the image, a camera simulator generates rays along which light is known to contribute to that position, e.g.
  - A ray from the eye through the image position
  - A ray that considers one or multiple lenses

Light Distribution

- Determining the amount of light energy arriving at the differential area around the intersection point
- Therefore, geometric and radiometric distribution of light has to be known
  - For emitted light from point light sources
  - For emitted light from area light sources
  - For reflected light for object surfaces

Ray-Object Intersection

- Determine whether a ray intersects an object
- Determine the first intersection
  (closest to the ray origin)
- Determine further geometric information, e.g.
  - Surface normal
  - Partial derivatives of position and normal
    with respect to the local surface parameterization
- Efficient implementations heavily rely
  on spatial data structures

Visibility

- Determine whether a light source is visible from a surface point to be shaded
- Shadow rays are casted from the object to the light source
- If the distance to the first ray-object intersection along this ray is shorter than the distance to the light source, the surface point is in shadow

Surface Scattering

- Computes radiance scattered back along a viewing ray
- From previous components, we have
  - Ray-object intersection and further geometric information
  - Information on incident lighting
- We further know appearance properties, e.g.
  - A local illumination model
  - A Bidirectional Reflectance Distribution Function BRDF (how much light is reflected from an incoming direction to an outgoing direction)

Recursion

- Recursively invoke the ray-tracing components
- If, e.g., a viewing ray hits a mirror
  - The viewing ray can be reflected at the mirror
  - The ray-tracing routine is applied to the reflected ray
  - The resulting radiance is considered as additional illumination of the mirror
- To approximately solve the rendering equation,
  - Various rays are generated that sample the hemisphere above the surface (Monte Carlo integration)

Participating Media

- E.g., smoke, fog, dust
- In vacuum, radiance along a ray does not change
- In presence of participating media,
  light can be attenuated or extinguished
  by scattering it in different directions
- Participating media can be characterized
  by its transmittance